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Restoring riffle-pool structure in an incised, straightened urban stream channel using an ecohydraulic modeling approach

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ABSTRACT

Streams in urban and urbanizing watersheds are impacted by altered runoff hydrology and sediment yields, floodplain modifications, and channel relocations. One morphological response to urbanization is degradation of riffle-pool sequences. Pools and riffles are fundamental mesohabitat units where many lotic biota have evolved to occupy preferentially, and support diverse biological communities. Restoring self-maintaining pool-riffle structures is essential to the ecological rehabilitation of urban streams when lost. However restoring these structures can be problematic in straightened urban streams constrained by civil infrastructure preventing channel re-meandering. The project goal was to utilize geomorphic, hydraulic, and ecological principles to rehabilitate a study reach in a confined geomorphic setting with a primary emphasis on developing a stable riffle design that improves habitat patch dynamics. A 270-m tree-lined study site was selected on Beaver Creek, Knox County, East Tennessee. Through experimental 3D and 2D hydraulic modeling, a riffle-pool design was developed consisting of removing trees at expanded channel locations, placing 3.8-cm gravel substrate for the riffle bed, and deepening the pool prior to riffle entrance. Riffle-pool maintenance processes of the proposed design included occurrence of shear stress reversal between low- and high-flows, and high-flow acceleration-deceleration from pools to riffles. Cobble was interspersed on riffle surfaces for leaf pack formation. Root wads were positioned at bank locations potentially vulnerable to erosion. River2D provided useful design information to assess pre-construction channel stability and habitat quality. In this case study, an ecohydraulic modeling approach to urban stream restoration is described. Construction of four riffle-pool structures was completed in March 2012, and a geomorphic survey completed in April 2013 observed the riffle structures remained stable even with the project site experiencing eight bankfull events. Post-construction monitoring has shown that the unique design for planform-constrained urban channels has promise for increasing hydraulic habitat diversity and improving biotic integrity in these stressed environments.

1. Introduction

Streams in urban and urbanizing watersheds are impacted by hydromodification and channelization which degrade macro-bedform structure providing essential habitat for aquatic biota (Booth and Jackson, 1997; Wang et al., 2001; Fitzpatrick et al., 2004; Walsh et al., 2005a; Bernhardt and Palmer, 2007). Hydromodification from increased impervious surfaces results in higher peak flows, greater runoff volumes, and decreased summer baseflows compared with streams in unaltered watersheds (Paul and Meyer, 2001; Jennings and Jarnagin, 2002; Annable et al., 2012). Channelization includes relocation and straightening to accommodate urban land development, and where agriculture practices prior to urbanization used it to increase valley-bottom utilization and improve drainage (Morris and Moses, 1999; Wohl, 2005; O'Driscoll et al., 2010). In urbanizing watersheds, streams can become laterally constrained by adjacent floodplain development, modifying natural geomorphological processes (Wade et al., 2002; McBride and Booth, 2005; Kang and Marston, 2006). Documented modifications to natural processes include channel incision, a deepening and widening of the form morphology, and a loss of riffle-pool sequences (Simon and Hupp, 1990; Gregory et al., 1994; Simon, 1995; Bledsoe and Watson, 2001; Cianfrani et al.,

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2006; Colosimo and Wilcock, 2007). As a consequence, the loss of riffle-pool sequences severely degrades stream habitat quality and ecological function. Thus restoring stable riffle-pool structures must be a primary stream restoration objective (Emery et al., 2003; Sear and Newson, 2004; Schwartz and Herricks, 2007).

The ecological importance of riffle-pool structures is widely recognized across multiple US ecoregions because biotic communities, particularly fish and benthic macroinvertebrates have evolved to selectively occupy pools and riffles (Lamouroux et al., 2002; Poff et al., 2006; Schwartz et al., 2011; Keck et al., 2014). Based on individual species functional traits and life histories, pool or riffle habitat use are partitioned spatially extracting different tropic resources and expressing varying ecological functions, i.e., feeding, reproduction, predation and hydraulic refugia (Matthews 1990; Aadland. 1993; Newson and Newson, 2000; Schwartz and Herricks, 2005, 2008). Stream restoration efforts enhancing habitat structure need to consider the ecological functions associated with species life histories for a diverse biological community (Rabeni and Sowa, 1996; Schwartz, 2002; Clifford et al., 2006). Achieving self-maintaining riffle-pool sequences as habitat structure is problematic when geomorphological processes are impacted by urban hydromodification (Harper et al., 1998; Walsh et al., 2005b).

Self-maintaining riffle-pool morphology in natural alluvial channels occurs when adequate bedload sediment supply is transported and deposited by local hydraulics such that this morphology operates in dynamic equilibrium with channel forming flows (Hey and Thorne, 1986; Clifford, 1993; Sear, 1996; Knighton, 1998; De Almeida and Rodriguez, 2011). These flows are generally recognized with a 1.5- to 2-year return frequency, and riffle cross-sectional areas are wider and shallower than pools, and riffle spacing longitudinally averages 5–7 channel unit widths (Richards, 1976; Keller and Melborn, 1978; Gregory et al., 1994; Millar, 2004; Johnson and Fecko, 2008). Several geomorphological processes have been suggested as key principles for the development and maintenance of riffle-pool structures. These processes include the velocity or shear stress reversal hypothesis, reach-scale helical flow patterns, and turbulence scaling (Rhoads and Welford, 1991; Yalin, 1992; Cao et al., 2003).

The velocity or shear stress reversal hypothesis describes riffles with greater velocity and bed shear stress than pools during low-stage flows, opposite of which during high flows where greater velocity and shear scour pools compared to riffles where bedload deposits (Lisle, 1979; Keller and Florsheim, 1993; Carling and Wood, 1994; Cao et al., 2003; Wilkinson et al., 2004). This hypothesis characterizes a geomorphic process for a self-maintaining morphology, however hydraulic resistance from bed and banks and its influence on reach-scale hydraulics and scaling turbulence patterns also appear to be a dominant process (Nelson et al., 1995; Lawless and Robert, 2001; Ma et al., 2002; Rodriguez and Garcia, 2008). Reach-scale helical flow patterns form from

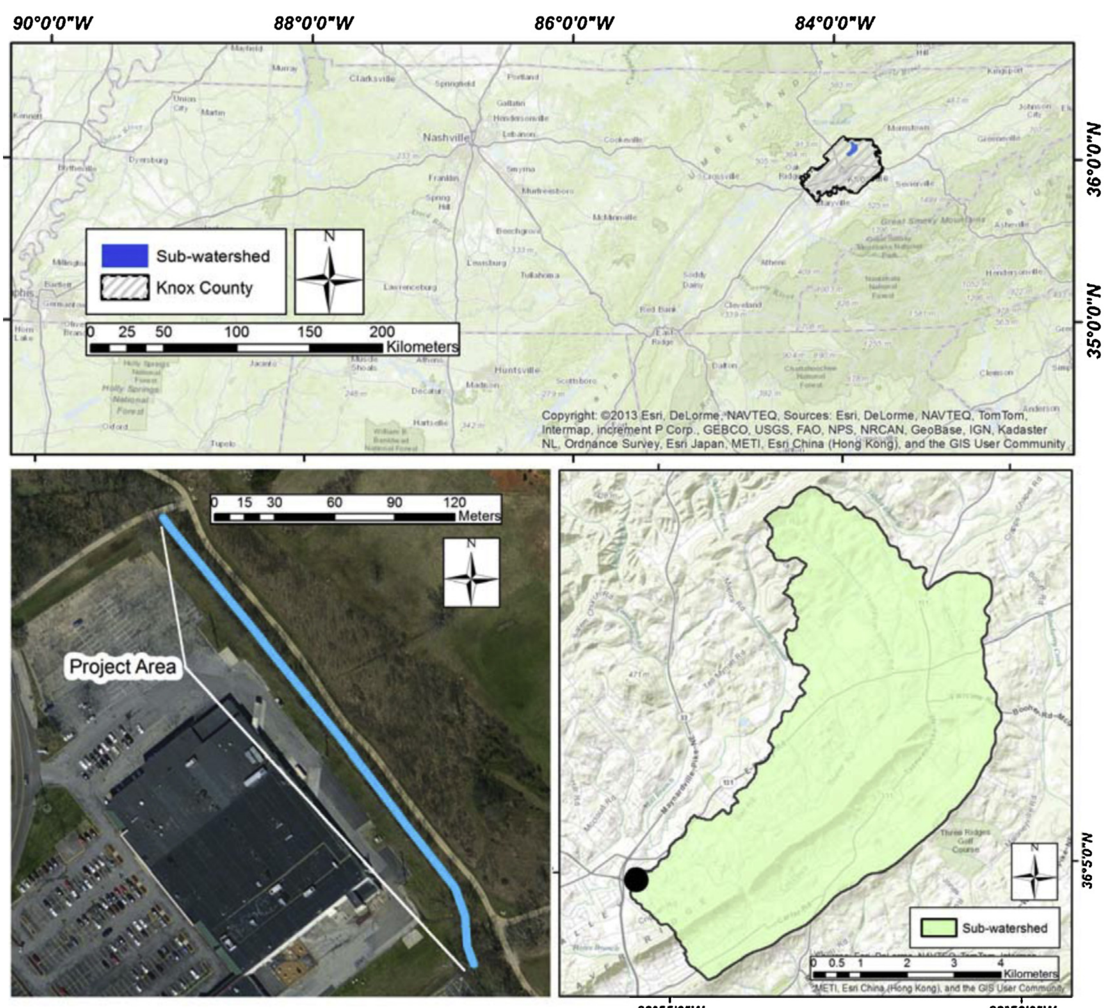

Fig. 1. Location map of Beaver Creek study site in Knox County, Tennessee. Aerial view from Google Earth™ (2009) with project site in red box and arrow showing creek flow direction.

boundary flow resistance, creating geomorphic processes for riffle-pool (bar unit) self-maintenance in both straight and meandering channels without excessive in-stream structural elements (Dietrich, 1987; Rhoads and Welford, 1991; Tamburrino and Gulliver, 1999; Frothingham and Rhoads, 2003). Yalin (1992) describes turbulent eddy development and a "bursting" cycle associated with boundary resistance in which turbulent flow structures scale to channel depth leading to riffle-pool sequence development and self-maintenance. Others have described the role of near-bed turbulence structure on macro-bedform maintenance in gravel-bed rivers (Papanicolaou et al., 2001; Roy et al., 2004; Lamarre and Roy, 2005). Less known is how bank vegetation affects reach-scale hydraulic patterns and turbulence scaling, affecting riffle-pool maintenance processes although it is well-documented that bank vegetation influences stream hydraulics and overall channel stability (Rhoads et al., 2003; Hession et al., 2003; Simon and Rinaldi, 2006; Clark and Wynn, 2007). Relationships between bed and bank structures and their influence on reach-scale turbulence patterns need to be considered for restoration designs.

A fundamental question remains whether these hydraulic and geomorphic processes can be applied in urban streams such that a stable 'natural' channel can sustain a riffle-pool sequence form over time while confining lateral adjustment. In general, stream restoration practices today have not applied multi-dimensional free-surface hydraulics, mostly relying on an anti-log reference reach approach (Rosgen, 2006; Niezgoda and Johnson, 2005). Conflicting assessments of the reference reach approach for stream restoration has been discussed (Shields et al., 2003; Bernhardt and Palmer, 2007; Nagle, 2007; Slate et al., 2007; Simon et al., 2007; Rosgen, 2008). In urban streams impacted by watershed hydro-modification, this approach can be problematic due to the fact reference reaches may not appropriately represent urban streams in geomorphic non-equilibrium (Bledsoe and Watson, 2001; Doyle et al., 2007).

A common restoration practice in non-equilibrium streams with incising channels is to use hydraulic grade controls consisting of various weir structures (Rosgen, 1996; Niezgoda and Johnson, 2006; Bledsoe et al., 2012). However in low-gradient streams, weir structures can create long pools and because of their height potentially create an upstream backwater inundating riffles during low flow. Many design problems for stream restoration in non-equilibrium conditions can be aided by the use of hydrologic and hydraulic models that quantify changing flow regimes associated with urbanization. Models are also valuable tools to test design ideas for stable riffle-pool structures and apply ecohydraulic concepts (Shamloo et al., 2002; Bockelmann et al., 2004; Booker et al., 2003; Booker and Dunbar, 2004; Smith and Prestegaard, 2005). Noting that the return to a pristine is not possible in urban streams, an ecological engineering approach is essential to improve biological integrity (Van Bohemen, 1998; Schwartz et al., 2001).

