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Hydrologic response to channel reconfiguration on Silver Bow Creek, Montana ☆

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ABSTRACT

Hydrologic residence time in streams is rarely considered as a response variable for assessing restoration design strategies. However, residence time is an important control on ecosystem processes such as the biotic uptake and processing of excess nutrients and other pollutants in streams. Interactions between the physical structure of streambeds and the patterns of flow through the channel determine hydrologic residence time and largely control solute transport and exchange among various channel habitats and the hyporheic zone. The influence of reach-scale channel reconfiguration on residence time is not well characterized despite documented linkages between streambed topography, channel pattern, hydrologic retention, water quality, and in-stream habitat. This study documents changes in hydrologic transport and variation in channel water velocity prior to and immediately following large-scale channel realignment along Silver Bow Creek in southwestern Montana. Channel restoration increased water residence time in the channel by increasing sinuosity, decreasing channel slope, and increasing pool frequency. However, channel realignment yielded a reduction in the fine-scale variation in streambed topography. Water velocity profiles in post-realignment channels, thus, exhibited greater uniformity at short spatial scales. As a result, and possibly due to loss of hyporheic exchange, transient storage within the system declined after channel realignment, offsetting some of the increase in residence time associated with slower advective velocities. We conclude that restoration actions may be more effective at recovering normative hydrologic function if goal setting, planning and design efforts consider the hydrologic effects and ecological benefits of fine-scale (cm–m) topographic stream-bed variation and the bio-geomorphic processes that create and maintain such fine-scale variation over time.

1. Introduction

Hydrologic transport dynamics in channels influence stream ecosystems by creating habitat diversity and by mediating opportunities for bioreactive solutes to interact with sediments and microbial assemblages. Reductions in solute transport velocity facilitated by the flux of water between stream channels, surface-water dead zones and streambed sediments (jointly referred to as transient storage) exposes solutes to a variety of redox states (Fernald et al., 2006; Hinkle et al., 2001; Storey et al., 2004) and can create "hotspots" of elevated biogeochemical activity (Boulton et al., 1998; Duval and Hill, 2007; McClain et al., 2003) that may influence whole-ecosystem function by transforming nutrients, heavy metals, and pollutants (Baker and Vervier, 2004; Bencala, 2005; Boulton et al., 1998; Ensign and Doyle, 2005; Findlay, 1995; Hinkle et al., 2001; McClain et al., 2003; Mulholland and DeAngelis, 2000). Further, water exchanges between the channel and hyporheic zone can directly influence channel temperature regimes (Arrigoni et al., 2008), physiology and behavior of aquatic species (Baxter and Hauer, 2000), and rates of stream metabolism (Fellows et al., 2001). Thus, the effect of water and solute movement along relatively slow-moving flowpaths created by in-channel storage or hyporheic exchange on overall hydrologic residence time may be a critical determinant of habitat quality and a stream's resilience to excess nutrient loading (e.g. wastewater effluent, agricultural runoff) and/or contamination by major ions and metals (e.g. acid mine drainage, industrial effluent, urban runoff).

The role of physical structure in governing patterns of water and solute movement is important to restoration strategies that seek to improve the ecological function of stream systems. Exchanges between the advective portion of the stream channel, surface-water storage zones, hyporheic zones, and groundwater are assumed most prevalent where channel morphology is complex (e.g. high sinuosity, frequent side channels and mid-channel bars, well-formed pool/riffle sequences, and variable channel slope). This supposition is supported by research indicating that channel-unit spacing (Cardenas, 2008; Cardenas et al., 2004), sinuosity (Gooseff et al., 2006), the presence of channel obstructions (Ensign and Doyle, 2005), and the characteristics of the alluvial

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aquifer in the catchment (Poole et al., 2006) govern the spatial arrangement of hydrologic flowpaths at the channel-unit scale and that geomorphic structures along the streambed and banks (Cardenas et al., 2004; Kasahara and Hill, 2006), breaks in slope (Anderson et al., 2005; Gooseff et al., 2006), and hydraulic conductivities of subsurface sediments (Packman and Salehin, 2003) can be useful predictors of the arrangement and persistence of such flowpaths at the bedform scale. Where channel form has been simplified, transient storage is apt to be reduced and the associated ecological benefits lost. Despite documented linkages between individual restoration structures/features, hydrologic retention, habitat diversity, and solute transport characteristics (Crispell and Endreny, 2009; Kasahara and Hill, 2006; Mutz et al., 2007), very few studies have investigated the role of reach-scale geomorphic channel restoration on hydrologic transport processes. Thus, hydrologic transport and exchange is an important yet often overlooked intermediate consideration for attaining many common restoration goals. Further assessment of hydrologic response to channel reconfiguration should allow for more effective adaptive assessment of the efficacy of various restoration practices.

An increasing awareness of existing research gaps and data gaps left by post-restoration monitoring plans prompted recent calls to investigate the effect of stream restoration on spatio-temporal patterns of water and solute movement (Hester and Gooseff, 2010). Here, we report measured changes in channel hydrology and solute transport resulting from a massive stream restoration project on Silver Bow Creek (SBC), Montana, USA. We hypothesized that channel realignment would alter streambed topography, velocity fields and, consequently, patterns of water and solute movement. Specifically, we anticipated that: (1) measures of hydrogeomorphic channel complexity would be greater in restored channel segments at a range of spatial scales, resulting in (2) lower advective transport velocities and increased transient storage. We tested these predictions by conducting hydrogeomorphic surveys and stream tracer experiments on multiple channel segments prior to and following realignment of the stream channel.

