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HYDRAULIC AND PHYSICAL STRUCTURE OF RUNS AND GLIDES FOLLOWING STREAM RESTORATION

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ABSTRACT

Hydraulic units are often linked to ecological habitat through geomorphic structure, and a better understanding of the turbulent characteristics of the units is needed. Our work examined the near-bed turbulent structure of runs and glides in a restored river and investigated the physical characteristics that influenced the near-bed hydraulics in these units. The research was completed in three restored reaches and one reference reach at the Virginia Tech Stream Research, Education, and Management Laboratory. The laboratory is unique because three different restoration treatments were applied contiguously along a stream, and the restoration practices ranged from passive to active. The passive reach included cattle exclusion, while the active reaches included cattle exclusion as well as vegetation plantings, bank sloping and the construction of inset floodplains. Three-dimensional velocities were measured near the channel bed in run and glide biotopes within the three restored reaches, as well as an upstream reference reach. The velocities were utilized to analyse and compare near-bed turbulent structure across the reaches. While the restoration activities did not address the channel bed directly, differences in physical structure of the two physical biotopes were observed among restoration treatments, likely because of changes in bank shape and roughness due to vegetation differences. Differences between reference and restored reaches were still evident approximately 3 years after cattle exclusion and construction activities. Few differences were observed in the hydraulic structure between runs and glides, and the near-bed flow structure in both runs and glides was related to local roughness. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: turbulent flow; river restoration; physical biotopes; runs and glides

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INTRODUCTION

Non-tidal streams are composed of a series of hydraulically homogeneous units known as 'physical biotopes' (e.g. riffles, runs, pools and glides; Wadeson, 1994; Wadeson and Rowntree, 1998). Physical biotopes have been defined by hydraulic conditions based on mean flow values such as Froude number, slope and velocity/depth ratio (Jowett, 1993; Wadeson, 1994; Padmore, 1998; Newson and Cl, 2000). For example, Jowett (1993) classified approximately 65% of riffles, runs and pools in a gravel-bed river based on surface slope and velocity/depth ratio or Froude Number. Wadeson (1994) further showed that Froude number could be used to define biotope categories (i.e. runs, transition, riffle and pool). Often, the intent is to relate these hydraulic units to ecological significance, and the hydraulic metrics used to describe the physical biotopes may be linked to the aquatic assemblages present (Jowett *et al*., 1991; Jowet, 1993; Newson and Newson, 2000). Therefore, the physical biotope is often considered as the basic unit for assessing biological habitat and diversity and is important in river habitat assessments (Padmore, 1998).

Recent research has shown that small-scale features are ecologically important. For instance, bed microtopography impacts crawling behaviour of stream benthic macroinvertebrates (Lancaster *et al*., 2006), and drift distance of larvae is inversely related to bed roughness (Holomuzki and Van Loan, 2002). Macroinvertebrate diversity is greater in the highly turbulent wake region of boulders (Boukaert and Davis, 1998). Velocity and shear stress affect dislodgement and abrasion of aquatic organisms (Borchardt, 1993). Two-dimensional and three-dimensional models have been used to quantify how river features interact with flow, providing hydraulic metrics to identify areas of biological importance (e.g. Crowder and Diplas, 2000, 2006; Shen and Diplas, 2008; Kozarek *et al*., 2010).

The turbulent structure resulting from flow over small-scale features (e.g. pebble clusters and boulders) have been examined in laboratory and field studies. This work has shown that ejections (slow moving fluid 'ejected' towards the surface) and sweeps (high-speed fluid 'sweeping' towards the bed) exist in flow over gravel beds, vortex shedding around bed features like pebble clusters contribute to turbulence and the development of flow structure scales with roughness

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(Buffin-Bélanger and Roy, 1998; Buffin-Bélanger *et al.*, 2000; Lacey and Roy, 2008a, 2008b; Tan and Curran, 2012). Ejections and sweeps are the largest contributors to stress in the turbulent layer (Lu and Willmarth, 1973). This progress needs to be extended to the specific turbulent structure within varying types of biotopes.

Harvey and Clifford (2009) were among the few to examine the turbulent structure of physical biotopes. They found increasing hydraulic complexity in flow characteristics from glide to riffle to pool. There was ejection–sweep structure in the glide, vortex shedding from roughness in the riffle and both vortex shedding and burst–sweep structure in the pools. Harvey and Clifford (2009) recognized the need to expand data to additional biotopes in additional stream types. In addition, because stream restoration activities can alter bed substrate and near-bed hydraulics directly or through changes in channel cross section and riparian vegetation, additional data and research are needed to quantify characteristics of these biotopes (Schwartz and Herricks, 2008; Milner and Gilvear, 2012; Hill *et al.*, 2013).

Our work examined the near-bed turbulent structure of runs and glides in a restored stream using different treatments in Western Virginia, USA and investigated the physical characteristics that influenced the near-bed hydraulics in these units. We hypothesized that changes in cross-sectional size and riparian roughness resulting from reach-scale restoration treatment produced changes in patch-scale physical characteristics of the hydraulic units and that these physical characteristics impact near-bed turbulence structure. We also addressed the hypothesis that there are differences in near-bed hydraulic properties between runs and glides in a restored channel subjected to different treatments of active and passive restoration. Finally, we compared hydraulic properties in biotopes of the restored channel with an upstream reference reach.

METHODS

Study site

The research was completed in three restored reaches and one reference reach at the Virginia Tech Stream Research, Education, and Management (StREAM) Laboratory (Blacksburg, VA, USA) (Figure 1). The StREAM