As a case study, the goal of this paper is to describe an ecohydraulic design process in order to restore self-maintaining riffle-pool structures in a straightened, incised urban stream where channel planform is laterally constrained by infrastructure. The specific objectives of this study were to: (1) assess geomorphic concepts for self-maintaining riffle-pool sequences utilizing multi-dimensional hydraulic models; (2) utilize ecological data and integrate that data into a hydraulic modeling design process; and (3) from a newly proposed riffle-pool design, construct field-scale structures and assess stability and biological integrity.

2. Background information

2.1. Study site

The study site included a 270-m reach of Beaver Creek located in Knox County, Tennessee (Fig. 1). The watershed lies in the Ridge and Valley physiological providences, consisting of a trellis drainage pattern. The drainage area is 39 km^2 containing 14.2% urban developed lands (residential, commercial, and industrial) based on the USGS 2006 National Land Cover Database. In general, the upper Beaver Creek watershed has been urbanized concurrently with the overall metropolitan growth of Knoxville. Historically, the stream was channelized when the adjacent land was used for dairy production with local residents indicating channelization occurred in the 1930s, but no direct evidence was obtained on an exact date.

The channel has incised over the past decade likely due to hydromodification as evidenced by the tree trunk curvature (Fig. 2). The 6.5-m wide channelized reach has an average slope of 0.0001 m/m, and both bank and bed consist of cohesive soils. Trees line the channel on both banks and impede flows greater than 1.7 m^3/s. Bankfull flow was approximately 4.0 m^3/s, defined as the stage overtopping the bank onto the floodplain. A GlobalWater WL400 stage recorder was installed in August 2009, and has continuously recorded flow stage at 15-min intervals. Mass bank-failures have not occurred likely due to the cohesive soil property and the dense woody vegetation on the banks. The study reach was observed with diminished riffle-pool morphology, with the habitat structure consisting mostly of long glides and local scour pools adjacent to large bank root masses (Dworak, 2005).

The straight channel is bordered on the west with a Food City grocery store and parking lot, and on the east bank with a paved greenway (Fig. 1). The Knox County Parks and Recreation Department manages the greenway. At the end of the study reach

Fig. 2. Photos of the 6.5-m wide incised channel showing dense woody vegetation on the banks (left) and flood flow near bankfull (right).

protecting a pedestrian bridge to the greenway is a rip-rap rock grade control spanning the channel. Both sides of the Beaver Creek were constrained with urban development, including buried optical communication lines preventing a natural channel design approach per Hey (2006) utilizing re-meandering.

2.2. Pre-Construction geomorphic and biological site data

Sediment particles sizes for bed material and transported bedload, and bank critical shear stress (τ_c) were geomorphic data obtained to support the restoration design process. Beaver Creek was incised into cohesive material, with the bed covered with thin-veneer patches of sand and fine gravel mixtures. The D_{50} of the bed sediment per standard pebble count was measured as 6 mm (Cantrell, 2009). Cantrell (2009) also measured bedload transport with Bunte et al. (2004) net traps determining the reach was supply-limited with the transported material measured as 1.4-mm D_{50} and 18-mm $D_{\max}$. Because urbanization has the potential to reduce bedload sources through stormwater drainage piping and detention facilities (MacRae 1997), it was important to understand whether the reach was supply- or capacity-limited. Thus the measurements by Cantrell (2009) indicated that the design must specify placement of riffle gravel substrate. The τ_c for the cohesive bank material was also needed in the design process to identify potential locations where excessive erosion could compromise channel stability. The bank τ_c was determined as 3.8 Pa utilizing a Hanson, (1990) jet test device (Mallison, 2008). This τ_c was compared with bed shear stress (τ_0) estimates from River2D model simulations at bankfull discharge (4 m^3/s) to identify susceptible locations that may require local bank scour protection.

Biological data included pre-construction surveys for benthic macroinvertebrates and fish. Benthic macroinvertebrate data identified the Beaver Creek site as water quality impaired from “siltation” and habitat alternation, and the site was reported on the state 303(d) list (TDEC, 2006). Williams (2005) states a Tennessee Macroinvertebrate Index (TMI) score of 28 (TMI range 0–42), which is considered partially impaired by state water quality statues. Within the Beaver Creek watershed, fish Indices of Biotic Integrity (IBI) ranged from 27 to 50 (IBI range 0–60), and were inversely correlated with percent urban land cover (Sain, 2006). Sain (2006) found healthy fish communities within the watershed as potential fish source areas in order to recolonize degraded reaches, including many intolerant Centrarchidae, Cyprinidae, and Percidae species. The fish surveys indicated that restored riffle-pool habitat would likely benefit fish communities at the Beaver Creek study reach.

3. Development of a riffle-pool design for urban stream restoration

As noted above, development of a riffle-pool design for a low-gradient, straight urban stream constrained by urban development required the use of hydraulic models. Three- and two-dimensional (3D, 2D) hydraulic models were used to investigate the influence of bank vegetation on reach-scale helical flow patterns, flow deceleration-acceleration zones longitudinally through proposed riffle-pool sequences, and shear-stress reversal for riffles and pools between low- and high-flow stages. Design development also included the application of fluid mass continuity where a 2D model illustrated the effect of increased channel cross-sectional area at proposed riffle locations on decreasing average velocities. Understanding flow resistance and turbulence patterns from tree-lined banks, and the potential role it plays in riffle-pool maintenance was particularly important in developing an urban stream restoration design strategy for forested ecoregions (Fig. 2).

The proposed conceptual design to be qualitatively assessed by hydraulic models consisted of removing trees at laterally-expanded channel areas to form a deceleration zone during high flows, and maintaining the existing narrow tree-lined channel to promote acceleration (Fig. 3). Within the context of the proposed design, several geomorphic questions were posed and investigated through modeling; they were: (1) does tree bank vegetation and the scaling of turbulence structure to bank trees prevent development of reach-scale helical flow patterns; (2) can acceleration-deceleration zones be created with alternating high- and low-resistant sections of stream bank, relative to each other as tree-lined and not; (3) can deceleration zones be accomplished at constructed riffles by channel expansions based on continuity principles; (4) how important is the entrance slope into a riffle structure for energy dispersion and prevention of riffle thawleg scour; and (5) is velocity/shear stress reversal observed from low- to high flow?

In addition to assessing the proposed riffle-pool structures and consistency with published geomorphic theories on maintenance processes, this case study illustrated the utility of 2D hydraulic models in restoration as an ecohydraulic design approach. Ecological criteria were incorporated into the hydraulic modeling effort based on Physical Habitat Simulation (PHABSIM) methodology (Ghanem et al., 1996; Schwartz, 2003; Booker and Dunbar, 2004; Ernst et al., 2010). Overall, an ecohydraulic approach to restoration design integrates fluvial geomorphology, hydraulics, and ecological principles.

3.1. Geomorphic concepts and hydraulic model design simulations

3.1.1. Influence of bank trees on reach-scale hydraulic patterns

3.1.1.1. Background. Many theories and geomorphic process mechanisms support why riffle-pool sequences are maintained in alluvial streams (Knighton, 1998). Sequences commonly occur between 5 and 7 channel unit widths in succession in both straight and sinuous channels, and are strongly influenced by cross-sectional width to depth ratios (Keller and Melhorn, 1978; Dietrich, 1987; Gregory et al., 1994). Development and maintenance processes involve the hydrodynamics of sediment transport in the channel, and scaling of turbulence structures to form oscillating patterns of bed deposition and scour (Yalin, 1992; Clifford, 1993). In straight channels, Yalin (1992) theoretically explained development of riffle-pool sequences as based on macroturbulent flow scaling and an eddy bursting process

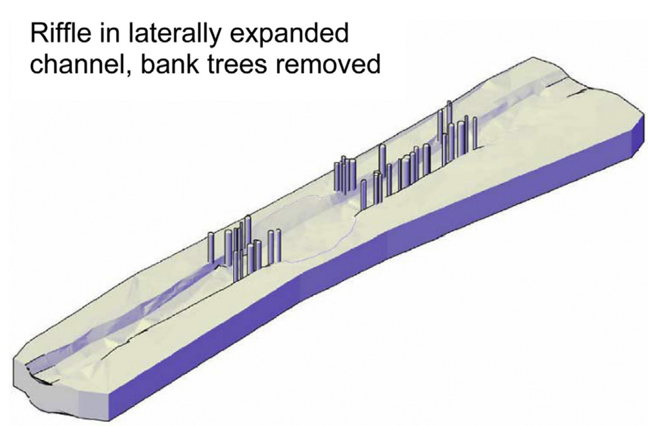

Fig. 3. Topographic rendering of proposed conceptual design for the constructed riffle areas forming hydraulic acceleration-deceleration-acceleration patterns. Model section approximately 105 m in length and bed and bank topography from site survey.

initiated by differential high- and low-speed flow layers. Turbulent eddy development and final bursting scales to water depth, where it creates “sweep” velocity vectors orientated towards the bed inducing scour and sets up a feedback loop of continued scour sequencing at approximating six flow depths.

No one theory explains the riffle-pool formation, but observations and modeling has illustrated the importance of acceleration-deceleration patterns and longitudinal flow alternating convergent-divergent patterns (Thompson, 1986; Rhoads and Welford, 1991). Convergent-divergent flow, combined with secondary circulation currents form helical patterns where surface flow convergence occurs at pools increasing bed shear and inducing scour during high flows, and at riffles flow convergence occurs at the stream bed reducing shear and favoring sediment deposition (Lane et al., 1998). Because the downstream velocity is greatest compared to the secondary circulation, a helical flow pattern is theoretically maintained (Frothingham and Rhoads, 2003). However most modeling and field measurements have been conducted on channels without excessive bank resistance, as which occurs in forested Appalachian streams. In general it is agreed that once formed, riffle-pool morphology controls hydraulic scour and deposition patterns through sediment transport and sorting, thereby playing a key role in equilibrium dynamics of channels (Heritage and Milan, 2004; Rodríguez and Garica, 2008).

3.1.1.2. Method. Computational fluid dynamics (CDF) model simulations were performed in order to characterize flow structures during bankfull stage examining the influence of tree-lined banks on flow resistance and reach-scale hydraulic patterns (Dworak, 2005). FLOW-3D®, a three-dimensional CFD model with a graphical user interface was used to generate study reach simulations. Study site topography was surveyed with a Trimble® total station and Recon® data-logger, extending 105 m with topography and tree locations imported as ASCII formatted *x–y–z* files into FLOW-3D® (Fig. 4). Trees along banks were generated as model subcomponents and represented as symmetric vertical cylinders; measured diameters were applied to 102 trees surveyed on both banks. A 3D finite element grid was generated for the entire flow field with grid spacing capable to resolve vortices around trees. A 1.68 m^3/s discharge and corresponding stage of 1.72 m was simulated in which trees on both banks impeded flow. The turbulence closure scheme for Reynolds stresses utilized the k-ε model. The roughness height coefficient “k” was computed by a FLOW3D® algorithm based on hydraulic radius and a selected Manning n of 0.019. Steady-state conditions were modeled, in which computational stability was achieved over the simulation time. Full details of the FLOW3D® model set-up, boundary conditions, and model performance parameters can be found in Dworak (2005).

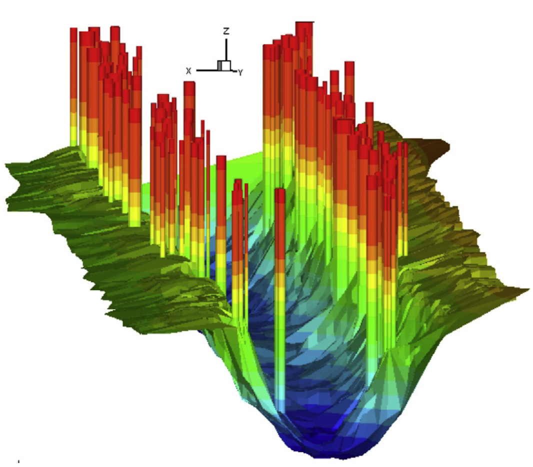

Fig. 4. Topographic image with trees as vertical cylinders used for the FLOW3D® model boundary.