2. Site description

Silver Bow Creek is situated at the headwaters of the Clark Fork River watershed in southwestern Montana, and drains an area heavily impacted by more than a century of hard-rock mining activities. We studied approximately 2 km of SBC near Fairmont, Montana at the south end of the Deer Lodge Valley (Fig. 1). At a stream gauge immediately downstream of the study site (USGS gauge 12323600, Lat. 46°06′28″, Long. 112°48′17″), SBC drains an area of 940 km^2. The floodplain is composed of Quaternary alluvium. Prior to restoration, the stream flowed over coarse, embedded native alluvium and exhibited primarily run habitat throughout its length (Pioneer Technical Services, Inc. and Applied Geomorphology, Inc., 2008). The study site lies within a 42 km long section of stream corridor designated by the Environmental Protection Agency as a federal superfund site. Extensive remediation and restoration activities are ongoing on SBC due to a suite of historical injuries including a series of floods in the early 1900s that transported metal-rich mine tailings along the stream corridor and buried floodplain soils with up to 2 m of contaminated sediments (Gammons et al., 2006) and large-scale placer mining activities that manifested in the excavation and channelization of the streambed.

Restoration goals for the site included removing contaminated sediments, improving aquatic habitat, enhancing the aesthetic appeal of the floodplain, and promoting the function of dynamic riverine processes (MNRDP et al., 2005). Achievement of these goals necessitated removal and replacement of contaminated floodplain soils and complete realignment of the stream channel. Restoration took place on successive valley sections between 400 m and 1.0 km in length. Construction of restored channels occurred at a depth such that the streambed ran through the same native valley-fill sediments that pre-realignment channels flowed through. Hydrogeomorphic and solute transport data collection occurred along multiple pre- and post-realignment channel segments across a range of flow states during the summer and fall of 2009.

3. Methods

Hydrogeomorphic and conservative solute transport characterization of individual channel reaches occurred prior to and following channel realignment. Data collected from multiple channel segments were aggregated according the structural state of the channel (pre-realignment vs. post-realignment). We deemed this approach reasonable as observations showed channel hydraulics and geomorphology of pre-realignment channels to be relatively constant across the study area. Similarly, the design principles and construction techniques used to construct restored channel segments did not vary between the segments selected for study.

3.1. Geomorphic and hydraulic characterization

We conducted geomorphic and hydraulic comparisons of pre- and post-realignment channel segments on SBC. Such characterizations are frequently used in conjunction with tracer studies because the methodological constraints of the stream tracer approach necessitate some degree of speculation about the mechanisms responsible for observed hydrologic transport and storage processes (Gooseff et al., 2007). Digitization of thalweg lines from aerial photos and planform channel design plans within a GIS identified changes in channel sinuosity following restoration. Comparison of pre-restoration floodplain surveys and design plans for restored channels identified changes in reach-averaged channel

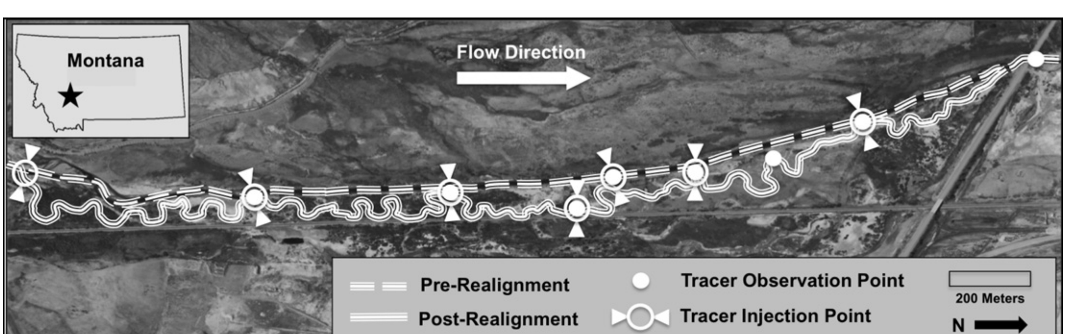

Fig. 1. Silver Bow Creek study site.

slope. Velocity and depth data was collected directly in the field. A StreamPro (Teledyne RD Instruments, Poway, California, USA[1]) acoustic Doppler current profiler (ADCP) mounted on a floating platform measured water velocity fields and vectors of stream depth. The operating principles of ADCPs are described in greater detail elsewhere (Gordon, 1996). Teledyne's proprietary WinRiver II software interfaced with the ADCP to collect and post-process data. High-resolution depth and velocity profiles were collected with the ADCP set to Mode 11. The default settings in the WinRiver II software for this profiling mode were used to remove unreliable data points. We operated the instrument in the field by attaching a long aluminum handle to the downstream side of the floating platform and pushing it at a constant rate both perpendicular to the main direction of flow (cross-sectional profiles) and along the channel thalweg (longitudinal profiles).