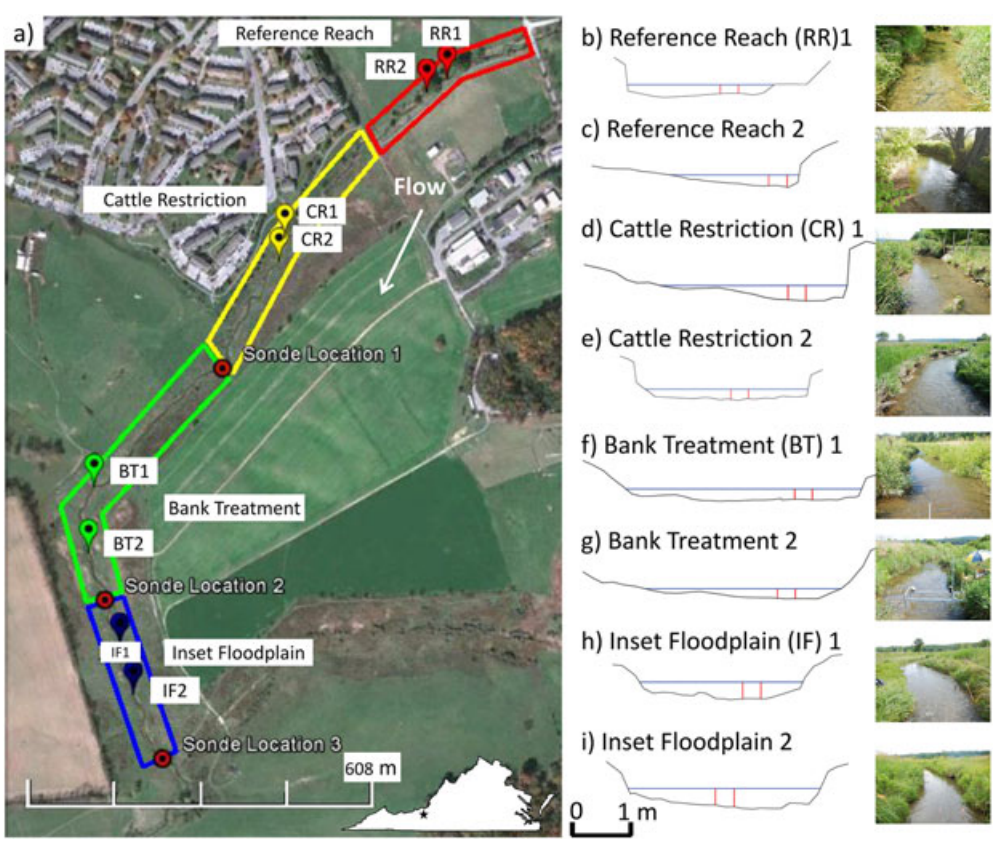

Figure 1. (a) Stream Research, Education, and Management (StREAM) laboratory with sampling locations within the reference, cattle restriction (CR), bank treatment (BT) and inset floodplain (If) reaches; (b)–(i) cross-sectional geometry of each sampling location (flow into the page, pictures are looking downstream and no vertical exaggeration). Discharge measured at Sonde Location 1. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

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Laboratory is unique because three different restoration treatments were applied contiguously along 1.4 km of Stroubles Creek, and the restoration practices ranged from passive to active. Passive restoration allows a system to recover naturally by eliminating degradation activities. It is conventional thought that channels will meet a reference condition given adequate time following passive restoration, but that length of time is not defined. Active restoration includes moderate changes such as planting riparian vegetation as well as aggressive activities like altering the channel pattern and planform (Kauffman *et al*., 1997). This reach-scale approach to restoration is a common restoration strategy (Newson and Newson, 2000; Hassett *et al*., 2005; Sudduth *et al*., 2007) and is often driven by access, cost and mitigation practices.

The Stroubles Creek watershed above the StREAM Lab is approximately 15 km^2 and includes the Virginia Tech campus and most of the town of Blacksburg. The watershed is predominately urban and residential landuse (84%) with a smaller influence of agricultural (13%) and forest (3%). The land surrounding the reaches comprising the StREAM Laboratory was once used for livestock (mostly cattle) grazing (Stroubles Creek, 2006). As part of the Total Maximum Daily Loads implementation plan to reduce sediment loads, three restoration techniques were completed to contiguous reaches of Stroubles Creek, a third-order stream (U.S. Geological Survey (USGS), 2013). In the first restored reach (T1: 0.5 km), cattle were restricted to allow for natural re-vegetation in 2009 (passive restoration: termed 'CR' for cattle restriction). In the second reach (T2: 0.6 km), cattle were restricted, vertical streambanks were reshaped to a 3:1 (vertical : horizontal) slope, and banks and riparian areas were re-vegetated through plantings in 2009 (active restoration: termed 'BT' for bank treatment). In the third reach (T3: 0.3 km), cattle were removed in 2009; a two-stage channel with 3:1 inset floodplains was created based on sediment transport analysis, and the benches and banks were re-vegetated by May 2010 (active restoration: termed 'IF' for inset floodplain). The two-stage channel was designed such that the lower bench is inundated annually and has the capacity to transport sand and cobbles. The upper bench was designed to be inundated every 2.5 years (Wynn *et al*., 2010; Thompson *et al*., 2012; Figure 1). In addition to the three restored reaches, the 0.35 km reach immediately upstream where cattle have been restricted for approximately 20 years was included (T0: termed 'RR' for reference reach).

The four study reaches were contiguous, so watershed size and characteristics were nearly equivalent, and differences were assumed to be due to local conditions (Hession *et al*., 2003). Two test sites were selected within each study reach, resulting in a total of eight sampling locations (Figure 1). All experimental sites had similar morphology of runs (RR2, CR2 and BT1) and glides (RR1, CR1, BT2, IF1 and IF2) as defined by Wadeson and Rowntree (1998). All sites had rough uneven bed surfaces characteristic of an armoured bed. We confirmed our in-field designation of the hydraulic biotopes by examining the Froude number (Fr), Reynolds number (Re), velocity/depth ratio ($\langle M\rangle/Z$), shear velocity (V^*) and roughness Reynolds number (Re^*) (Jowett, 1993; Wadeson and Rowntree, 1998; Shoffner and Royall, 2008):

$$\mathrm{Fr} = \frac{\langle M\rangle}{\sqrt{gZ}} \tag{1}$$

$$\mathrm{Re} = \frac{\langle M\rangle Z}{\nu} \tag{2}$$

$$V^* = \frac{\langle M\rangle}{5.75\log\left(\frac{12.3\langle Z\rangle}{D_{50}}\right)} \tag{3}$$

$$\mathrm{Re}^* = \frac{\langle M\rangle D_{50}}{\nu} \tag{4}$$

where $\langle M\rangle$ is the patch-mean velocity, g is the acceleration due to gravity, Z is the mean water depth, D_{50} is the median bed particle size and ν is the kinematic viscosity of water (10^{-6} m^2/s).