FLOW3D® modeling scenarios included: (1) incised channel with bank trees generating large-scale roughness, the existing condition of the study site; and (2) incised channel, where bank tree clusters were spaced 5–7 channel unit widths to create acceleration-deceleration flow patterns, a model modified condition. Dworak (2005) also modeled a scenario in the incised channel without bank trees, where bank roughness was a function of boundary morphology only, in which helical flow development was suggested by visual inspection of simulation output.

3.1.1.3. Results. FLOW3D® model results presented here within include cross-sectional velocities along a longitudinal sequence for the two scenarios defined above. The datum for the longitudinal distances along the 105-m modeled reach starts with zero at the downstream boundary. Velocity vectors near bank trees were pronounced representing flow deflection, and forming vortices immediately downstream of trees (Fig. 5). In most cross-sections, the downstream velocity vectors dominate in the mid-channel with near-bank vectors scaling to tree or boundary roughness. Cross-sections at longitudinal distances 59.90 m and 55.03 m showed development of channel-scale secondary flow vectors, and again at distance 49.62 m. A noticeable immediate depression in the streambed at longitudinal distance 45.84 m of the channel caused downward directed vectors. Large-scale heterogeneity in bed-topography, such as channel morphology and ledges within the streambed, and the presence of trees on the banks appeared to prevent the development of helical flow patterns along the modeled channel length. Scaling of turbulence structures near the trees is evident per modeling output in Dworak (2005); where the dissipation rate per unit mass of turbulent kinetic energy (TKE) exceeded 0.01 J/kg-s downstream of trees impeding flow. It is noted that the model was not field verified; although field measurements by a Sontek™ acoustic Doppler velocity (ADV) meter were obtained in 2007 and velocities compared well with model simulations of the unaltered channel (unpublished data). In general, the CFD results illustrate the potential for flow resistance and reach-scale turbulence structures to be heavily influenced by the densely-spaced bank trees, and potentially affecting riffle-pool maintenance hydraulics.

In order to examine the influence of sequencing bank roughness on creating acceleration-deceleration zones, a FLOW3D® modeling scenario removed the tree (cylinders) on both banks from longitudinal distances approximately 30 m–58 m and 75 m–96 m (Dworak, 2005). Cross-sectional velocities from model were plotted along a longitudinal sequence for the same distances as with all trees modeled. Per visual inspection, development of reach-scale secondary flows appeared to occur and potentially in a helical pattern (Fig. 6). At longitudinal distance 79.85 m, secondary flow vectors appeared orientated “left”, followed by two circulation cells with converging vectors at the water surface at distance 77.09 m, and a reversal of secondary flow to the “right” at 60.17 m. The same downward directed velocities as observed in Fig. 5 due to a bed slope drop is observed in Fig. 6 under this modeling scenario. Results suggest that modifying tree bank resistance to promote acceleration-deceleration zones could potentially be a useful strategy for stream restoration. Further research is needed to investigate this hydraulic phenomenon; however, for the purpose of developing a riffle design for straight urban streams these CFD results will be applied in this study.

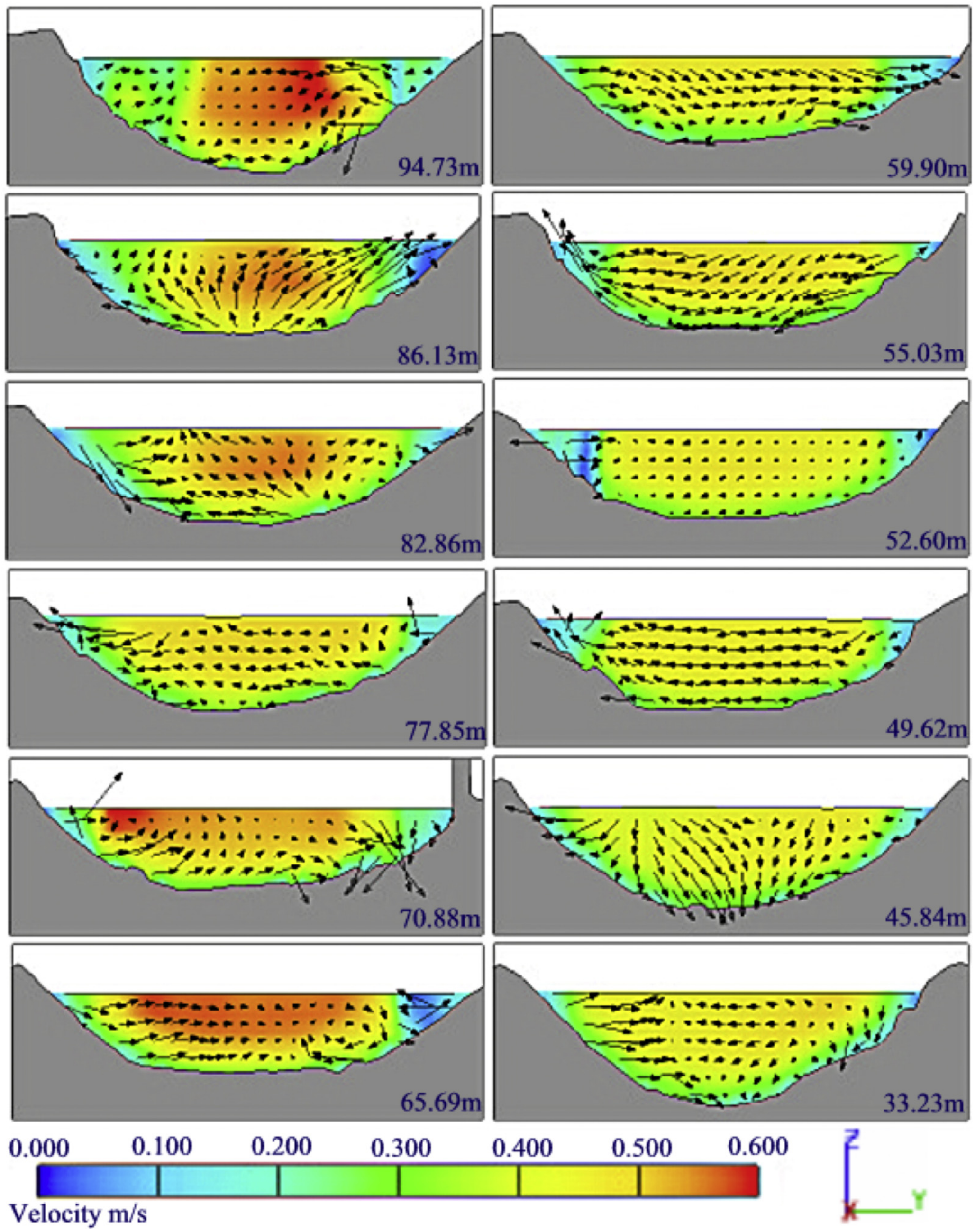

Fig. 5. FLOW3D modeled maximum velocity magnitude and velocity magnitude vectors.

3.1.2. Influence of channel width expansions and riffle incline slope on hydraulic patterns

3.1.2.1. Background. In order to examine the influence of channel width expansions and riffle incline slope on reach-scale hydraulics as potential design considerations, River2D was used. River2D utilizes 2D shallow-water, depth-averaged Saint Venant equations conserving mass and momentum through an unstructured finite element mesh (Steffler and Blackburn, 2002). For computational stability, finite element solutions are based on the Streamline Upwind Petrov-Galerkin weighted residual formulation (Ghanem et al., 1996). River2D has wetting-drying capability on banks utilizing groundwater flow equations and transmissivity. Model output from River2D includes plots per finite element cell for velocity, water depth, water surface elevation, Froude number, and shear velocity (Schwartz and Neff, 2011).

Assessing the influence of gradual channel expansions on flow deceleration by mass continuity principles, River2D modeled expanded channel widths at four proposed riffle locations (Fig. 3). Fluid mass continuity was assumed for steady flow with a constant discharge which is a function of cross-sectional average velocity (V) times area (A), thus by increasing A, V must decrease (Sturm, 2010). As a general design approach, pre-restoration channel morphology in the model can be modified by expanding the channel width until sufficient deceleration achieves a stable riffle. In this case study, the project site was planform-constrained so the question became what were the reduced riffle velocities for the maximum allowable channel width that did not interfere with existing civil infrastructure. In addition to creating acceleration-deceleration patterns at riffle-pool sequences, River2D simulations were used to observe whether velocity and shear stress reversals occurred from low-flow to high-flow stages, fundamental to

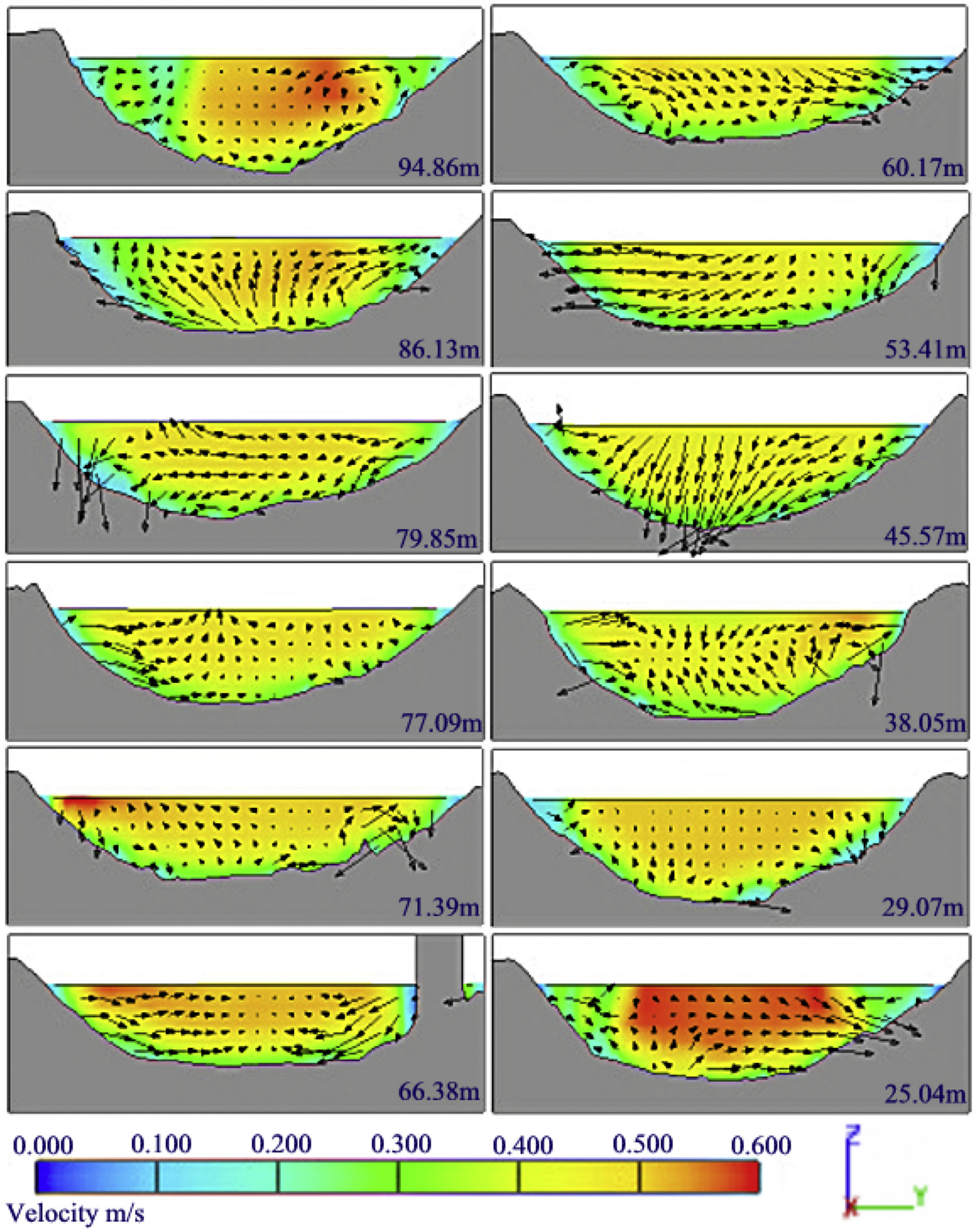

Fig. 6. FLOW3D modeled maximum velocity magnitude and velocity magnitude vectors illustrated in *y*–*z* cross-sections in the channel with the restoration design implemented.

sequence maintenance. As noted earlier, the velocity/shear stress reversal hypothesis describes riffles at low-flow stages with higher velocities and shear stress relative to pools, and during high-flow stages higher velocities and shear stresses scour pools, compared with riffles where sediment tends to deposit (Keller and Florsheim, 1993; Cao et al., 2003). This sediment sorting process maintains this bedform. Dietrich (1987) elucidates this description of sediment sorting processes through a bar unit, consisting of a bar-riffle-pool structure in meanders.