Direct comparison of ADCP data collected from 27 randomly selected cross-sections on each of two adjacent channel segments—one pre-realignment and one post-realignment—during summer baseflow conditions ($Q \approx 800\ s^{-1}$) identified changes in channel width, cross-sectional area, hydraulic depth, wetted perimeter, hydraulic radius, and Froude number. Frequency distributions of stream depth collected along the channel thalweg and along individual cross-sections were calculated by summing the lengths of streambed that fell within various depth ranges and dividing by the total measured thalweg or cross-sectional length. Thus, we assessed the probability that stream depth fell within a given depth range as:

$$P[d_{\min} < d < d_{\max}] = \left(\sum_{i=1}^{n} x_i\right) \Big/ L \tag{1}$$

where $d_{\min}$ and $d_{\max}$ define the minimum and maximum of the depth range, respectively, d is the stream depth measured over some distance x, $x_{1\ldots n}$ are the lengths of stream that have depths within the depth range, and L is the total measured stream length. Aggregation of cross-sectional data collected along a given channel segment was yielded a single distribution. Frequency distributions of stream velocity were calculated by summing the measured longitudinal and cross-sectional profile area fractions falling within various velocity ranges and dividing by the total measured profile area. We computed the probability that velocity fell within a given range as:

$$P[v_{\min} < v \leqslant v_{\max}] = \left(\sum_{i=1}^{n} a_n\right) \Big/ A_l \tag{2}$$

where $v_{\min}$ and $v_{\max}$ define the minimum and maximum of the velocity range, respectively, v is the stream velocity measured over some longitudinal or cross-sectional profile area a, $a_{1\ldots n}$ is the profile area falling within the velocity range, and A_l is the total area of the profile. Aggregation of cross-sectional data collected along a given channel segment yielded a single distribution.

We investigated spatial patterns of velocity and depth data through application of geostatistical methods. These methods, including calculations of semivariance, are gaining popularity as a tool for assessing the spatial organization of stream hydraulics and bathymetry (Legleiter et al., 2007; Shields et al., 2003). We calculated semivariance (γ) for depth and velocity data as:

$$\gamma(h) = \frac{1}{2n_h}\sum_{i=1}^{n_h}(z(x_i + h) - z(x_i))^2 \tag{3}$$

where h is the lag distance between pairs of ordered data of some variable z measured at points $x_{1\ldots n}$. We used a constant lag distance of 10 cm in our calculations of semivariance. Prior to calculation of semivariance, the underlying assumption of stationarity was tested. Data were visually checked for first-order trends by plotting measured velocity values against stream depth. No such trends were observed.

We used experimental semivariograms to explore the spatial organization of measured depth and velocity values at three flow states: $800\ s^{-1}$, $1100\ s^{-1}$, and $1400\ s^{-1}$. Data collected from adjacent 400 m long pre- and post-realignment channel segments produced longitudinal velocity and depth semivariograms. Aggregation of semivariance values calculated at various lag distances from multiple cross-sections within a single channel segment yielded cross-sectional semivariograms. We quantified differences in spatial structure by fitting spherical semivariogram model structures or pure nugget effect model structures to the data:

$$\gamma_{\text{spherical}}(h) = n + (s - n) * \left[\left(\frac{3h}{2r}\right) - 0.5\left(\frac{h^3}{r^2}\right)\right] \tag{4}$$

$$\begin{aligned}\gamma_{\text{spherical}}(h) &= 0 \quad \text{when } |h| = 0\\ &= s \quad \text{when } |h| \neq 0\end{aligned} \tag{5}$$

where the sill (s) is equal to the maximum variance of the data set, n is the nugget, and r is the range. We selected model type a priori through visual assessment of individual semivariograms. Monte Carlo sampling identified best-fit model parameters by drawing 10^3 random samples for r and n from uniform distributions. Visual inspection of experimental semivariograms suggested the upper and lower bounds for sampled parameter distributions. The parameter set that produced the model with the smallest sum of squared errors when evaluated against the experimental semivariogram was selected as the optimal set. We related each component of the semivariogram (as described by model parameters) back to the physical organization of stream topography or velocity fields.

3.2. Stream tracer experiments

Stream tracer experiments are frequently used to characterize hydrologic residence time distributions (RTDs) and identify mechanisms of solute storage and exchange in streams (Anderson et al., 2005; Gooseff et al., 2008; Haggerty et al., 2002; Harvey et al., 1996; Wondzell, 2006). We conducted 58 stream tracer experiments on pre-realignment ($n = 35$) and post-realignment ($n = 23$) study reaches during the summer and fall of 2009. We selected reach lengths for tracer experiments such that RTDs could be compared across similar channel distances, valley distances, and average in-channel residence times. Experimental reach lengths ranged from 135 m to 2730 m. Reaches were grouped by restoration condition (pre- vs. post-) and did not always correspond to the lengths of individual restoration segments. Thus, by conducting tracer experiments across two or more adjacent reaches, it was possible to observe solute transport characteristics at reach lengths much longer than would be possible if experiments were restricted to individual restoration segments. Each experiment consisted of an instantaneous release of sodium chloride (NaCl) at a site sufficiently upstream of the downstream monitoring location(s) to ensure complete vertical and lateral mixing. Periodic co-injection of fluorescent dyes with salt slugs allowed for visual assessment of appropriate mixing lengths. The assumption of adequate mixing on short reaches was further assessed by multiplying the observed solute concentration values by stream discharge as measured by the ADCP. This calculation produced an estimate of mass recovery that could be compared to the injection mass. Observed mass recoveries very near 100% suggested adequate vertical and lateral mixing. CS547A probes connected to CR1000 dataloggers (Campbell Scientific Inc., Logan, Utah, USA[1]) collected electrical conductivity (EC) and stream temperature data from all monitoring locations at 5 s intervals. Probes were fixed to stakes in the thalweg

[1] Manufacturers are listed for informational purposes only and do not constitute an endorsement by the authors.

at approximately 50% of channel depth. We used independent calibration curves developed for each probe in the lab prior to the 2009 field season to convert field measurements of temperature and EC into NaCl concentration breakthrough curves (BTCs). We assumed changes in background EC over the duration of an individual experiment were linear and corrected for them by subtraction.