Field methods

Velocities were measured during baseflow conditions (flowrate = 0.04–0.08 m^3/s) in the eight locations identified in Figure 1 and were measured twice in each location during June and July 2012 (Figure 2). A Sontek 16-MHz Micro acoustic Doppler velocimeter (MicroADV; SonTek, San Diego, CA, USA) was used to measure three-dimensional velocities (±1 cm/s) at 50 Hz for 120 s, meeting the minimum record length (Buffin-Bélanger and Roy, 2005). At each test location, a 30 cm × 30 cm grid was centred over the field observed channel thalweg; measurements were not made near the channel banks. Velocities were measured at a uniform 5-cm spacing, and all velocity measurements were completed at a vertical distance of 7 cm from the bed ($n = 49$ per measurement location), which was the minimum distance that allowed reliable measurements. The ADV was aligned with the main flow direction using streamers attached to the ADV mount. Velocity data were filtered following the guidelines of Wahl (2000) and Goring and Nikora (2002).

Local flow depths were measured concurrently with each velocity measurement (±5 mm). Modified Wolman pebble counts were completed after each set of velocity measurements using a sample grid of 60 cm × 60 cm that encompassed the velocity measurement area (Wolman, 1954). Cross-sectional surveys were completed for each

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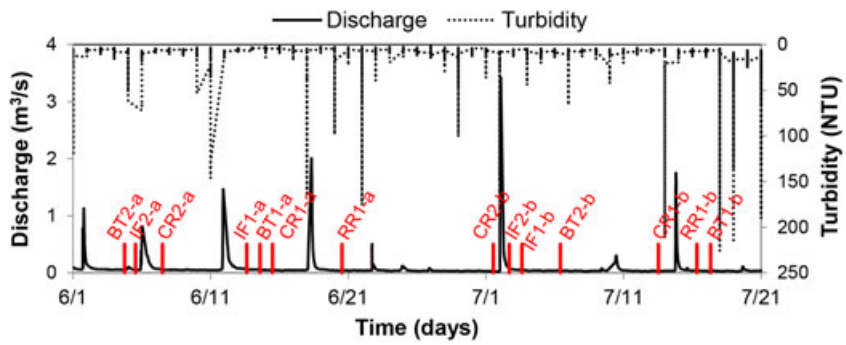

Figure 2. Time of velocity measurements for seven locations (indicated in red) and monitored discharge and turbidity measured at Sonde Location 1 (Figure 1). Velocities were measured twice per location (a and b). RR, reference reach; CR, cattle restriction; BT, bank treatment; IF, inset floodplain. (RR2 not shown, removed in data filtering). This figure is available in colour online at wileyonlinelibrary.com/journal/rra

experimental location (Harrelson *et al.*, 1994). Because we hypothesized that local, patch-scale physical characteristics impacted near-bed turbulence structure, the measurement locations were characterized by dimensionless depth (z/Z), aspect ratio (B/Z) and two relative roughness values (D_{50}/Z and D_{84}/Z) where z is the measurement depth (7 cm), B is the channel width, D_{50} is the median particle size and D_{84} is the course sediment fraction (84th percentile).

Velocity and turbulence statistics

Mean turbulence variables were quantified using the three-dimensional velocity data. The velocities u, v and w were defined as velocity in the streamwise (x), lateral (y) and vertical (z) directions, respectively (where $u = \overline{u} + u'$, u is the mean velocity and u' is the instantaneous velocity fluctuation). Velocity vector magnitude, M, was calculated for each velocity time series $\left(M = \sqrt{\overline{u}^2 + \overline{v}^2 + \overline{w}^2}\right)$.

Turbulent kinetic energy (TKE), mean kinetic energy per unit mass, was calculated for each velocity measurement:

$$\mathrm{TKE} = 0.5\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right) \tag{5}$$

where $\overline{u'^2}$, $\overline{v'^2}$ and $\overline{w'^2}$ represent turbulent intensities. Reynolds stresses were calculated using the covariance of the streamwise and vertical velocity component (Eq. 6) and using the covariance of the streamwise and lateral velocity component (Eq. 7):

$$\tau_{xz} = -\rho\overline{u'w'} \tag{6}$$

$$\tau_{xy} = -\rho\overline{u'v'} \tag{7}$$

where ρ is water density.

Statistical analysis

Ward's hierarchical clustering method was completed using the dimensionless parameters (z/Z, B/Z, D_{50}/Z and D_{84}/Z) to determine if glides and runs could be defined by patch-level physical characteristics. Tukey's HSD (honest significant difference) was used to compare turbulence statistics (TKE, τ_{xz}, τ_{xy}) because it accounts for differences in sample size. Principle components analysis (PCA) was used to reduce the turbulence statistics: TKE, τ_{xz}, and τ_{xy}. Data were transformed into z-scores before the PCA was performed to account for differences in scale. Best subset regression was used to determine the physical dimensionless variables (z/Z, B/Z, D_{50}/Z and D_{84}/Z) that best explain the variability in the near-bed turbulence statistics. The best subset analysis was repeated after removing the data for the run locations. The analysis was not repeated on run data because of the small dataset ($n = 4$). A significance level of $\alpha = 0.05$ was assumed for all tests. All statistical analyses were completed with patch mean values. Statistical analysis was conducted using JMP software v.9.0.0(SAS Institute, Cary, NC, USA) (JMP, 2007).

RESULTS

Hydraulic biotopes: runs and glides

We first compared characteristics of our experimental hydraulic biotopes with previously published data to confirm our in-field designation. For the runs, Froude number ranged from 0.23 to 0.36, and flow was fully turbulent (Re > 42,000). On average, the runs had a velocity to depth ratio value of 2.4. These values as well as V^* (0.02–0.04) and Re* (271–557) were within the ranges reported by previous studies (Jowett, 1993; Shoffner and Royall, 2008). In the glide locations, Froude number (0.17–0.30) and velocity to depth ratio values (1.0–2.3) were less than the run locations. V^* (0.2–0.4) and Re* (220–1036) values

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in the glides were similar to the run locations. Reynolds numbers were higher in the glides (>53 000). Shoffner and Royall (2008) reported on 37 glides in urban and rural streams in North Carolina, and our data compare with the hydraulic indices reported in their work. Therefore, we were confident in the in-field designation of the runs and glides in Stroubles Creek.