Yang (1971) hypothesized that riffle-pool formation is a function of streams tending towards a minimum energy dissipation rate, thus relating to energy loss through this macro-bedform and particularly to the riffle entrance incline slope. Hydraulic principles suggest that the riffle entrance incline slope creates converging flow paths in the vertical enhancing turbulence and increasing energy dissipation rates. Qualitatively, a stable riffle design should include energy dissipation concepts, reducing local high-velocity flow paths, such as a riffle thawleg “jet”. River2D was used to examine velocity dissipation into the modeled riffle design by varying depth of the preceding upstream pool, thus the entrance slope into the riffle.

3.1.2.2. Method. Comparisons among River2D model scenarios were used to address questions related to development of a stable riffle design for straight, incised urban channels. With River2D, the entire 270-m project reach was used in model simulations based on the site topography survey (Fig. 1). River2D finite element mesh development and hydraulic modeling procedures were followed as described in Steffler and Blackburn (2002). A 4.0 m^3/s discharge was used for bankfull conditions, and 0.5 m^3/s was used for low-flow conditions.

Modeling efforts included: (1) water depth and velocity comparison of the original channel morphology to the designed channel with expanded widths at riffles, without entrance slope modifications; (2) water depth and velocity comparison of expanded channel widths at riffles without entrance slope modifications to same lateral morphology but added approximately 0.3 m depth to the existing pre-riffle pool increasing riffle entrance incline slopes; and (3) shear velocity comparison between low- and high-flows for the designed channel with expanded width areas and deepened entrance pools in order to assess the occurrence of shear stress reversals.

3.1.2.3. Results. The original topography was modeled for high- and low-flows in order to illustrate the lack of flow acceleration-deceleration zones and riffle-pool sequences (Fig. 7). These River2D simulations showed a high-velocity core mid-channel, with lower velocity very near the banks. River2D could not fully capture the effect of the tree-lined bank, but was addressed in the model by an increased roughness height (k_s) of 0.1 m compared to a 0.02 m k_s for the channel bed. Water depth at low-flow stage remained relatively constant along the thawleg between 0.4 and 0.6 m, lacking riffle-pool features. One deep pool occurred near the upstream end of the modeled reach that was approximately 0.85 m in depth, formed adjacent to a large exposed root mass.

The initial modeling simulations did not modify the bed topography at the entrance of the proposed riffles (Fig. 8a). Model results showed deceleration through the riffle compared with the upstream and downstream narrower channels; however high-velocity jets extended into riffle thawlegs from the riffle entrance to the mid-riffle cross-section. By having a high-velocity jet entering the riffle, it was believed that this could ultimately lead to an unstable riffle bed.

Next, River2D modeling simulations consisted of deepening the bed topography at the riffle entrance with the idea that this would cause converging flow paths, increasing turbulence and energy dissipation. The change in bed elevation pre-riffle to riffle for initial design with no bed modification was between 0.1 and 0.2 m (Fig. 8a), whereas for the final design with bed modification the change in bed elevation was approximately 0.45 m (Fig. 8b). The slight deepening of the bed pre-riffle was sufficient enough to reduce the pronounced high-velocity jet. In general this modeling simulation illustrated the importance of riffle entrance incline slope as to a deeper pre-riffle pool to dissipate flow jets. Further research could lead to more specific restoration design criteria.

Finally, the River2D model was used to investigate shear stress reversal by comparing shear velocity (u_*) as the model output parameter between low- and high-flow stages. Per visual inspection, it is apparent with the final channel design with expanded widths at riffles and pre-riffle pools, bed shear stress reversal occurs (Fig. 9). During the low-flow stage, u_* was greater in the riffles than the pools, approximately 0.05–0.08 m/s and 0.03 m/s, respectively. During high-flow stage, u_* was greater in the pools than the riffles, approximately 0.08–0.10 m/s and 0.04–0.07 m/s, respectively.

In addition to justifying riffle-pool maintenance flows per shear stress reversal, u_* was used to compute τ_0 in order to (1) identify potential areas prone to scour and (2) size gravel material for the engineered riffles. Through this mapping exercise, locations of high τ_0 greater than field-measured bank τ_c identified bank areas that may need scour protection, e.g., toe rock and root wads. Per inspection of the River2D model output, the maximum u_* on the bed and bank were 0.135 m/s and 0.08 m/s, equating to a τ_0 of 18.2 Pa and 6.4 Pa, respectively (Fig. 9). The measured bank τ_c from the jet test device was 3.8 Pa, indicating some locations on the bank needed scour protection. Vulnerable locations to erosion required engineering judgment by either (1) modifying the design morphology, and/or (2) incorporating a root wad structure into the bank. From River2D, the maximum bed τ_0 of 18.2 Pa and using the Shields diagram (Sturm, 2010), a minimum gravel diameter of 2.5 cm for incipient motion was estimated. The gravel size specified for riffle construction was 3.8 cm diameter. The shear velocity plot in River2D provided a useful tool assessing designs for local channel stability, and estimating rock size to be imported for riffle beds.

3.1.3. Ecohydraulic modeling approach to support restoration design

3.1.3.1. Background. River2D incorporates a habitat module using PHABSIM methodology that computes weighted usable areas (WUAs) per stream surface area (Bovee et al., 1998; Blackburn and Steffler, 2002). WUAs are based on a combination of hydraulic (velocity and depth) and substrate characteristics, multiplied by the composite probability of use per fish or other aquatic biota.

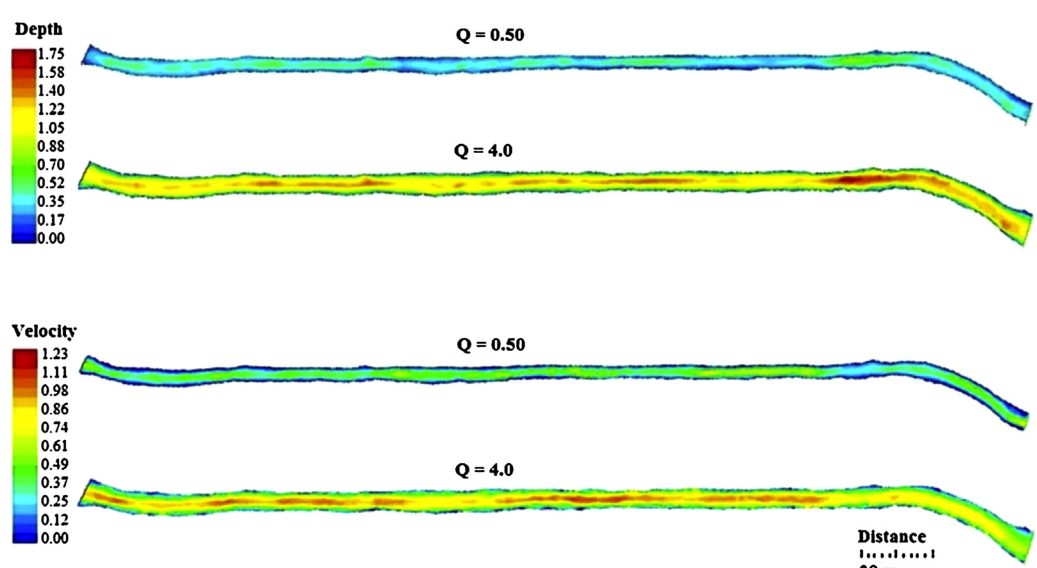

Fig. 7. River2D model for original channel topography showing water depth (m) and velocity (m/s) for (a) low-flow (0.5 m3/s) and (b) bankfull flow (4.0 m^3/s).

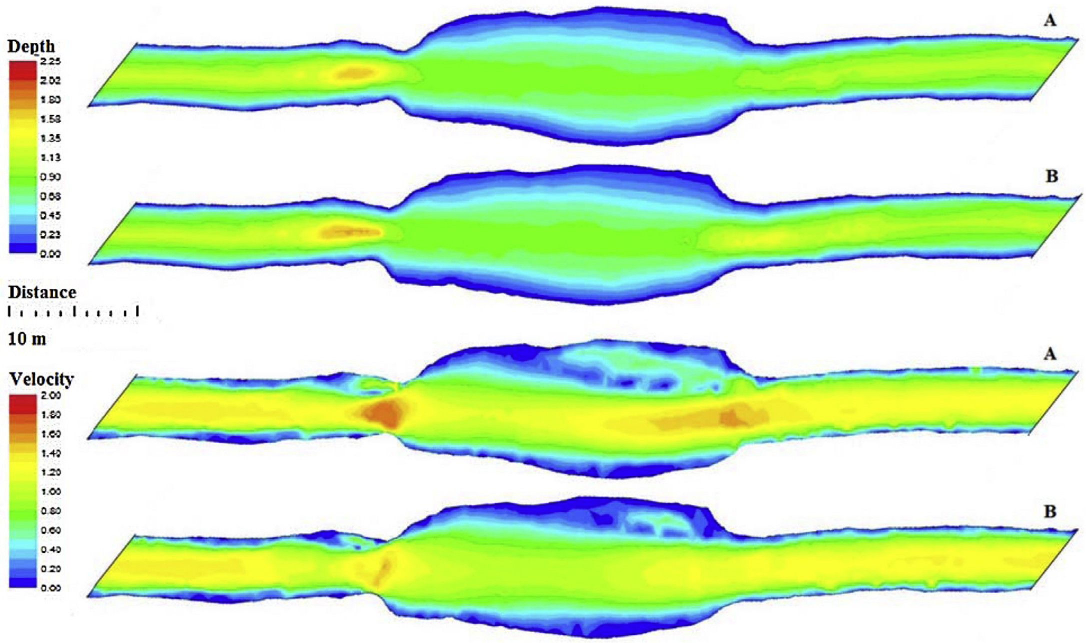

Fig. 8. River2D model for proposed four riffles located at expanded channel width with flow direction right to left as shown, for (a) an initial condition with no bed topography modifications at the riffle entrance, and (b) a final design condition with deepening of the bed topography at the riffle entrance. Model discharge was bankfull flow at 4.0 m^3/s.

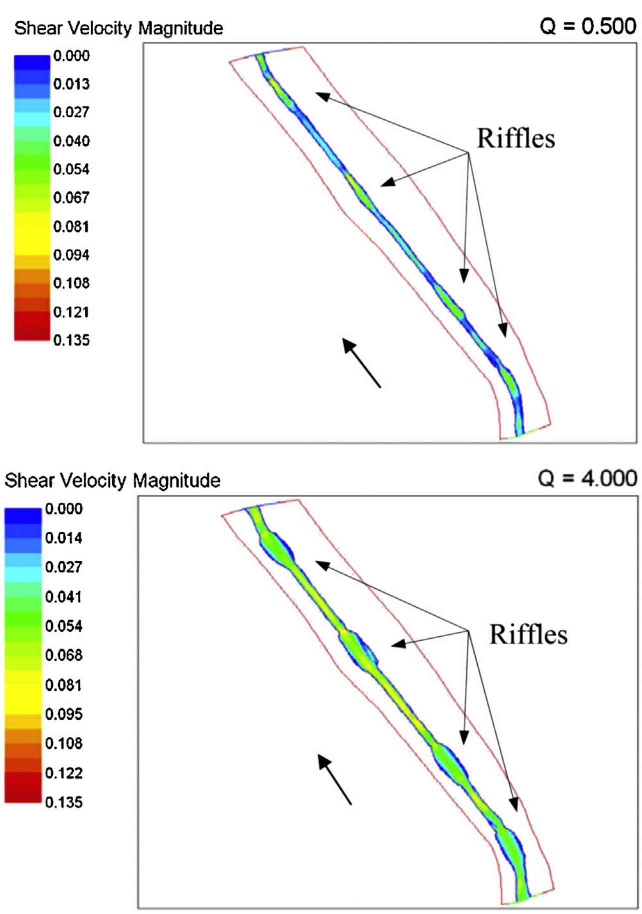

Fig. 9. River2D model for proposed four riffles showing shear velocity (m/s) for low-flow (0.5 m3/s) and bankfull flow (4.0 m3/s), and bed shear stress reversal between stages.