For instantaneous tracer releases, BTCs are a direct reflection of the hydrologic RTD of the system, provided the system is linear. Jones and Mulholland (2000) provide an extensive review of this and other assumptions made when analyzing data produced by stream tracer injections. Previous studies of the stream tracer approach show that the peak of a RTD contains information about the advective portion of flow, while the tail contains information about transient storage behavior (Harvey et al., 1996). Thus, the effect of channel realignment on hydrologic transport processes can be investigated by directly comparing the shape of hydrologic RTDs. However, because sinuosity changes markedly from pre- to post-realignment channels on SBC, a case can be made for comparing RTDs where water moves along the same channel distance, the same down-valley distance, or after water spends the same amount of time in each channel. The "channel distance" comparison is useful for understanding changes in solute transport along the channel. The "valley distance" comparison is useful for understanding changes in solute transport within a drainage network, and the "residence time" comparison is useful for documenting temporal rates of advection, dispersion, and transient storage within the channel.

To carry out RTD comparisons, we calculated modal stream channel velocity, modal down-valley velocity (down-valley travel rate, excluding sinuosity), and an index of transient storage. We calculated the modal stream channel velocity as the time to RTD peak divided by the thalweg distance between the injection and observation points. We calculated the modal down-valley velocity as the time to RTD peak divided by the straight line distance between the injection and observation points. The relationship between the time to RTD peak and the time at which 99% of the recovered tracer mass passed by the solute observation point provided an index of transient storage. We assumed that the time at which 99% of the recovered tracer mass passed the observation point was sufficiently distal to the mode of the RTD to be an independent measure of transient storage, unaffected by dispersion. Other investigators have similarly compared RTD tailing behavior directly by normalizing the time axis of observed BTCs to the median solute transport time (Gooseff et al., 2007).

We used multiple regression methods to assess the significance of observed differences in transport characteristics between pre- and post-realignment data sets for channel distance, valley distance, and residence time comparisons, multiple regression techniques represent an effective means for exploring relationships between continuous explanatory and dependent variables (e.g. discharge, modal velocity) in data sets where group membership (e.g. pre- vs. post-realignment) is expected to influence those relationships. We tested four model structures (single-mean, two-means, parallel-lines, and separate-lines) for each between-group comparison and used *F*-tests to identify the most parsimonious model. This approach to model selection provided an objective means for testing for interactions between discharge and restoration state (pre- vs. post-). It is important to note here that stream tracer data is most frequently assessed by parameterization and curve-fitting of a numerical transient storage model like OTIS-P. We initially endeavored to analyze our data in this manner. However, application of the Generalized Likelihood Uncertainty Estimation (Beven and Freer, 2001) approach to the OTIS model showed output to be fairly insensitive to large ranges in parameter values.

3.3. Hydrologic gains and losses

Connections between floodplain groundwater systems and the stream channel directly influence the magnitude and timing of stream discharge observed at various points along the stream corridor. Gross losses of stream water are indicative of long spatio-temporal exchange and storage mechanisms not readily apparent from RTD analysis alone. We used modified synoptic discharge measurement techniques and conservative tracer recovery estimates to assess the timing and magnitude of gross gains and losses to and from the alluvial aquifer along our study reaches. We estimated gross hydrologic gains (Q_{gain}) and gross hydrologic losses (Q_{loss}) using the steady-state water balance equation:

$$Q_A - Q_B = Q_{gain} + Q_{loss} \tag{6}$$

where Q_A is stream discharge at the downstream end of the reach and Q_B is stream discharge at the upstream end of the reach. The ADCP produced estimates of Q_A and Q_B. We completed at least four sequential discharge measurements at each measurement location to provide estimates of the mean and variance in discharge. Additional measurements were completed if the coefficient of variation from the original four passes exceeded 4%. We frequently completed supplemental passes along cross-sections upstream or downstream of the measurement site to ensure that variation in channel geometry did not bias discharge estimates. Integration of the concentration BTC for a given tracer release provided an estimate of the total tracer mass recovered at the downstream end of the reach. The percentage of tracer mass lost approximated $Q_{loss.}$ Algebraic substitution then yielded Q_{gain}. The solute transport theory describing the relationships between conservative tracer recovery and hydrologic gains and losses is presented in detail elsewhere (Covino and McGlynn, 2007; Harvey and Wagner, 2000; Payn et al., 2009).

4. Results

4.1. Hydrogeomorphic comparisons

Comparisons of channel geometry and frequency distributions of stream depth and stream velocity for pre- and post-realignment channels highlighted the distinct changes in longitudinal and cross-sectional structure evident in Fig. 2. Shifts in cross-sectional channel geometry are presented in Fig. 3 and ANOVA comparison results are listed in Table 1. Generally, restoration produced narrower, deeper channels. Prior to restoration, the distribution of longitudinal stream depths was unimodal and very peaked, reflecting the relatively planar morphology at the channel-unit scale (10^0–10^1 m) (Fig. 4C). Conversely, restoration produced bimodal longitudinal depth distributions that exhibited greater overall variance. The bimodal behavior of these distributions coincided with the distinct differences in the depth of engineered riffle-run sequences and pools. Cross-sectional depth distributions mirrored those collected along the channel thalweg (Fig. 4D).