Results from the clustering analysis show that aggressive active restoration treatments may have some effect on the physical characteristics of the hydraulic unit (Figure 3). Glides of the IF reach were grouped at the highest cut level. Glides and runs of the other restored reaches (BT and CR) were grouped, but the glides of the reference reach were similar to the runs of the restored reaches; the glide in the reference reach was generally shallow and narrow in comparison with the glides in restored reaches (Table I). The restoration activities did not directly impact the channel bed; construction and planting activities were conducted outside channel bed within the banks and riparian zones. These results indicate that reach scale treatments will impact physical biotopes even when not installing hard structures (e.g. riffles, cross vanes and log jams). This is not surprising because simply restricting cattle access increases riparian vegetation (Hough-Snee *et al*., 2013) and channel roughness (Kamp *et al*., 2013); thereby, influencing bank stability (Scarsbrook and Halliday, 1999), sediment dynamics (Wohl and Carline, 1995) and possibly channel width (Trimble and Mendel, 1995).

Near-bed turbulence

Time-averaged velocity and turbulence statistics for each measurement location are summarized in Table II. Spatially

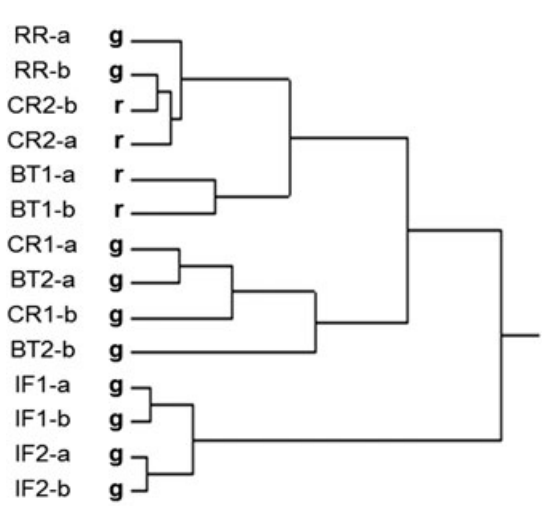

Figure 3. Clustering based on dimensionless parameters (z/Z, B/Z, D_{50}/Z, and D_{84}/Z). Letters 'g' and 'r' denote glide and run, respectively

Table I. Physical characteristics of measurement regions: relative depth (z/Z), aspect ratio (B/Z), relative roughness (D_{50}/Z, D_{84}/Z) and roughness (D_{50}, D_{84})

Reach	Type	z/Z	B/Z	D_{50}/Z	D_{84}/Z	D_{50} (mm)	D_{84} (mm)
			Sample 'a' (June)				
RR1	Glide	0.40	13.8	0.07	0.15	12	26
CR1	Glide	0.27	12.5	0.11	0.29	28	73
CR2	Run	0.42	16.4	0.09	0.17	15	28
BT1	Run	0.38	21.7	0.07	0.10	12	19
BT2	Glide	0.32	15.0	0.11	0.35	24	76
IF1	Glide	0.23	8.8	0.06	0.10	17	31
IF2	Glide	0.22	10.0	0.03	0.05	10	16
			Sample 'b' (July)				
RR1	Glide	0.46	15.7	0.07	0.17	11	26
CR1	Glide	0.29	13.1	0.07	0.18	18	44
CR2	Run	0.43	16.7	0.07	0.21	12	34
BT1	Run	0.47	26.9	0.08	0.15	12	23
BT2	Glide	0.37	17.6	0.15	0.48	29	90
IF1	Glide	0.25	9.7	0.05	0.10	15	29
IF2	Glide	0.23	10.7	0.04	0.06	11	18

RR, reference reach; CR, cattle restriction; BT, bank treatment; IF, inset floodplain.

averaged streamwise $\overline{u}$ ranges were 28.2–43.6 cm/s for runs and 24.3–50.0 cm/s for glides. This streamwise $\overline{u}$ contributed up to 99.8% of M. On average, the magnitudes of M measured during July were within 8% of the M measured in June. However, average velocity magnitudes at CR1, BT1 and IF2 were 16% less, 32% greater and 56% less in July than June, respectively. While the attempt was to measure at constant discharge values during baseflow conditions, there was some variability in discharge (0.05–0.07 m^3/s in June and 0.04–0.08 m^3/s in July). Glides are relatively uniform, and little variation in hydraulic parameters is expected with these small values of variable discharge (Harvey and Clifford, 2009). The hydraulic structure of runs has not been previously evaluated, but minimal impact on the hydraulic structure of the units was also expected because of these minor variations in discharge.

The spatial distribution of TKE within the measurement regions for each location and sampling time are shown in Figure 4. There is little variability among most of the experimental sites and no consistent spatial trend between measurement dates. Within the glide of the reference reach, TKE values were low, relatively uniform and similar between sampling dates. Similar results were observed in the run of the bank treatment reach (i.e. BT1). TKE values in the inset floodplain reach were also relatively low with little spatial variability, but TKE measured in July were greater than those measured in June. The difference in magnitude at IF2 was likely due to the difference in flow rates. In June, the flow rate at the time of measurement was 0.06 m^3/s,

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Table II. Summary of time-averaged velocities ($\overline{u}$, $\overline{v}$, $\overline{w}$) and turbulence statistics (TKE, τ_{xz}, τ_{xy}) at each measurement location

Reach	Type	$\overline{u}$ (cm/s)	$\overline{v}$ (cm/s)	$\overline{w}$ (cm/s)	TKE (cm^2/s^2)	τ_{xz} (N/m^2)	τ_{xy} (N/m^2)
				Sample 'a' (June)			
RR1	Glide	31.8 (2.1)	3.5 (1.2)	−1.3 (0.5)	33 (3.8)	0.7 (0.12)	0.2 (0.3)
CR1	Glide	24.3 (6.4)	4.6 (1.8)	−2.1 (1.5)	53 (8.6)	1.2 (0.39)	0.5 (0.8)
CR2	Run	43.6 (9.1)	4.5 (3.2)	−2.9 (2.0)	105 (54)	3.1 (2.8)	−0.3 (1.3)
BT1	Run	41.6 (4.9)	−2.8 (1.1)	0.7 (0.6)	56 (10)	0.9 (0.4)	0.3 (0.9)
BT2	Glide	40.5 (13.4)	−1.4 (3.4)	1.1 (1.8)	97 (30)	2.3 (1.4)	−0.7 (1.7)
IF1	Glide	41.7 (3.6)	5.1 (3.1)	−4.0 (1.9)	70 (10)	1.2 (0.4)	0.6 (0.4)
IF2	Glide	31.2 (1.2)	−6.7 (0.7)	0.6 (0.6)	47 (12)	0.4 (0.2)	−0.3 (0.4)
				Sample 'b' (July)			
RR1	Glide	33.1 (2.2)	2.5 (0.9)	−0.9 (0.4)	26 (3.1)	0.6 (0.12)	0.2 (0.1)
CR1	Glide	27.3 (5.8)	8.0 (1.8)	−2.6 (2.1)	93 (50)	2.1 (1.4)	0.2 (1.1)
CR2	Run	42.0 (5.6)	2.0 (2.5)	−2.4 (1.8)	94 (18)	2.0 (0.6)	−0.04 (1.6)
BT1	Run	28.2 (1.4)	−2.6 (0.9)	−0.7 (0.4)	27 (2.6)	0.5 (0.1)	0.1 (0.1)
BT2	Glide	36.5 (13.3)	4.1 (2.4)	−1.1 (2.8)	114 (45)	2.5 (2.0)	−0.6 (2.4)
IF1	Glide	41.2 (2.9)	3.9 (1.4)	−0.8 (0.6)	97 (22)	0.3 (0.6)	0.5 (1.0)
IF2	Glide	50.0 (5.6)	−4.6 (2.2)	−1.9 (2.4)	94 (9.2)	0.2 (0.5)	1.2 (2.1)