Probabilities are referred to as habitat suitability indices (HSI) and are associated with species' habitat quality preferences for velocity, depth, and substrate type. The hydraulics module in River2D provides the habitat module with water depth and depth-average velocity per finite element cells. Two additional input files are needed to run the habitat module; they are the channel index file defined by the user a numeric code for substrate types (e.g., clay/silt = 1, sand = 2, gravel = 3; cobble = 4; bank cover = 6, and rock = 7). A second file consists of HSI species preferences ranging from 0 to 1 (0 = no preference, 1 = full preference). Fish HSI are typically obtained through field studies using pre-positioned areal electrofishing devices (Schwartz and Herricks, 2004; Zale et al., 2013). If not collected individually, HSI data can be found in reports from the U.S. Fish & Wildlife Service, Instream Flow Incremental Methodology (IFIM) studies by power companies, consulting firms, and other agency sources.

3.1.3.2. Method. Computing WUAs for three fish species, WUAs were compared between the original channel and final design morphologies to ecologically assess potential improvements in biotic integrity by enhancing the riffle-pool morphology. Computations were conducted for stream discharges of 0.5 m^3/s (low-flow) and 4.0 m^3/s (high-flow). The fish species included rock bass (*Ambloplites rupestris*) a pool-orientated species, greenside darter (*Etheostoma blenniodes*) a riffle-orientated species, and northern hogsucker (*Hypentelium nigricans*) a habitat generalist, and per Sain (2006) all species reside in the Beaver Creek watershed. HSI relationships for velocity, depth, and channel substrate for these three species were obtained from Payne (2008) based on field studies from the southern Appalachian region.

3.1.3.3. Results. WUAs increased from the original channel to the designed channel for both low- and high-flow stages, and all fish except rock bass at low-flow stages (Table 1). The greatest increase in WUAs was for the greenside darter, which correlated with the added riffles structures not present in the original channel (Fig. 10). Per Table 1, River2D results indicated rock bass habitat, as pool

Table 1
Habitat composite WUAs for low-and high-flow stages comparing the original channel to the design channel morphology with four riffle-pool structures. Three fish species used in the River2D model were: rock bass, greenside darter, and northern hogsucker.

Channel morphology	Discharge (m^3/s)	Weighted usable area (m^2)		
		Rock bass	Greenside darter	Northern hogsucker
Original Channel	0.5	17.7	34.8	318.6
Design Channel	0.5	11.7	164.4	419.6
Original Channel	4.0	2.7	7.5	487.7
Design Channel	4.0	6.8	132.3	714.0

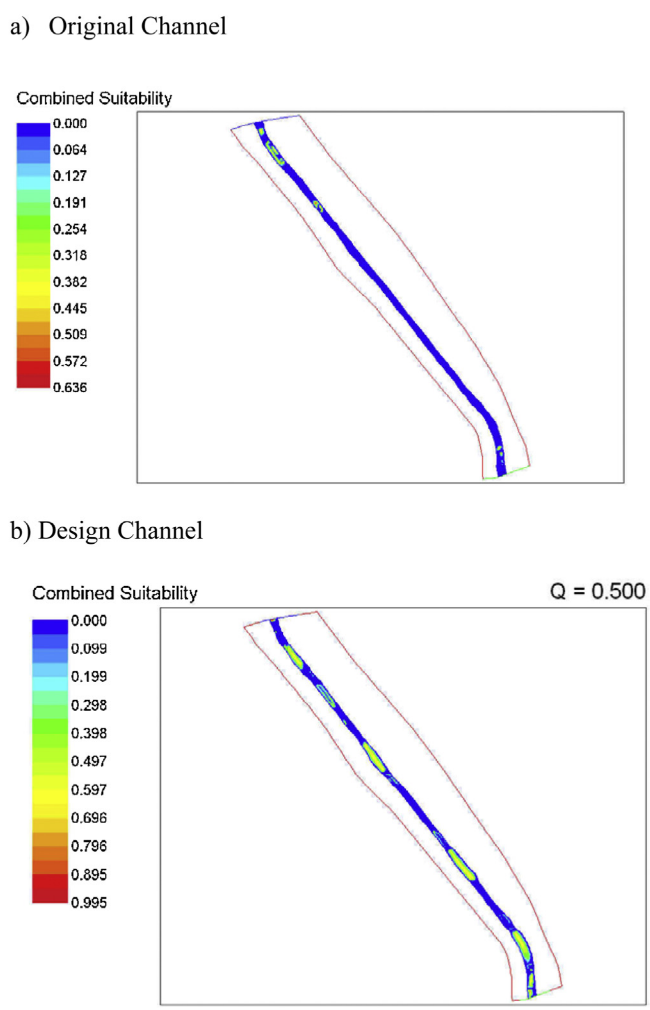

Fig. 10. River2D model for low-flow stage (0.5 m3/s), habitat composite WUAs for the greenside darter comparing the original channel to the design channel morphology with four riffle-pool structures.

habitat could be added to the design. The results also indicated that the new riffle structures provide the northern hogsucker with high-flow refugia (Fig. 11).

River2D is a useful tool to examine how proposed design morphologies may influence improvement of habitat quality relatively. Spatially-displayed WUAs locate areas that could be enhanced through channel morphological modifications. Locating areas for habitat enhancement from 2D modeled results constitutes the ecohydraulic design process for stream restoration. One must caution the interpretation of the results, in that model WUAs only indicates the availability of quality habitat and not whether a fish species will ultimately occupy newly constructed habitat. Watershed biological surveys provide important information of the recolonization potential of a restoration site (Nienhuis et al., 2002). Sain (2006) provided that information in Beaver Creek indicating a diversity of fish species had access to the study site for recolonization. Overall this design process remains qualitative, in that the model generates WUAs showing relative improvements from a proposed design, but knowing what the target WUAs should be requires additional species-specific research.

3.2. Summary: ecohydraulic design integration

The ecohydraulic approach for stream restoration design integrated various lotic ecology concepts concurrently with physical-based techniques. The physical-based techniques applied geomorphic and hydraulic principles for a stable riffle-pool design understanding constraints imposed by a straight urban stream. It is assumed that by adding riffle-pool structures biotic integrity will only be incrementally improved recognizing urbanizing streams cannot be returned to a pristine, equilibrium state.

Through the experimental CFD modeling efforts completed in this study, it appeared that self-maintaining riffle-pool structures can be achieved in planform-constrained urban streams by: (1) expanding the channel width and removing bank trees at riffle locations resulting in high-flow deceleration and bed shear stress reduction compared with pools; (2) deepening the upstream pool prior to riffle to reduce formation of a concentrated thalweg jet into the riffle promoting energy dispersion; (3) preserving the existing narrow channel with bank trees to promote flow acceleration for pool maintenance; and (4) installing bank protection at modeled locations of excessive boundary shear stress, generally located at the riffle exit (Fig. 12).

Riffle and pools are critical habitat features where stream biota have evolved and developed life histories to specifically exploit its space and tropic resources necessary for survival (Poff, 1997; Schwartz, 2002). Ecologically, riffles provide habitat for benthic macroinvertebrates, the food generators for various omnivore and insectivore fish species (Vannote et al., 1980; Allan and Castillo, 2007). Riffles within 2nd- to 3rd-order streams commonly will form leaf packs at larger rocks or wood on the stream bed, providing some macroinvertebrate's their food source. Therefore in addition to specifying placement of 3.8-cm gravel substrate in the riffle design, 12- to 18-cm sized cobble was placed on the gravel for leaf pack development and ecosystem enhancement.

The ecohydraulic design approach considered the biological resource needs at multiple flow stages, which was applied by a PHABSIM approach using the River2D habitat module. Broadly, this design element applied the patch dynamic concept, where habitats are recognized as a mosaic of temporarily-variable space primarily governed by fluctuating flow stages (Pringle et al., 1988; Thorp et al., 2006). The key design application was to provide for hydraulic habitat diversity, which ecological theory suggests patchiness promotes a more diverse and healthy ecosystem (Lake, 2000). Riffle-pool structures represent mesohabitat patches varying in ecological function by flow stage. During low-flow

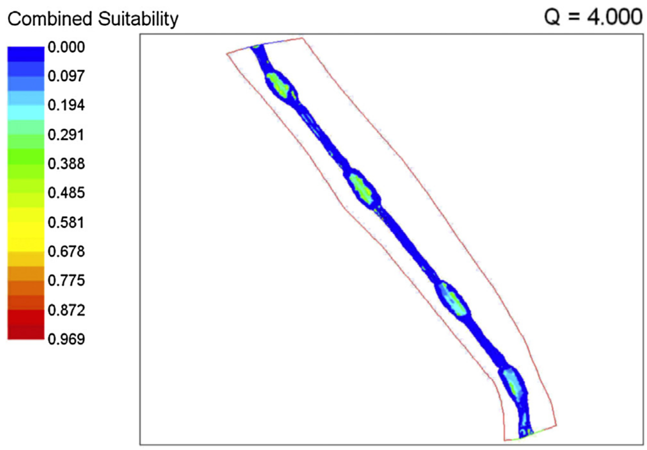

Fig. 11. River2D model for high-flow stage (4.0 m3/s), habitat composite WUAs for the northern hogsucker for the design channel morphology with four riffle-pool structures.

the adjacent upstream riffle. With the overall gradient and a 7-cm drop across the riffle, four riffles could be fitted into the 270-m length project reach. Riffle locations were also selected based on existing bank tree configurations utilizing them as bank protectors at riffle-pool transition areas (Fig. 12). Geolift banks were constructed with coir matting and native soils at 3:1 side-slopes, and seeded with grass and planted with willow live-stakes. Root wads were installed at locations with excessive shear stress as identified from River2D, and using on-site trees. Within the riffle bed, 3.8 cm gravel was placed for the alluvial veneer layer approximately 15–20 cm thick. Cobble rock 12–18 cm in diameter were placed on the riffle gravel, and spaced 1–2 m apart to create bed structure for leaf pack generation (Fig. 13). Project construction began in October 2011, and was completed March 2012.

5. Project monitoring

The main focus of this case study was the development of an ecohydraulic design for riffle-pool structures in urban streams

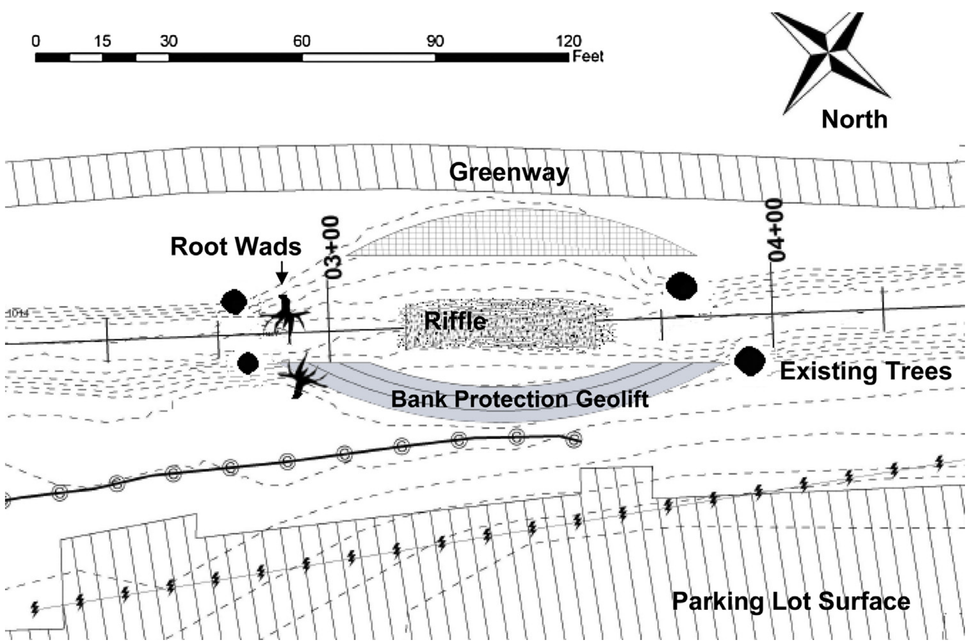

Fig. 12. Plan view of final riffle design constructed at the study site. Topography contour intervals are 2-ft.

stages, pools provide rearing and feeding habitat, and use is partitioned by hydraulics (Schwartz and Herricks, 2008). Riffle morphology at high-flow stages provides hydraulic refugia during flood events (Schwartz and Herricks, 2005), and as shown in Figs. 8–11 the new riffle design provides that refugia. Microhabitat patches during low flow include the riffle cobble and pool-riffle root wads. Ecological criteria are place-based and will vary depending by ecoregion, and because stream ecosystems are naturally variable its application for restoration design becomes a qualitative process (Palmer et al., 2005). However by the use of computed WUAs, ecological design for stream restoration can be advanced with quantitative information.