We observed correlations between differences in channel form and the characteristics of velocity distributions. In pre-realignment reaches, longitudinal and cross-sectional distributions of channel velocities were near Gaussian (Figs. 4A and 5C). Post-realignment longitudinal velocity distributions exhibited a lower mean and a characteristic positive skew that reflected the large fraction of stream volume contained in deep pools. Post-realignment cross-sectional velocity distributions did not exhibit this characteristic, which likely resulted from a random sampling strategy that selected a greater number of riffles and runs than pools. Variability in stream discharge did not affect general conclusions reached from comparisons of velocity distributions. While mean velocity

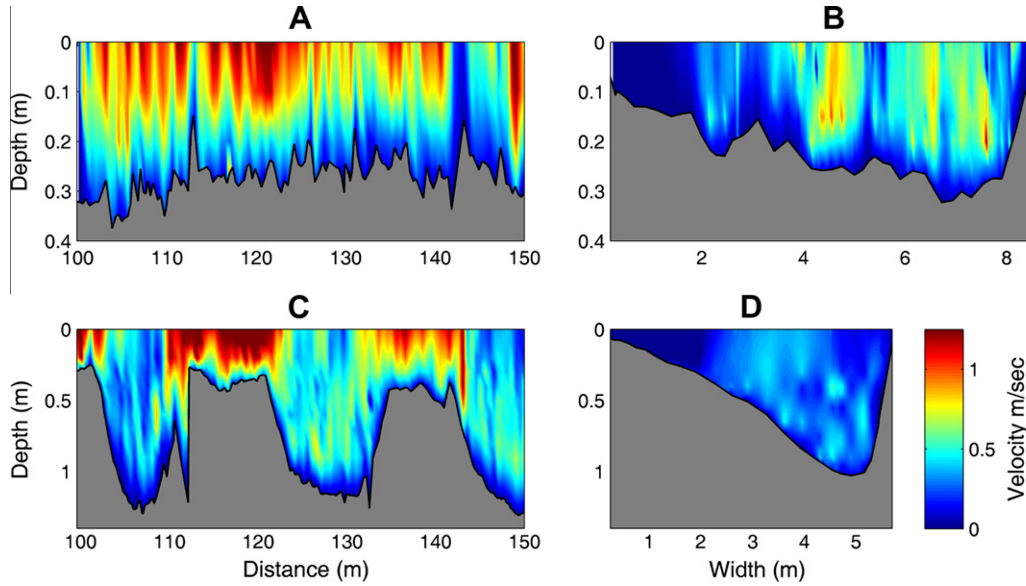

Fig. 2. Pre-realignment velocity and depth profiles collected (A) along the channel thalweg and (B) from a representative cross-section. Post-realignment velocity and depth profiles collected (C) along the channel thalweg and (D) from a representative cross-section. Continuous velocity surfaces were kriged with the spatial covariance structures defined by a best-fit spherical model for each data set's experimental semivariogram. Depth data was linearly interpolated between measured points. Vertical axes are scaled for clarity.

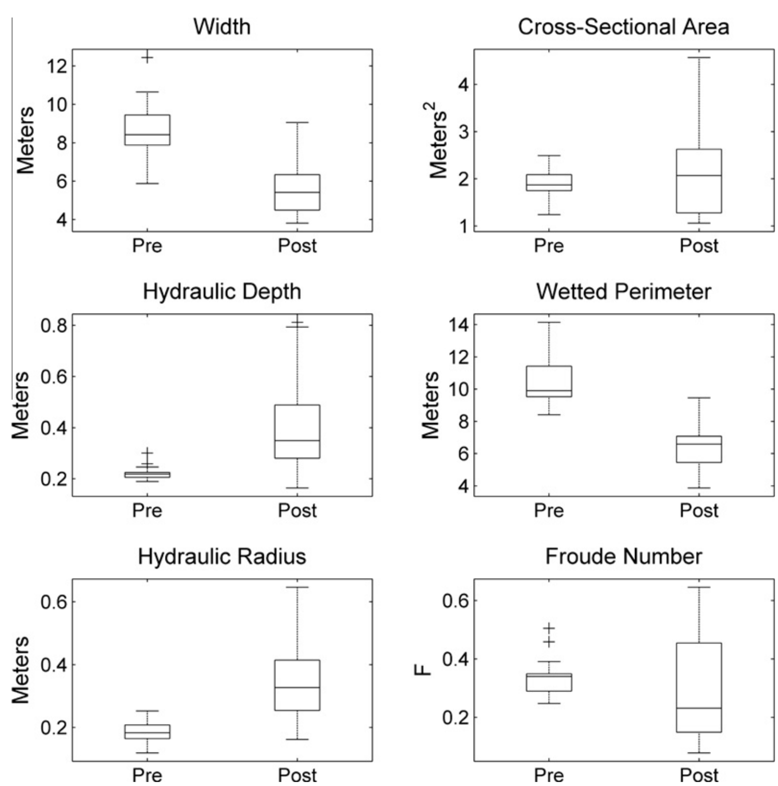

Fig. 3. Characterization of cross-sectional channel geometry. Data was collected from pre- and post-realignment stream channels during summer baseflow conditions (n = 27 pre-restoration cross-sectional profiles and 27 post-restoration profiles).

values increased with discharge in both pre- and post-realignment channels, the patterns of differences in mean, variance, and skewness illustrated in Fig. 4 remained relatively unchanged.

4.2. Geostatistical comparisons

Experimental semivariograms for depth and velocity profiles elucidated differences in hydrogeomorphic structure at a range of spatial scales (Fig. 5). We fit a pure nugget effect model to the longitudinal stream depth semivariance data from pre-realignment channels (Table 2). The very low sill, reflecting a low overall variability in depth, was corroborated by depth frequency distributions (Fig. 4C). We fit a spherical covariance model structure to the longitudinal depth semivariance data from post-realignment reaches (Table 2). The large sill coincided with the introduction of riffle/pool/run morphology. The greatest

Table 1
Hydrogeomorphic characteristics of experimental reaches. Sinuosity and slope values are derived from channel design surveys/plans. All other metrics are reported as the mean plus or minus the standard deviation where $n = 27$ cross-sections from each channel type. Reported p-values are results from one-way ANOVA comparisons.