TKE, turbulent kinetic energy; RR, reference reach; CR, cattle restriction; BT, bank treatment; IF, inset floodplain.
Mean and standard deviation (in parentheses) are reported ($n = 49$ per location).

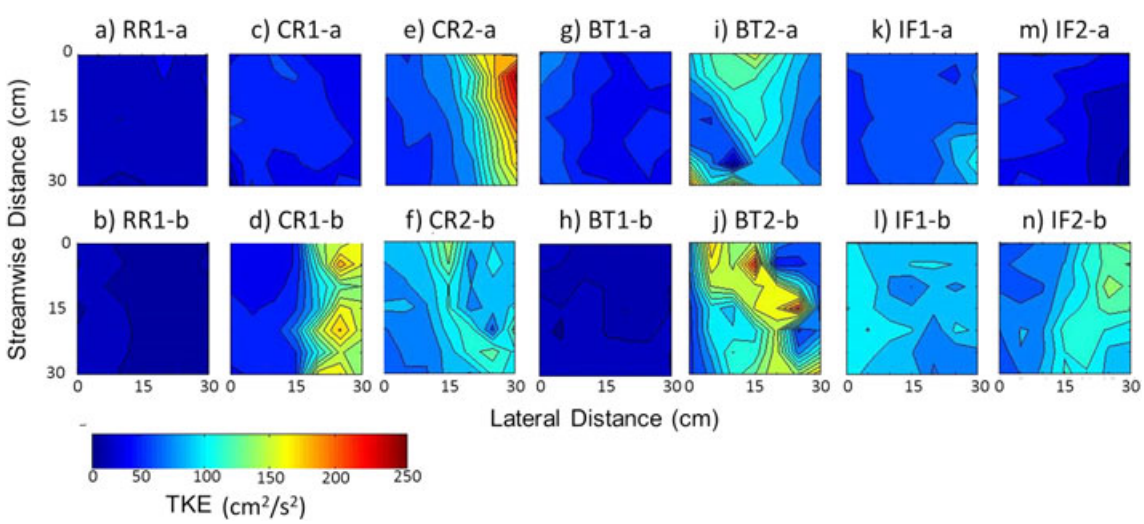

Figure 4. Spatial distribution of turbulent kinetic energy (TKE) for each location and sample time. The main flow direction is the positive streamwise direction. RR, reference reach; CR, cattle restriction; BT, bank treatment; IF, inset floodplain (glides: RR1, CR2; BT2, IF1, IF2; runs: CR2, BT1). This figure is available in colour online at wileyonlinelibrary.com/journal/rra

while the flowrate increased to 0.08 m^3/s in July (Figure 2). Greater variability was observed in the other locations: CR1 (glide), CR2 (run) and BT2 (glide). The high magnitude and variability of TKE observed at BT2 were likely attributed to large relative roughness ($D_{50}/Z = 0.08$–0.15; $D_{84}/Z = 0.35$–0.48), which were the largest of all locations.

The magnitude of the variation in TKE within the individual biotopes was likely related to bed roughness. Tan and Curran (2012) also reported a uniform near-bed spatial distribution of Reynolds stresses and TKE over a gravel bed with no bedforms. In their flume study, TKE increased locally because of bed roughness on the order of 50 cm^2/s^2, and the increase was attributed to a local relative roughness value of 0.06. This roughness is comparable with our reaches where we observed an increase of TKE on the order of 100–250 cm^2/s^2. Because much of the turbulence was generated by the roughness, there was likely minimal energy exchanged throughout the water column (Tan and Curran, 2012).

For the RR, CR and BT, τ_{xz} was 1.7–9.6 greater than τ_{xy} (Table II). Reynolds stress, τ_{xz}, represents the tangential on

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the vertical–longitudinal plane, and the dominance of that component indicates momentum exchange in the streamwise direction. This result is consistent with Lacey and Roy (2008a) who reported that τ_{xz} was three to five times greater than τ_{xy} in the wake of a cluster with a relative roughness of 0.4. Reynolds stress τ_{xz} was not always greater than τ_{xy} in the glides of the inset floodplain reach; τ_{xz} was 0.2–2.2 times τ_{xy}. Measurements in this location may have had influenced of secondary flows or wall effects because of the lower aspect ratios of less than 10.7 (Table I). Increased streamwise vorticity has been observed at low aspect ratios with a maximum expected at $B/Z = 2$ (Knight *et al*., 1984). The distribution of τ_{xz} in the measurement region for all locations at both sample times are shown in Figure 5. Similar spatial trends in τ_{xz} as the TKE distribution were observed.

There were differences in turbulence structure with time. The spatial distribution in TKE and τ_{xz} varied substantially between the two sets of measurements at CR1, CR2 and BT2 (Figures 4 and 5). On average, τ_{xz} was 75% greater, 35% less and 9% greater in July than June at CR1, CR2 and BT2, respectively, and similar trends existed for TKE. These differences were likely related to the change in relative roughness between measurement times, resulting from the storm events between measurements (Figure 2, Table I) because uneven surfaces of armoured beds generally generate small-scale turbulent structures (Tan and Curran, 2012).