4. Project construction

The final riffle-pool design that was constructed consisting of four riffle structures spaced about 35–49 m apart, based on the general criteria of 5–7 bankfull widths. However, the available vertical drop in the low-gradient reach presented a design constraint so that a backwater from one riffle would not reach

through CFD modeling, followed by construction of the proposed design. Baseline monitoring was obtained for use in the design as described above. Post-construction monitoring and assessment was implemented, but at this time does not constitute enough data for a statistical analysis of geomorphic and biological differences from baseline data. It only represents a preliminary assessment after one-year post construction with two primary objectives: (1) to identify if the project riffle structures remained stable over the first year after installment, and (2) report qualitatively on biota metric trends post-project construction. Continued site monitoring is on-going for the accrual of long-term data so that a statistically valid analysis can be conducted as part of future research.

5.1. Geomorphic surveys and hydrology

In March 2012, immediately following completion of project construction, representative cross-sections of both the riffle and pool sections were surveyed between permanent rebar datum monuments. In April 2013 these cross-sections were resurveyed to

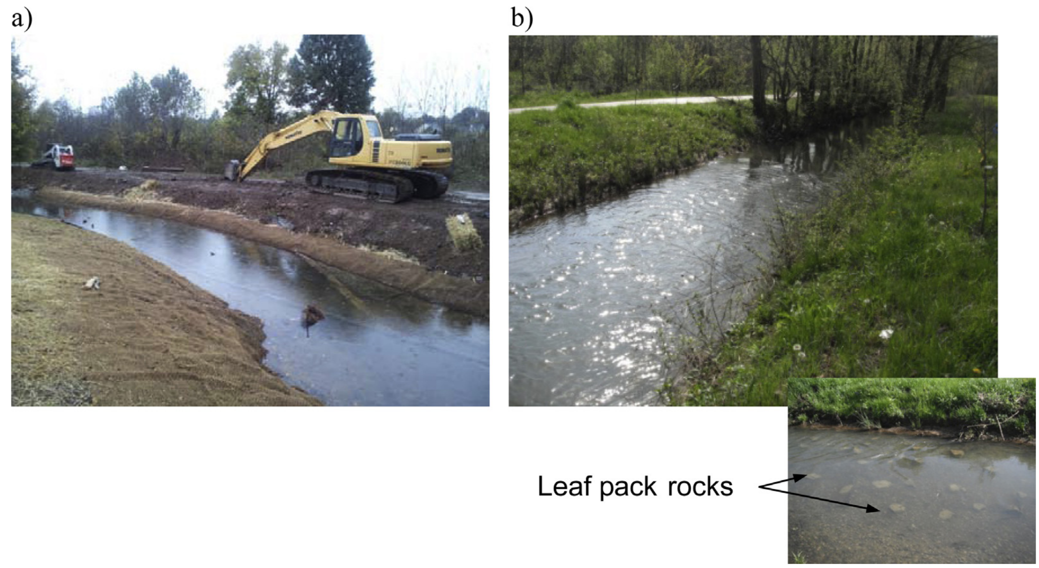

Fig. 13. Site photos of (a) riffle under construction in October 2010, and completed riffle after one-year following construction completion in April 2012.

identify whether any major adjustments in channel form occurred in response to hydrologic events over this period. Cross-sections were surveyed with a Trimble total station and Recon data logger.

Stage data were recorded between March 2012 and April 2013 utilizing a Global Water™ WL400 Level Sensor. Review of the stage data indicated over the bank floodplain inundation for eight hydrologic events. Even with this excessive number of bankfull events (>1–2 events per year), cross-sectional form was relatively stable among all cross-sections with no apparent indications of fluvial erosion or bed aggradation (Fig. 14).

5.2. Biological surveys

Tennessee, like most U.S. states, relies on biotic integrity indicators to determine whether a stream is water quality impaired based on benthic macroinvertebrate samples (Barbour et al., 1999). The Tennessee Macroinvertebrate Index (TMI) utilizes a semi-quantitative single habitat survey (SQKICK) to measure biometrics based on guild community structure, and both tolerant and intolerant species (TDEC, 2011). Biometrics expected to decrease with increased pollution and/or habitat degradation include: total taxa richness (TR), Ephemeroptera Plecoptera Trichoptera richness (EPT-Tax), EPT abundance excluding Cheumatopsyche (%EPT-Cheum), and percent contribution of organisms that build fixed retreats or have adaptations to attach to surfaces in flowing waters (%ClingP). Biometrics expected to increase with increased degradation include: percent Oligochaetes and Chironomids (%OC), North Carolina Biotic Index (NCBI), and percent Tennessee nutrient tolerant organisms (%TNutol).

In July 2009 a SQKICK sampling effort was completed at the restoration site prior to any construction activities. In August 2012; and 2013 after project construction, SQKICK sampling efforts were conducted by Knox County Stormwater Engineering Department. Comparison of these surveys generally showed a slight improvement in both intolerant and tolerant metrics (Table 2). EPT-Tax increased from 3 to 6 species from pre- to post-construction however remained impaired after restoration where 9 species is the score for biotic reference streams. The NCBI and %TNutol showed an improvement with an increase in intolerant species, to a level indicating partial supporting. Although this assessment only represents a one-year period, the lack of significant improvements may be due to the eight bankfull events repeatedly disturbing the benthic macroinvertebrate community and/or continued excessive fine sediment transport from upstream sources.

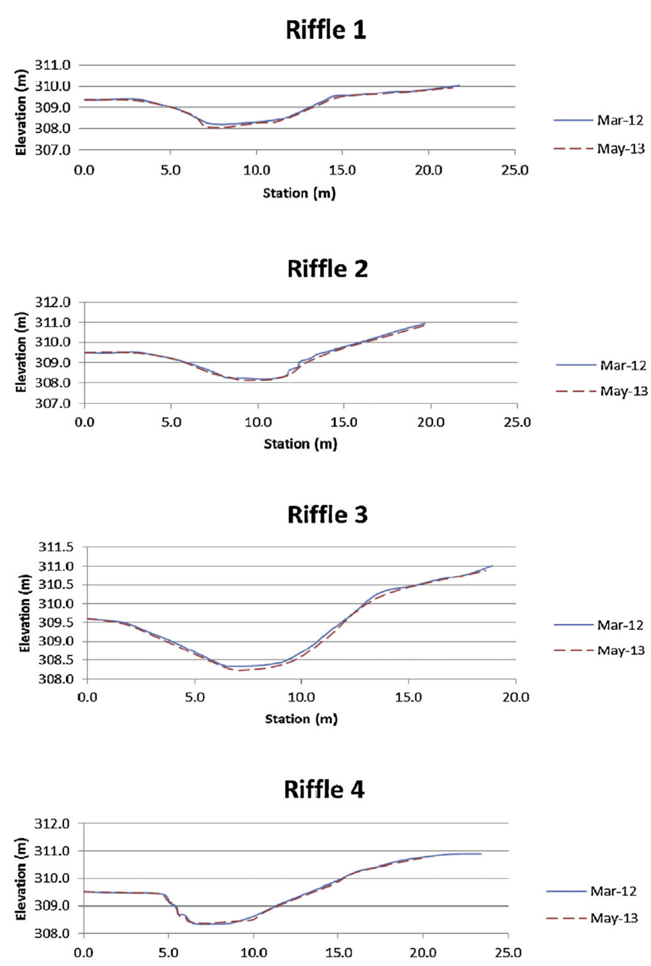

Fig. 14. Post-construction monitoring for channel stability at riffle cross-sections conducted in March 2011 and April 2012.

Table 2
Tennessee macroinvertebrate index (TMI) biometric scores for pre- and post-construction periods at the beaver Creek study site, and TMI reference stream scores.

Survey date	TMI Biometric Scores						
	TR	EPT-Tax	%ClingP	%EPT-Cheum	%OC	NCBI	%TNutol
July 2009	21	3	45.1	16	38.3	5.68	64.2
August 2012	21	6	71.4	27.3	17.8	5.39	52.4
August 2013	27	6	52.0	20.8	57.9	5.18	45.0
Integrity Trend[a]	+	+	+	+	+/–	+	+
Reference Stream[b]	>28	>9	>54.3	>44.7	<27.3	<4.87	<30.1

[a] All trends were not statistically significant ($p < 0.05$) per linear regression.
[b] TMI scores from TDEC (2011) for ecoregion 67, greater than 2 square miles drainage area.

The fish Index of Biotic Integrity (IBI) is a biological survey also developed to measure biotic integrity of streams and it is based on 12 sub-index scores (Sain, 2006). IBI sub-indices expected to increase with decreased pollution and/or habitat degradation include: number of native fish species, number of darter species, number of sunfish species, number of sucker species, number of intolerant species, percent specialized insectivores, and percent piscivores. IBI sub-indices expected to increase with increased degradation include percent tolerant species, percent omnivores and stoneroller species, percent hybrids, and percent anomalies. In January 2010 and September 2013, IBI collections were completed by TDEC personnel at the restoration site pre- and post-construction, respectively (Table 3). Comparison of the two surveys indicates incremental improvements in fish community diversity increasing taxa richness from 10 to 16, however the improvement is well below the biotic reference stream score of 42. As observed in Schwartz and Herricks (2007); habitat enhancement without water quality improvements generally lead to increased species, but mostly tolerant species. Showing some incremental improvement the tax increase did include one intolerant darter species and rock bass. The increased omnivores and stoneroller score was likely due to the open tree canopy above the new riffle structures increasing periphyton growth. Per field inspection in April 2013, excessive periphyton growth was not observed. In general, more long-term data is needed to assess the ecological response from the newly constructed riffle-pool structures.

6. Restoration implications and conclusions

The riffle-pool design developed in this study and pilot project constructed from the design demonstrated as a case study that urban stream habitat can potentially be rehabilitated with incremental improvements in biotic integrity. This case study also demonstrated to stream restoration practitioners a methodological design approach founded in ecological engineering principles. Considering hydromodification disrupts an urban channel's dynamic equilibrium and stability, it is suggested that use of geomorphic and hydraulic principles rather than an anti-log approach is more applicable for mesohabitat design in urbanizing streams. River2D modeling provided key information that a practitioner can use to assess channel stability, integrated with field measurements of critical shear stress on the banks and bedload transport characteristics. In addition as an ecohydraulic design approach, River2D modeling incorporated a pre-construction assessment of habitat quality, integrating fluvial geomorphology, hydraulics, and ecological data. Because of the stressed environmental condition of urban streams, including a host of multi-stressors i.e., poor water quality, habitat alteration and sedimentation, and invasive species, innovative approaches for stream restoration are necessary to enhance ecosystems to the maximum extent possible. Knowledge gained from this case study will be applied to future research investigating sustainable geomorphic and ecological processes in urban watersheds.

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Table 3
Fish IBI sub-index scores for pre- and post-construction period site surveys.