	Sinuosity	Reach avg. slope (%)	Width (m)	Cross-sectional area (m^2)	Hydraulic depth (m)	Wetted perimeter (m)	Hydraulic radius (m)	Froude number
Pre	1.04	0.72	8.67 ± 1.38	1.89 ± 0.27	0.22 ± 0.02	10.35 ± 1.31	0.18 ± 0.03	0.33 ± 0.06
Post	1.64	0.41	5.53 ± 1.24	2.2 ± 0.96	0.41 ± 0.18	6.36 ± 1.29	0.35 ± 0.13	0.28 ± 0.17
p-value	–	–	7.84E−12	0.1139	1.86E−06	1.44E−15	1.10E−07	0.1437

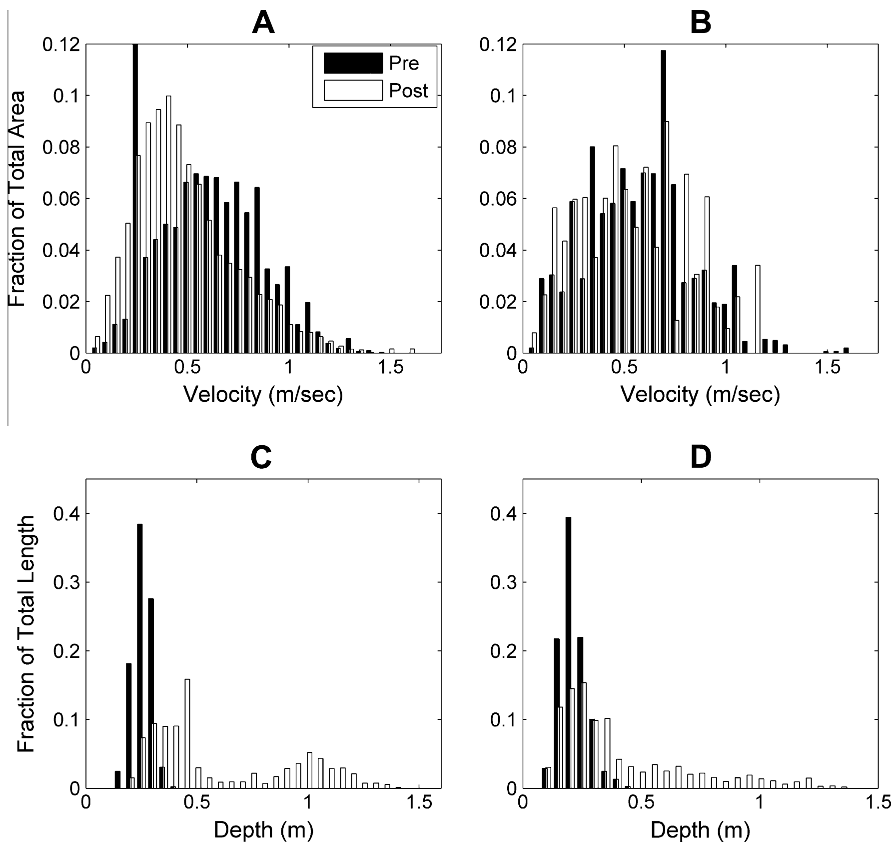

Fig. 4. Frequency distributions of (A) longitudinal velocity, (B) cross-sectional velocity, (C) longitudinal depth, and (D) cross-sectional depth collected during summer baseflow conditions. Cross-sectional distributions represent aggregated data from 12 pre-realignment cross-sections and 12 post-realignment cross-sections.

semivariance in longitudinal depth in these channels occurred at thalweg distances approximating the average spacing of riffle/run sequences and pools (15–20 m). Restoration increased the semivariance in stream depth at the cannel-unit scale but decreased calculated semivariance values for lag distances between 0 and 10 cm ($\gamma = 1.13 \times 10^{-4}$) when compared to pre-realignment channels ($\gamma = 3.41 \times 10^{-4}$), indicating that more fine-scale variability existed in channel bedform structure before restoration took place. Cross-sectional depth semivariograms displayed similar characteristics to their longitudinal counterparts (Fig. 5H). Pre-realignment data exhibited a low sill that reflected the low overall variance in cross-sectional stream depth in these channels (Table 2). Post-realignment data exhibited a much higher sill and a range value that approximated the average width of restored channels (≈4 m).

Spatial patterns illustrated by velocity and depth semivariograms for both pre- and post-realignment channels indicated strong relationships between velocity fields and the characteristics of streambed topography (Fig. 5). We fit longitudinal velocity semivariograms from both pre- and post-realignment channels with spherical covariance model structures (Table 3). The sill characterizing data from both channels was similar across all three observed flow states. Prior to restoration, longitudinal velocity fields exhibited a large nugget effect and a range that increased with discharge. Longitudinal velocity fields in post-realignment channels exhibited range values that remained relatively constant and approximately equal to average channel unit spacing across all three flow states. Semivariograms and modeling results suggested that spatial correlation existed in longitudinal velocity fields at a coarser scale in post-realignment reaches than in pre-realignment reaches. Differences in cross-sectional semivariograms were similar to those observed in longitudinal data structures (Fig. 5). Both pre- and post-realignment cross-sectional data were fit with spherical covariance model structures (Table 4). Pre-realignment cross-sectional data exhibited a higher nugget and larger sill than post-realignment cross-sections at low flow, indicating spatial correlation existed across larger distances following restoration. The respective values of these parameters for pre- and post- channels converged as discharge increased.