We further evaluated the turbulence statistics to determine if there were differences between the glide and run locations. All measurements were included in this analysis (glides: $n = 490$; runs: $n = 196$). Reynolds stresses, τ_{xz}, were significantly different between runs and glides ($p = 0.0012$). There were no differences in τ_{xy} and TKE between hydraulic unit types ($p = 0.2125$–0.3027). In addition, differences in turbulence intensities were evaluated, and differences were only found for the z-component ($p = 0.0234$) (Figure 6).

Principle components analysis was completed using the turbulence statistics (τ_{xz}, τ_{xy} and TKE). We used both the patch mean values (as a z-score), as well as the coefficient of variation of each statistic in the analyses. The coefficients of variation are not discussed because including coefficients of variation reduced the explanation of variability in the first PCA axis (i.e. Component 1). The scores on Component 1 explained 67% of the variability for the entire dataset ($n = 14$) and was composed primarily of TKE and τ_{xz} (Figure 7a); 94% of the variability was explained by two components. The regression analysis suggested that relative roughness based on the large fraction (D_{84}/Z) as the main driver of the Component 1 scores for the full data set. Relative roughness values were also significantly related to τ_{xz} and τ_{xy}. There was no significant regression with TKE (Table III).

Differences were identified between runs and glides for τ_{xz} in the previously discussed analysis, so the PCA analysis was repeated for the glide locations only ($n = 10$). The analysis was not completed for the run locations because of the small dataset ($n = 4$). The scores on Component 1 explained 62% of the variability for the glides; 92% of the variability was explained with two components (Figure 7b). The regression analysis showed that the channel geometry (z/Z and B/Z) were significantly related to the Component 1 scores, unlike the full data set. There again was no significant relationship with TKE at an α-value of 0.5. The best regression resulted in a p-value of 0.073 with significant regressors of relative depth and aspect ratio (Table III).

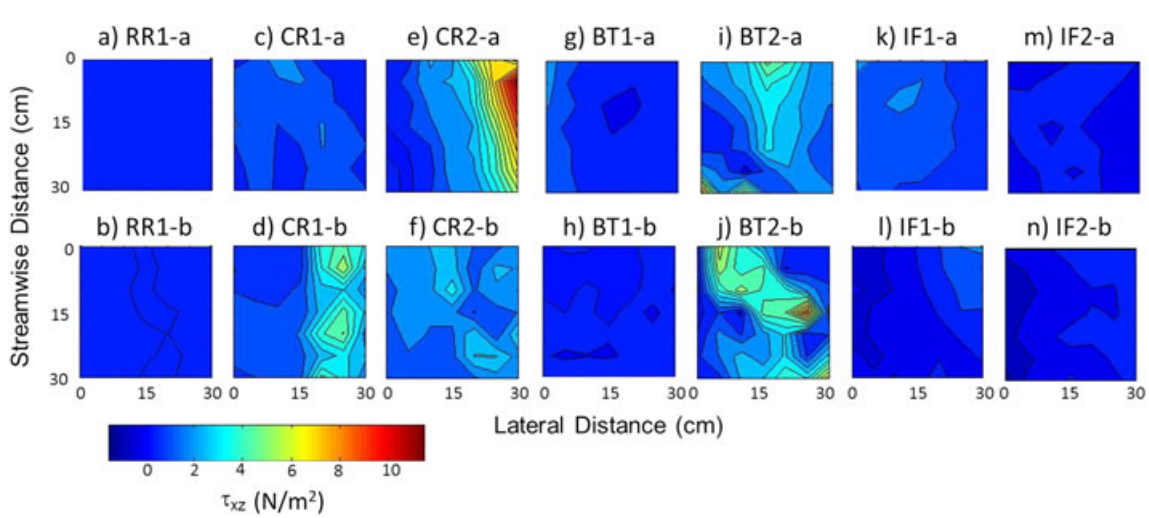

Figure 5. Spatial distribution of τ_{xz} for each location and sample time. The main flow direction is the positive streamwise direction. RR, reference reach; CR, cattle restriction; BT, bank treatment; IF, inset floodplain (glides: RR1, CR2; BT2, IF1, IF2; runs: CR2, BT1). This figure is available in colour online at wileyonlinelibrary.com/journal/rra

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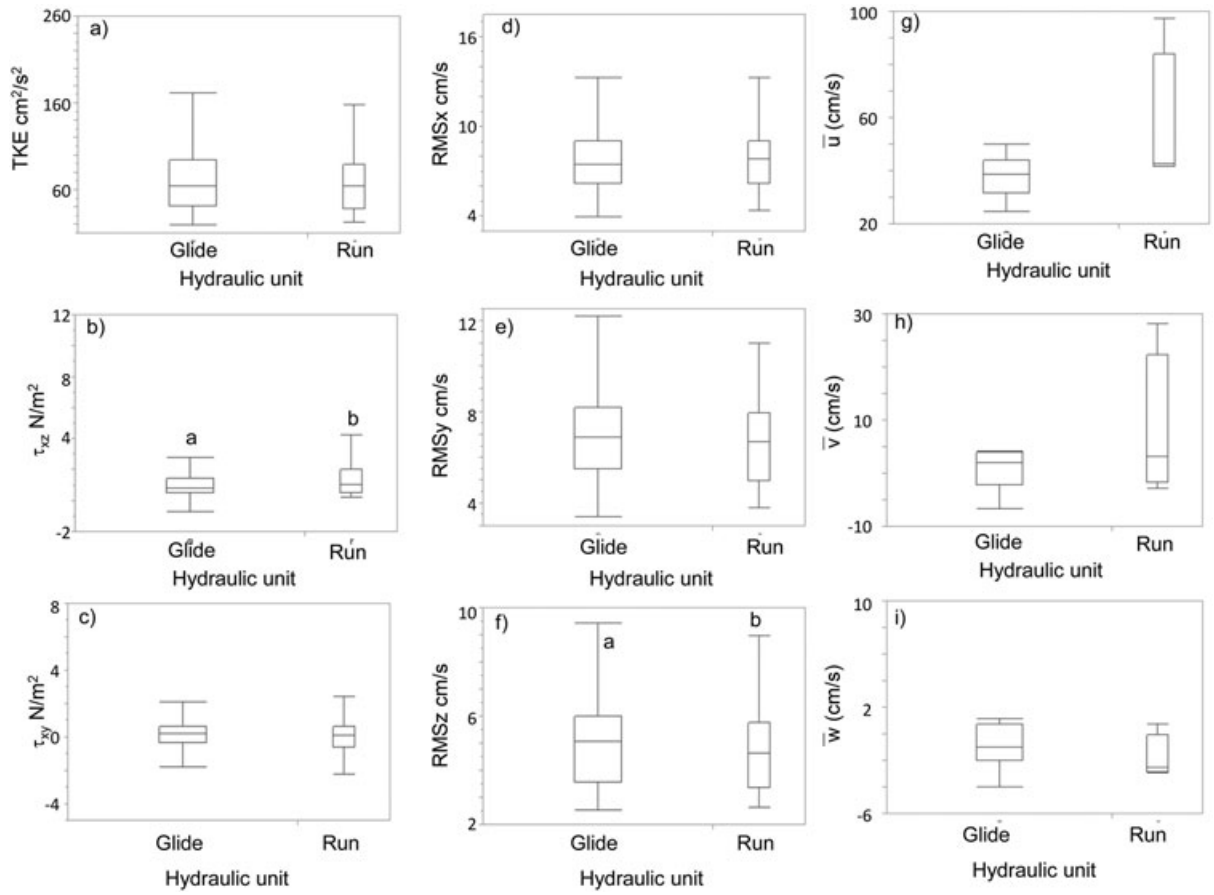