Fish IBI sub-indices	1/7/2010 Score	9/18/2013 Score	Integrity Trend	Reference Stream[a]
Number of native fish species	10	16	+	>42
Number of darter species	3	4	+	>8
Number of Sunfish species (excl. *Micropterus*)	1	3	+	>4
Number of sucker species	1	1	0	>8
Number of intolerant species	2	2	0	>5
Percent tolerant species	1%	6.7%	–	<10%
Percent omnivores and stoneroller species	20%	30.8%	–	<10%
Percent specialized insectivores	54%	46.0%	–	>50%
Percent piscivores	7%	2.9%	–	>4%
Catch rate (per 300 sq. ft.)	4%	NA		Varies
Percent hybrids	0%	0%	0	0%
Percent anomalies	1%	0%	+	<2%

[a] IBI Sub-index scores from Tennessee Valley Authority field protocol manual.

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References

Aadland, L.P., 1993. Stream habitat types: their fish assemblages and relationship to flow. N. Am. J. Fish. Manage. 13, 790–806.
Allan, J.D., Castillo, M.M., 2007. Stream Ecology: Structure and Function of Running Waters. Springer.
Annable, W.K., Watson, C.C., Thompson, P.J., 2012. Quasi-equilibrium conditions of urban gravel-bed stream channels in southern Ontario, Canada. Regul. Rivers 28, 302–325.
Barbour, M.T., Gerritsen, J., Snyder, B.D., Stribling, J.B., 1999. Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers. EPA 841-B-99-002. U.S. Environmental Protection Agency, Office of Water, Washington D.C.
Bernhardt, E.S., Palmer, M.A., 2007. Restoring streams in an urbanizing world. Freshwater Biol. 52, 738–751.
Blackburn, J., Steffler, P., 2002. River2D, Two-dimensional Depth Averaged Model of River Hydrodynamics and Fish Habitat, River2D Tutorial Fish Habitat Tools. University of Alberta, Canada.
Bledsoe, B.P., Stein, E.D., Hawley, R.J., Booth, D., 2012. Framework and tool for rapid assessment of stream susceptibility to hydromodification. J. Am. Water Resour. As. 48, 788–808.
Bledsoe, B.P., Watson, C.C., 2001. Effects of urbanization on channel stability. J. Am. Water Resour. As. 37, 255–270.
Bockelmann, B.N., Fenrich, E.K., Lin, B., Falconer, R.A., 2004. Development of ecohydraulics model for stream restoration and river restoration. J. Ecol. Eng. 22, 227–235.
Booker, D.J., Dunbar, M.J., 2004. Application of physical habitat simulation (PHABSIM) modelling to modified urban river channels. River Res. Appl. 20, 167–183.
Booth, D.B., Jackson, C.R., 1997. Urbanization of aquatic systems - degradation thresholds, stormwater detection, and the limits of mitigation. J. Am. Water Resour. As. 33, 1077–1090.
Bovee, K.D., Lamb, B.L., Bartholow, J.M., Stalnaker, C.B., Taylor, J., Henroksen, J., 1998. Stream Habitat Analysis Using the Instream Flow Incremental Methodology. US Geological Survey, Biological Resources Division Information and Technology Report. USGS/BRD-1998-0004.
Bunte, K., Abt, S.R., Polondy, J.P., Ryan, S.E., 2004. Measurement of coarse gravel and cobble transport using portable bedload traps. J. Hydraul. Eng.-ASCE 130 (9), 879–893.
Cantrell, W., 2009. Method of Evaluation for Stream Bed Shear Stress and Sediment Transport Capacity in Urbanizing Watershed: Implications for Stream Restoration. MS Thesis. University of Tennessee, Knoxville.
Cao, Z., Carling, P., Oakley, R., 2003. Flow reversal over a natural pool-riffle sequence: a computational study. Earth Surf. Proc. Land. 28, 689–705.
Carling, P.A., Wood, N., 1994. Simulation of flow over pool-riffle topography: a consideration of the velocity reversal hypothesis. Earth Surf. Proc. Land. 19, 319–322.
Cianfrani, C.M., Hession, W.C., Rizzo, D.M., 2006. Watershed imperviousness impacts on channel condition in southeastern Pennsylvania. J. Am. Water Resour. As. 42, 941–956.
Clark, L.A., Wynn, T.M., 2007. Methods for determining streambank critical shear stress and soil erodibility: implications for erosion rate predictions. Trans. ASABE 50, 95–106.
Clifford, N.J., 1993. Differential bed sedimentology and the maintenance of riffle-pool sequences. Catena 20, 447–468.
Clifford, N.J., Harmar, O.P., Harvey, G., Petts, G.E., 2006. Physical habitat, ecohydraulics and river design: a review and re-evaluation of some popular concepts and methods. Aquat. Conserv. 16, 389–408.
Colosimo, M.F., Wilcock, P.R., 2007. Alluvial sedimentation and erosion in an urbanizing watershed, Gwynns Falls, Maryland. J. Am. Water Resour. As. 43, 499–521.
De Almeida, G.A.M., Rodriguez, J.F., 2011. Understanding pool-riffle dynamics through continuous morphological simulations. Water Resour. Res. 47, 1–15.
Dietrich, W.E., 1987. In: Richards, K. (Ed.), Mechanics of Flow and Sediment Transport in River Bends. Basil Blackwell: River Channel Environment and Process.
Doyle, M.W., Shields, F.D., Boyd, K., Skidmore, P.B., Dominick, D., 2007. Channel-forming discharge selection in river restoration design. ASCE J. Hydrual. Eng. 133 (7), 831–837.
Dworak, F.J., 2005. Characterizing Turbulence Structure along Woody Vegetated Banks in Incised Channels: Implications for Stream Restoration. MS Thesis. University of Tennnesse, Knoxville.
Emery, J.C., Gurnell, A.M., Clifford, N.J., Petts, G.E., Morrissey, I.P., Soar, P.J., 2003. Classifying the hydraulic performance of riffle-pool bedforms for habitat assessment and river rehabilitation design. River Res. Appl. 19, 549–553.
Ernst, A.G., Baldigo, B.P., Mulvihill, C.I., 2010. Effects of natural-channel design restoration on habitat quality in Catskill Mountain streams, New York. T. Am. Fish. Soc. 139, 468–482.
Fitzpatrick, F.A., Harris, M.A., Arnold, T.L., Richards, K.D., 2004. Urbanization influences on aquatic communities in northwestern Illinois streams. J. Am. Water Resour. As. 40, 461–475.
Frothingham, K.M., Rhoads, B.L., 2003. Three-dimensional flow structure and channel change in an asymmetric compound meander loop, Embarras River, Illinois. Earth Surf. Proc. Land. 28, 625–644.
Ghanem, A., Steffler, P., Hicks, F., Katopodis, C., 1996. Two-dimensional hydraulic simulation of physical habitat conditions in flowing streams. Regul. Rivers 12, 185–200.
Gregory, K.J., Gurnell, A.M., Hill, C.T., Toooth, S., 1994. Stability of the pool-riffle sequence in changing river channels. Regul. Rivers 9, 35–43.
Hanson, G.J., 1990. Surface erodibility of earthen channels at high stresses. Part II - Developing an in situ testing device. Trans. ASAE 33, 132–137.
Harper, D., Ebrahimnezhad, M., Cot, F.C.I., 1998. Artificial riffles in river rehabilitation: setting the goals and measuring the successes. Aquat. Conserv. 8, 5–16.
Heritage, G., Milan, D., 2004. A conceptual model of the role of excess energy in the maintenance of a riffle–pool sequence. Catena 58, 235–257.
Hession, C.W., Pizzuto, J.E., Johnson, T.E., Horwitz, R.J., 2003. Influence of bank vegetation on channel morphology in rural and urban watersheds. Geology 31, 147–150.
Hey, R.D., 2006. Fluvial geomorphological methodology for natural stable channel design. J. Am. Water Resour. As. 42, 357–374.
Hey, R.D., Thorne, C.R., 1986. Stable channels with mobile gravel beds. J. Hydraul. Eng.-ASCE 112, 671–689.
Jennings, D.B., Jarnagin, S.T., 2002. Changes in anthropogenic impervious surfaces, precipitation and daily streamflow discharge: a historical perspective in a mid-Atlantic subwatershed. Landscape Ecol. 17, 471–489.
Johnson, P.A., Fecko, B.J., 2008. Regional channel geometry equations: a statsitical comparison for physiographic provinces in the eastern US. River Res. Appl. 24, 823–834.
Kang, R.S., Marston, R.A., 2006. Geomorphic effects of rural-to-urban land use conversion on three streams in the Central Redbed Plains of Oklahoma. Geomorphology 79, 488–506.
Keck, B.P., Marion, Z.H., Martin, D.J., Kaufman, J.C., Harden, C.P., Schwartz, J.S., Strange, R.J., 2014. Fish functional traits correlated with environmental traits in a temperate biodiversity hot spot. PLoS. One. 9 (3), e93237. doi:http://dx.doi.org/10.1371/journal.pone.0093237.
Keller, E.A., Florsheim, J.L., 1993. Velocity-reversal hypothesis: a model approach. Earth Surf. Proc. Land. 18, 733–740.
Keller, E.A., Melhorn, W.N., 1978. Rhythmic spacing and origin of pools and riffles. Geol. Soc. Am. Bull. 89, 723–730.
Knighton, D., 1998. Fluvial Forms and Processes: A New Perspective. Arnold, London.
Lane, S.N., Biron, P.M., Bradbrook, K.F., Butler, J.B., Chandler, J.H., Crowell, M.D., McLelland, S.J., Richards, K.S., Roy, A.G., 1998. Three-dimensional measurement of river channel flow processes using acoustic Doppler velocimetry. Earth Surf. Proc. Land. 23, 1247–1267.
Lake, P.S., 2000. Disturbance, patchiness, and diversity in streams. J. N. Am. Benthol. Soc. 19 (4), 573–592.
Lamarre, H., Roy, A.G., 2005. Reach scale variability of turbulent flow charactertstics in a gravel-bed river. Geomorphology 68, 95–113.
Lamouroux, N., Poff, N.L., Angermeier, P.L., 2002. Intercontinental convergence of fish community traits along geomorphic and hydraulic gradients. Ecology 83, 1792–1807.
Lawless, M., Robert, A., 2001. Three-dimensional flow structure around small-scale bedforms in a simulated gravel-bed environment. Earth Surf. Proc. Land. 26, 507–522.
Lisle, T., 1979. A sorting mechanism for a riffle-pool sequence: summary. Geol. Soc. Am. Bull. 90 (Part I), 616–617.
Ma, L., Ashworth, P.J., Best, J.L., Elliott, L., Ingham, D.B., Whitcombe, L.J., 2002. Computational fluid dynamics and the physical modeling of an upland urban river. Geomorphology 44, 375–391.
Mallison, T.L., 2008. Comparing In Situ Submerged Jet Test Device and Laboratory Flume Methods to Estimate Erosional Properties of Cohesive Soils for Bank Stability Models. MS Thesis. University of Tennessee, Knoxville.
Matthews, W.J., 1990. Spatial and temporal variation in fishes of riffle habitats: a comparison of analytical approaches for the Roanoke River. Am. Midl. Nat. 124, 31–45.
MacRae, C.R., 1997. In: Roesner, L.A. (Ed.), Experience from morphological research on Canadian streams: Is control of the two-year frequency runoff event the best basis for stream channel protection? Effects of Watershed Development and Management on Aquatic Ecosystems. American Society of Civil Engineers, Washington DC, pp. 144–162.
McBride, M., Booth, D.B., 2005. Urban impacts on physical stream condition: effects of spatial scale, connectivity, and longitudinal trends. J. Am.Water Resour. As. 41, 565–580.
Millar, R.G., 2004. Theoretical regime equations for mobile gravel-bed rivers with stable banks. Geomorphology 64, 207–220.
Morris, S., Moses, T., 1999. Urban stream rehabilitation: a design and construction case study. Environ. Manage. 23, 165–177.
Nagle, G., 2007. Invited commentary for hydrological processes evaluating 'natural channel design' stream projects. Hydrol. Process. 21 (8), 2539–2545.
Nelson, J.M., Shreve, R.I., McLean, S.R., Drake, T.G., 1995. Role of near-bed turbulence structure in bedlaod transport and bedform mechanics. Water Resour. Res. 31 (8), 2071–2086.