4.3. Stream tracer experiments

Direct comparisons of hydrologic RTDs provided insights into changes in hydrologic transport and retention resulting from restoration for a given channel length, a given valley length, and a given

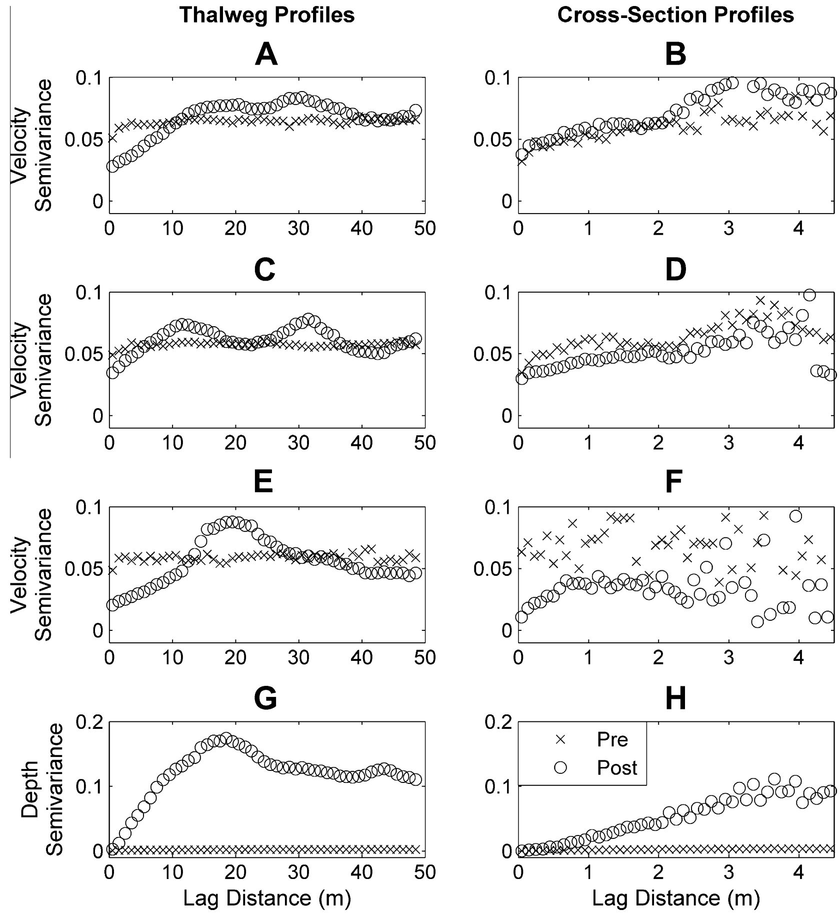

Fig. 5. Experimental semivariograms of (A) longitudinal and (B) cross-sectional velocity observed at $Q = 1400\ s^{-1}$; (C) longitudinal and (D) cross-sectional velocity observed at $Q = 1000\ s^{-1}$; (E) longitudinal and (F) cross sectional velocity observed at $Q = 800\ s^{-1}$; and (G) longitudinal and (H) cross-sectional depth.

channel residence time. We plotted modal stream velocity against discharge for 58 stream tracer experiments and grouped data by channel type (Fig. 6A). A parallel lines model adequately characterized trends in the data (Table 5) precluding the existence of interactive effects between discharge and restoration state (e.g. pre- vs. post-). The model estimated modal stream velocity to be 0.11 m/s greater in pre-realignment channels across all observed flow states. A similar approach compared differences in hydrologic transport over a given valley length. We plotted modal valley velocity against discharge for the same 58 stream tracer experiments (Fig. 7A). A parallel lines model adequately characterized trends in the data (Table 5), again precluding the existence of interactive effects between discharge and restoration state. The model estimated modal valley velocity to be 0.27 m/s greater in pre-realignment channels at any given discharge. We assessed differences in RTD tailing by plotting the modal hydrologic residence time against the time at which 99% of the recovered tracer mass passed by the solute observation point for all 58 tracer experiments (Fig. 8A). This comparison yielded an index of transient storage reflecting the persistence of RTD tailing as a function of the average solute residence time in the stream channel. A

Table 2
Semivariance modeling results for longitudinal and cross-sectional depth profiles collected along 400 m of channel thalweg and 27 randomly selected cross-sections on both pre- and post-realignment channel segments.

Profile type	Channel type	Model	Nugget g (h)	Range (m)	Sill g (h)
Longitudinal	Pre	Nugget	–	–	0.003
	Post	Spherical	0.0006	11.326	0.124
Cross-sectional	Pre	Nugget	–	–	0.003
	Post	Spherical	0	3.953	0.075

Table 3
Semivariance modeling results for longitudinal velocity profiles collected at three flow states.

Channel type	Q (s^{-1})	Model	Nugget g (h)	Range (m)	Sill g (h)
Pre	800	Spherical	0.043	2.127	0.060
	1100	Spherical	0.048	5.107	0.058
	1400	Spherical	0.053	8.032	0.065
Post	800	Spherical	0.015	16.531	0.058
	1100	Spherical	0.032	12.671	0.070
	1400	Spherical	0.023	15.241	0.070

Table 4
Semivariance modeling results for aggregated cross-sectional velocity data collected at three flow states.