Figure 6. Turbulence statistics compared by hydraulic unit; letters 'a' and 'b' are included on plots (b) and (f) to indicate a significant difference between glides and runs (median: line; 25%–75%: box; 5%–95%: whisker). TKE, turbulent kinetic energy

The Reynolds stresses were significantly related to relative roughness, like the full dataset. This result supports previous research by Harvey and Clifford (2009) who reported that the turbulent structure was dominated by ejections and sweeps, a structure that is related to boundary roughness. A quadrant analysis was also completed to determine the dominance of turbulent flow events contributing to $u'w'$ (Hole size, $H=0$ and $H=2$; Lacey and Roy, 2008a). The quadrant analysis confirmed that ejections and sweeps were dominant regardless of hole size in both the runs and glides (data not shown).

DISCUSSION

We hypothesized that changes in cross-sectional size and riparian vegetation, resulting from reach-scale restoration produced changes in substrate and structure of the hydraulic units because there is a complex interaction among cattle exclusion, riparian vegetation and actively changing channel shapes. For instance, Trimble and Mendel (1995) suggested livestock exclusion would result in increased grasses along the streambank, resulting in increased sediment trapping and channel narrowing. However, Kondolf (1993) evaluating the lag in stream channel adjustment due to cattle exclusion found that channel width had not changed in 24 years, suggesting that change might depend on site-specific conditions such as hydrology, sediment loads and climate. Regardless, over a longer term time period (>30 years) we might expect the channel to widen as the riparian forest matures (Davies-Colley, 1997; Ranganath *et al*., 2009; McBride *et al*., 2010).

The main restoration activities at Strouble Creek included removing cattle, planting vegetation along the riparian corridor, reducing streambank slopes and in some locations creating an inset floodplain to slow down high flows. No hydraulic features were added as is typical of Natural Channel Design, but our results suggest that the reach-scale restoration activities influence physical structure of the hydraulic biotopes measured at low flow. Even without the inclusion of hard structures, the physical characteristics of the glides within the IF were classified differently than the

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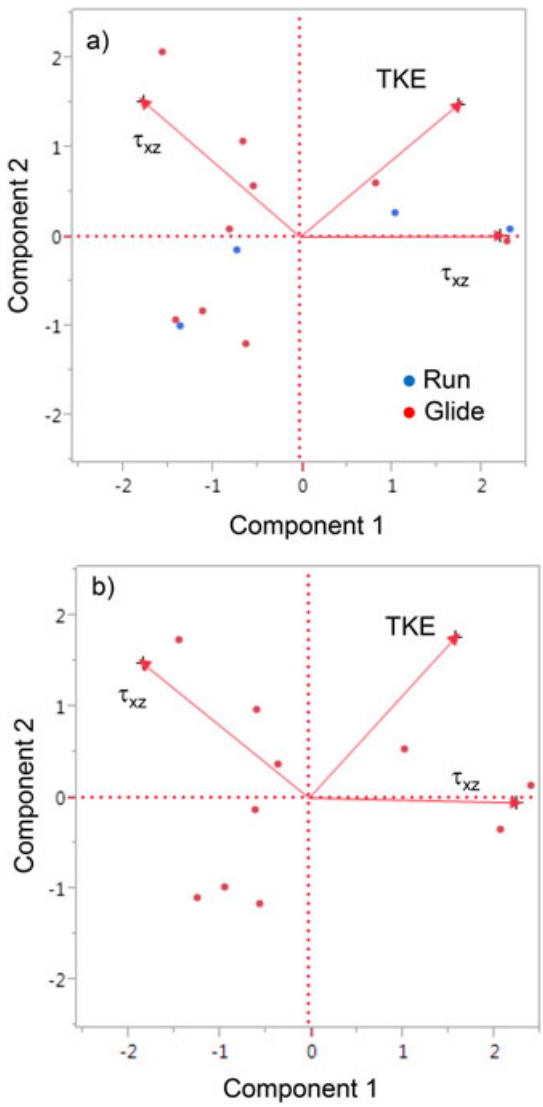

Figure 7. Principal components of (a) full data set and (b) glide data set. TKE, turbulent kinetic energy. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

glides in the BT, CR and RR and continued to this day (W. C. Hession, personal communication, 2015). Following restoration, the inset floodplain reach began to substantially narrow compared with the other restored and reference reaches. The combination of increased reach-scale roughness provided by the added riparian vegetation and reduced energy resulted in the trapping of sediment during high flows. Therefore, the measurement locations were characterized by low relative roughness and aspect ratios as compared with measurement locations in other reaches (Table I). This difference was highlighted in the cluster analysis as the glides of the inset floodplain were grouped at the highest-cut level (Figure 3).

The addition of bank vegetation and change of bank angle that occurred at the BT treatment is considered to be active restoration. However, the physical characteristics of the hydraulic units were similar to those of the reach with passive restoration (CR). While the bank treatment reach also narrowed in places, significant narrowing along the entire reach has not occurred, and substantial narrowing had not occurred at our measurement locations; channel geometry was more similar to the CR. This was evident in the cluster analysis results. At the second highest cut level, the glides of the BT and CR treatments were classified together (Figure 3). Similarly, the runs for the BT and CR treatments were grouped together.