Newson, M.D., Newson, C.L., 2000. Geomorphology, ecology and river channel habitat: meso-scale approaches to basin-scale challenges. Prog. Phys. Geog. 24, 195–217.
Nienhuis, P.H., Buijse, A.D., Leuven, R.S.E.W., Smits, A.J.M., de Nooij, R.J.W., Samborska, E.M., 2002. Ecological rehabilitation of the lowland basin of the river Rhine (NW Europe). Hydrobiologia 478, 53–72.
Niezgoda, S.L., Johnson, P.A., 2005. Improving the urban stream restoration effort: identifying critical form and processes relationships. Environ. Manage. 35, 579–592.
Niezgoda, S.L., Johnson, P.A., 2006. Modeling the long term impacts of using rigid structures in stream channel restoration. J. Am. Water Resour. As. 42, 1597–1613.
O'Driscoll, M., Clinton, S., Jefferson, A., Manda, A., McMillan, S., 2010. Urbanization effects on watershed hydrology and in-stream processes in the southern United States. Water 2, 605–648.
Papanicolaou, A.N., Diplas, P., Darcey, C.L., Balakishnan, M., 2001. Surface roughness effects in near-bed turbulence: implications to sediment entrainment. J. Eng. Mech.-ASCE 127 (3), 211–218.
Palmer, M.A., Bernhardt, E.S., Allan, J.D., Lake, P.S., Alexander, G., Brooks, S., Carr, J., Clayton, S., Dahm, C.N., Follstad Shah, J., Galat, D.L., Loss, S.G., Goodwin, P., Hart, D.D., Hassett, B., Jenkinson, R., Kondolf, G.M., Lave, R., Meyer, J.L., O'Donnell, T.K., Pagano, L., Sudduth, E., 2005. Standards for ecologically successful river restoration. J. Appl. Ecol. 42, 208–217.
Payne, T.R., 2008. Technical Memorandum to Appalachian Power Company; Instream Flow Needs Workgroup–Claytor Project 739-018. Thomas R. Payne & Associates, Arcata, CA.
Paul, M.J., Meyer, J.L., 2001. Streams in the urban landscape. Annu. Rev. Ecol. Syst. 32, 333–365.
Poff, N.L., 1997. Landscape filters and species traits: towards mechanistic understanding and prediction in stream ecology. J. N. Am. Benthol. Soc. 16, 391–409.
Poff, N.L., Olden, J.D., Vieira, N.K.M., Finn, D.S., Simmons, M.P., Kondratieff, B.C., 2006. Functional trait niches of North American lotic insects: traits-based ecological applications in light of phylogenetic relationships. J. N. Am. Benthol. Soc. 25, 730–755.
Pringle, C.M., Naiman, J.R., Bretschko, G., Karr, J.R., Oswood, M.W., Webster, J.R., Welcome, R.L., Winterbourn, M.J., 1988. Patch dynamics in lotic systems: the stream as a mosaic. J. N. Am. Benthol. Soc. 7 (4), 503–524.
Rabeni, C.F., Sowa, S.P., 1996. Integrating biological realism into habitat restoration and conservation strategies for small streams. Can. J. Fish. Aquat. Sci. 53, 252–259.
Rhoads, B.L., Schwartz, J.S., Porter, S., 2003. Stream geomorphology, bank vegetation, and three-dimensional habitat hydraulics for fish in midwestern agricultural streams. Water Resour. Res. 39, 1218–1230.
Rhoads, B.L., Welford, M.R., 1991. Initiation of river meandering. Prog. Phys. Geog. 15, 127–156.
Richards, K.S., 1976. The morphology of riffle-pool sequences. Earth Surf. Proc. Land. 1, 71–88.
Rodriguez, J.F., Garcia, 2008, M.H., 2008. Laboratory measurements of 3-D flow patterns and turbulence in straight open channel with rough bed. J. Hydraul. Res. 46, 454–465.
Rosgen, D.L., 1996. Applied River Morphology. Wildlands Hydrology, Colorado.
Rosgen, D.L., 2008. DISCUSSION: "Critical evaluation of how the Rosgen classification and associated 'natural channel design' methods fail to integrate and quantify fluvial processes and channel response". J. Am. Water Resour. As. 44, 782–792.
Roy, A.G., Buffin-Belanger, T., Lamarre, H., Kirkbridge, A.D., 2004. Size, shape, and dynamics of large-scale turbulent flow structures in a gravel-bed river. J. Fluid Mech. 500, 1–27.
Sain, R.L., 2006. Characterizing How Fish Communities and Physical Habitat Structure are Affected by Urbanization in an East Tennessee Watershed. MS Thesis. University of Tennessee, Knoxville.
Schwartz, J.S., 2002. Stream Habitat Characterized by Stage-specific Flows and Three-dimensional Geomorphological Complexity: Development of Ecological Criteria for Stream Restoration Design. PhD Dissertation. University of Illinois, Urbana-Champaign.
Schwartz, J.S., 2003. Use of a two-dimensional hydrodynamic model for restoration design of high-flow habitat in low-gradient Midwest streams. Pages 242–251. In: Clar, M., Carpenter, D., Garcie, J., Slate, L. (Eds.), Proceedings of the Symposium on the Protection and Restoration of Urban and Rural Streams. June 23–25, Philadelphia, PAAmerican Society of Civil Engineers, Reston, VA, pp. 242–251.
Schwartz, J.S., Herricks, E.E., 2004. Use of prepositioned areal electrofishing devices with rod electrodes in small streams. N. Am. J. Fish. Manage. 24, 1330–1340.
Schwartz, J.S., Herricks, E.E., 2005. Fish use of stage-specific fluvial habitats as refuge patches during a flood in a low-gradient Illinois stream. Can. J. Fish. Aquat. Sci. 62, 1540–1552.
Schwartz, J.S., Herricks, E.E., 2007. Evaluation of pool-riffle naturalization structures on habitat complexity and the fish community in an urban Illinois stream. River Res. Appl. 23, 451–466.
Schwartz, J.S., Herricks, E.E., 2008. Fish use of ecohydraulic-based mesohabitat units in a low-gradient Illinois stream: implications for stream restoration. Aquat. Conserv. 18, 852–866.
Schwartz, J.S., Herricks, E.E., Rhoads, B.L., 2001. Integrating Geomorphology, Hydraulics, and Ecological Criteria to Support Stream Naturalization in East-Central Illinois. ASCE/EWRI World Water and Environmental Resources Congress, Orlando, Florida.
Schwartz, J.S., Neff, K.J., 2011. Use of River2D hydrodynamic model for stream restoration assessment and design. Proceedings of the World Water & Environmental Resources Congress. Pages 2593-2602. May 22-26ASCE Environmental and Water Resources Institute, Palm Springs, CA, pp. 2593–2602. doi:http://dx.doi.org/10.1061/41173(414)269.
Schwartz, J.S., Simon, A., Klimetz, L., 2011. Use of fish functional traits to associate in-stream suspended sediment transport metrics with biological impairment. Environ. Monit. Assess. 179, 347–369.
Sear, D.A., 1996. Sediment transport processes in pool-riffle sequences. Earth Surf. Proc. Land. 21, 241–262.
Sear, D.A., Newson, M.D., 2004. The hydraulic impact and performance of a lowland rehabilitation scheme based on pool-riffle installation: the River Waveney, Scole, Suffolk, UK. River Res. Appl. 20, 847–863.
Shamloo, H., Rajaratnam, R., Katopodis, C., 2002. Hydraulics of simple habitat structures. J. Hydraul. Res. 39, 351–366.
Shields, F.D., Copeland, R.R., Klingeman, P.C., Doyle, M.W., Simon, A., 2003. Design for stream restoration. J. Hydraul. Eng.-ASCE 129, 575–584.
Simon, A., 1995. Adjustment and recovery of unstable alluvial channels: Identification and approaches for engineering management. Earth Surf. Proc. Land. 20, 611–628.
Simon, A., Doyle, M., Kondolf, M., Shields, F.D., Rhoads, B., McPhillips, M., 2007. Critical evaluation of how the Rosgen classification and associated "natural channel design" methods fail to integrate and quantify fluvial processes and channel response. J. Am. Water Resour. As. 43, 1117–1131.
Simon, A., Hupp, C.R., 1990. In: Thornes, J.B. (Ed.), The recovery of alluvial systems in response to imposed channel modifications, West Tennessee, USA. Vegetation and Erosion. John Wiley & Sons Ltd, London, pp. 145–160.
Simon, A., Rinaldi, M., 2006. Disturbance, stream incision, and channel evolution: the roles of excess transport capacity and boundary materials in controlling channel response. Geomorphology 79, 361–383.
Slate, L.O., Shields, F.D., Schwartz, J.S., Carpenter, D.D., Freeman, G., 2007. Engineering design standards and liability for stream channel restoration. J. Hydraul. Eng.-ASCE 133, 1099–1102.
Smith, S.M., Prestegaard, K.L., 2005. Hydraulic performance of a morphology-based stream channel design. Water Resour. Res. 41 doi:http://dx.doi.org/10.1029/2004WR003926.
Steffler, P., Blackburn, J., 2002. River2D Two-dimensional Depth Averaged Model of River Hydrodynamics and Fish Habitat Introduction to Depth Averaged Modeling and User's Manual. University of Alberta, Canada.
Sturm, T.W., 2010. Open Channel Hydraulics. McGraw-Hill.
Tamburrino, A., Gulliver, J.S., 1999. Large flow structures in tubulent open channel flow. J. Hydrauli. Res. 37 (3), 363–380.
TDEC, 2006. EPA Approved Final Version Year 2006 303(d) List.. Tennessee Department of Environment and Conservation, Nashville, TN. http:tn.gov/environment/water/docs/wpc/303d2006.
TDEC, 2011. Quality System Standard Operating Procedure for Macroinvertebrate Stream Surveys. Tennessee Department of Environment and Conservation, Nashville.
Thompson, A., 1986. Secondary flows and the pool-riffle unit: a case study of the processes of meander development. Earth Surf. Proc. Land. 11, 631–641.
Thorp, J.H., Thorms, M.C., Delong, M.D., 2006. The riverine ecosystem synthesis: biocomplexity in river networks across space and time. River Res. Appl. 22, 123–147.
Van Bohemen, H.D., 1998. Habitat fragmentation, infrastructure and ecological engineering. J. Ecol. Eng. 11, 199–207.
Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R., Cushing, C.E., 1980. The river continuum concept. Can. J. Fish. Aquat. Sci. 37, 130–137.
Wade, R.J., Rhoads, B.L., Rodriguez, J., Daniels, M., Wilson, D., Herricks, E.E., Bombardelli, F., Garcia, M., Schwartz, J.S., 2002. Integrating science and technology to support stream naturalization near Chicago, Illinois. J. Am. Water Resour. As. 38, 931–944.
Walsh, C.J., Fletcher, T.D., Ladson, A.R., 2005a. Stream restoration in urban catchments through redesigning stormwater systems: looking to the catchment to save the stream. J. N. Am. Benthol. Soc. 24, 690–705.
Walsh, C.J., Roy, A.H., Feminella, J.W., Cottingham, P.D., Groffman, P.M., Morgan II, R. P., 2005b. The urban stream syndrome: current knowledge and the search for a cure. J. N. Am. Benthol. Soc. 24, 706–723.
Wang, L., Lyons, J., Kanehl, P., 2001. Impacts of urbanization on stream habitat and fish across multiple spatial scales. Environ. Manage. 28, 255–266.
Williams, K.H., 2005. Linking Channel Stability and Bed Sediment Characteristics to Biological Integrity in Tennessee Ridge and Valley Streams. MS Thesis. University of Tennessee, Knoxville.
Wilkinson, S.N., Keller, R.J., Rutherfund, I.D., 2004. Phase-shifts in shear stress as an explanation for the maintenance of pool-riffle sequences. Earth Surf. Proc. Land. 29, 737–753.
Wohl, E., 2005. Compromised rivers: understanding historical human impacts on rivers in the context of restoration. Ecol. Soc. 10 (2), 2 (online).
Yalin, M.S., 1992. River Mechanics: Publ. Pergamon Press, Oxford.
Yang, C.T., 1971. Formation of riffles and pools. Water Resour. Res. 7, 1567–1574.
Zale, A.D., Parish, D.L., Sutton, T.M., 2013. Fisheries Techniques, third ed. American Fisheries Society, Bethesda, Maryland.