The glides of the reference reach had physical characteristics similar to runs of the restored reaches. Cattle were removed more than 20 years ago in the reference reach, so the riparian vegetation is more mature and denser than the downstream restoration reaches, contributing greater reach-scale roughness. Large shrubs and trees exist in close proximity to the stream in the reference reach, and many vertical banks still exist. These are generally not present along restored reaches. Compared with the reference reach, the glides of the restored reaches were 26% wider and 61% deeper. The relative roughness of the glides in the restored

Table III. Results of best regression analysis of turbulent statistics

Dependent variable	n	Intercept	z/Z	B/Z	D_{50}/Z	D_{84}/Z	p-value	Adjusted R^2
All field sites								
PCA Component 1	14	−1.53	—	—	—	8.38	0.0283	0.29
τ_{xz} (N/m^2)	14	−1.61	—		21.0	—	0.009	0.40
TKE (cm^2/s^2)[1]	14	94.01	−132.98			126.09	0.156	0.16
τ_{xy} (N/m^2)	14	0.92	—	—	—	−5.02	0.027	0.29
Glides								
PCA Component 1	10	−3.75	−25.80	0.91			0.027	0.54
TKE (cm^2/s^2)[1]	10	−0.15	−15.77	0.39	—	—	0.073	0.39
τ_{xz} (N/m^2)	10	−1.20	—	—	—	5.51	0.004	0.64
τ_{xy} (N/m^2)	10	−1.21	—	—	−95.82	−34.30	0.051	0.45

TKE, turbulent kinetic energy; PCA, principle components analysis.
[1]Not statistically significant at $\alpha = 0.05$ but presented to show best regression for TKE.

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reaches was also greater than the reference reach (65% and 84% greater for D_{50} and D_{84}, respectively). The differences were supported with the cluster analysis because the glides of the reference reach were grouped with the runs of the bank treatment and cattle restriction reach.

Conventional thought suggests that stream restoration designs will move towards a reference reach condition with time. The results suggest that the hydraulic biotopes in the RR have different physical structure than the restored reaches 2–3 years following restoration (Figure 3). The differences were also evident in the near-bed hydraulics. The glides of the restored reaches had more spatial variability of TKE and τ_{xz} than the glides of the reference reach (Figures 4 and 5). This result suggests that hydraulic variability may reduce in the restored reaches with time as the reach-scale roughness approaches conditions similar to the upstream reference reach. It should be noted that we attempted to evaluate a run within the reference reach, but the velocity data were removed in the filtering process.

Differences between runs and glides for the near-bed hydraulic statistics were expected because the glide has been described as the simplest flow structure (Harvey and Clifford, 2009). The only observed differences occurred for the flow variables τ_{xz} and RMS_z. These differences in near-bed turbulence structure were likely related to local roughness as discussed in previous studies (e.g. Hardy *et al*., 2010; Tan and Curran, 2012). In our study, no bedforms were observed in the hydraulic units, and the armoured bed was hydraulically rough. Results from the regression analysis suggest that near-bed τ_{xz} of the glides were significantly related to the large roughness because D_{84}/Z was a significant regressor. The relative roughness value D_{50}/Z was also significant for τ_{xy}. Greater bed roughness increases the frequency and magnitude of turbulent bursts (Papanicolaou *et al*., 2001).

Relative depth was not significant to define Reynolds stresses but was significant for TKE when considering the entire dataset (increasing α to $\alpha = 0.1$). All measurements were made 7 cm above the bed. This was the smallest distance that we were able to reliably measure instantaneous velocities. The intent was to measure as close to the bed as possible and to be within the inner region ($z/Z \leq 0.3$; as defined by Tan and Curran, 2012). Due to the varying water depths, all measurements were made at relative depths ranging from 0.22 to 0.46, and velocity was measured in the outer region ($z/Z \geq 0.4$) at several locations (RR1, CR2 and BT1). The result that relative depth was not significant in the regression analysis when considering Reynolds stresses as the dependent variable (Table III) was unexpected as Reynolds stresses are expected to reach a maximum value near the bed for multiple bed conditions (Venditti, 2007; Lacey and Roy, 2008b).

Due to the narrowing of the channel that followed reach-scale restoration, the aspect ratios of the glides in the IF reaches were smaller than the other reaches. However, aspect ratio was only significant in describing near-bed hydraulic structure of the glides (i.e. PCA Component 1 scores). As previously stated, all velocity measurements were made during baseflow conditions, so secondary flow structure may have been minor. However, the aspect ratio would potentially be significant during storm flows as aspect ratios approach lower values and stream vorticity increases (Knight *et al*., 1984).

SUMMARY AND CONCLUSIONS

Our study provides a detail *in situ* characterization of the near-bed turbulent structure within four distinct restoration zones of a single stream. We targeted the physical biotopes of runs and glides. The study sites had rough uneven bed surfaces characteristic of the armoured bed observed throughout the study channel. Major conclusions include the following:

- While the restoration activities did not address the channel bed directly, differences in physical structures of the two physical biotopes were observed between restoration treatments. The glides of the IF treatment were classified differently than the glides of the other treatments, and the glides of the reference reach were similar to runs of the restored reaches. The measurement locations were in reaches that were altered with bank cuts and plantings in the bank treatment and inset floodplain reaches. These modifications along with the changes in reach scale roughness likely influenced the physical structure of the glides and runs.
- The 2–3 years following restoration was not a sufficient time for the physical biotopes of the restored reaches to have the same physical structure as the reference reach. However, because the reference reach still has vertical banks, they may never be equivalent.
- Few differences were observed in the hydraulic structure between runs and glides. The only observed differences occurred for the flow variables τ_{xz} and RMS_z.
- The near-bed flow structure in the runs and glides was related to local roughness of the armoured beds. Relative roughness variables were significant regressors for most of the hydraulic statistics (i.e. PAC Component 1 scores, τ_{xz} and τ_{xy})

This work was limited to the study of two physical biotopes (runs and glides) at low flows. The turbulent structures of physical biotopes should be continued at flood flows at a wider range of biotypes. In addition, the complex

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interactions among cattle exclusion, riparian vegetation and actively changing the channel shapes highlight the need for more research to better understand the processes and interactions, as well as continued research to evaluate change over time.

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