Channel type	Q (s^{-1})	# Of x-sections	Model	Nugget g (h)	Range (m)	Sill g (h)
Pre	800	12	Spherical	0.060	4.995	0.077
	1100	8	Spherical	0.044	4.724	0.078
	1400	12	Spherical	0.038	3.711	0.070
Post	800	12	Spherical	0.013	1.477	0.042
	1100	8	Spherical	0.030	3.275	0.060
	1400	12	Spherical	0.042	4.935	0.098

separate lines model best described the differences in the data trends (Table 5). The interactive effect in this model suggested that transient storage affected hydrologic RTDs differently in pre- vs. post-realignment channels. The modeled slope that best characterized pre-realignment data was greater than the slope that best characterized post-realignment data, indicating a more pronounced tailing effect in the RTD of pre-restoration channels. This indicates that, for every unit of time water resided in the channel, rates of transient storage were higher in pre-restoration channels than in post-restoration channels.

4.4. Hydrologic gains and losses

Measurement of gross gains and losses provided a means for assessing concurrent hydrologic exchanges not easily resolved using RTD analysis alone. A Mann–Whitney *U*-test showed the

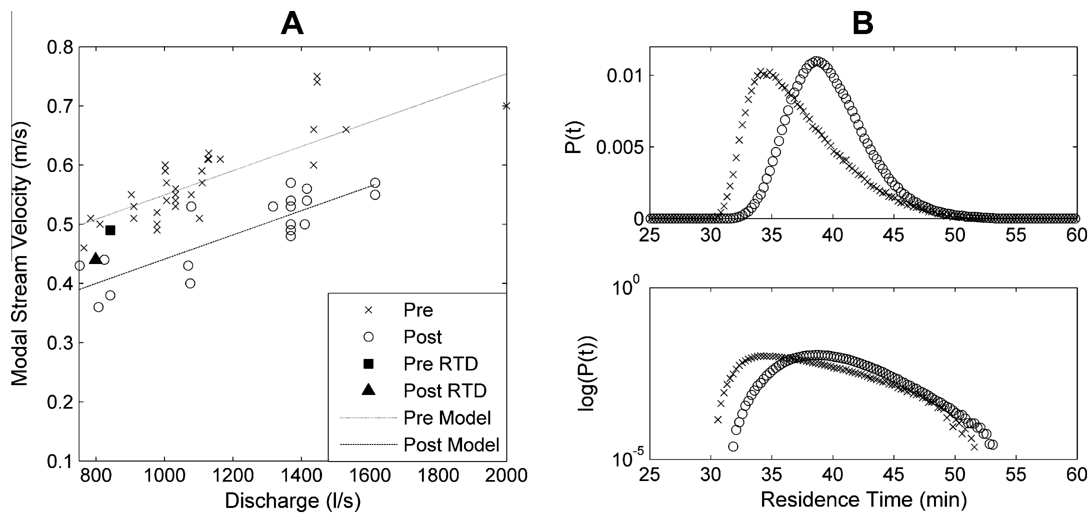

Fig. 6. (A) Average solute transport time calculated for the length of the thalweg between the upstream solute injection point and the downstream observation point in pre- and post-channels across a range of flow states. (B) Pre- and post-realignment RTDs observed after injected solute traversed approximately 1000 m of thalweg length in a pre-realignment and a post-realignment channel segment during baseflow conditions. RTDs are displayed in normal and semi-log space.

Table 5
Results from multiple regression comparisons of solute transport data.

Regression comparison	Test	*F*-stat	*p*-value	Selected model	Channel type	Intercept	Slope
Discharge vs. modal stream velocity	Same line vs. parallel lines	220.26	≈0	Parallel lines	Pre	0.345	0.0002
					Post	0.236	0.0002
Discharge vs. modal valley velocity	Same line vs. parallel lines	816.4	≈0	Parallel lines	Pre	0.317	0.0002
					Post	0.052	0.0002
Mean transport time vs. time to 99% mass recovery	Parallel lines vs. separate lines	28.62	4.48E−07	Separate lines	Pre	4.832	1.326
					Post	6.516	1.139

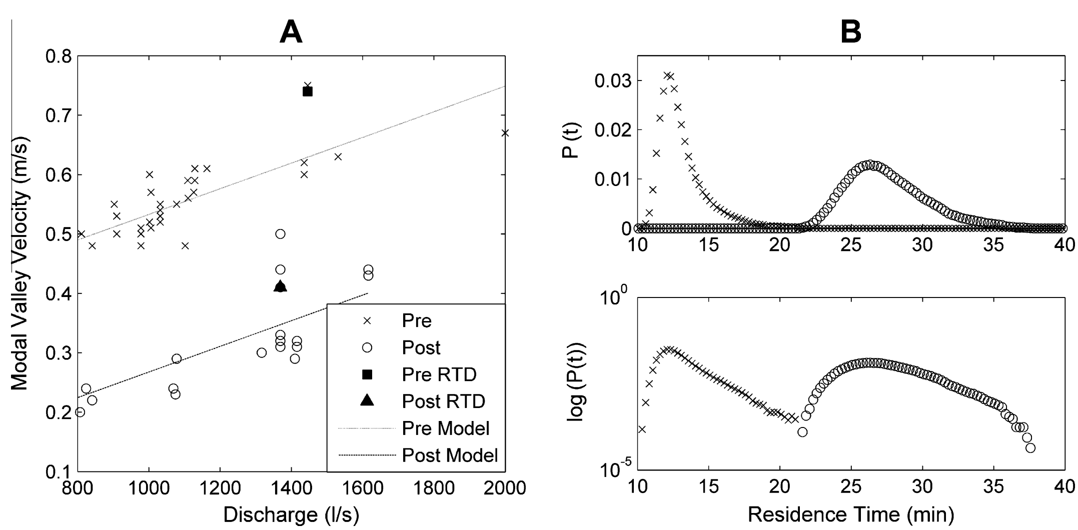

Fig. 7. (A) Average solute transport times calculated for the straight-line distance between the upstream solute injection point and the downstream observation point in pre- and post-channels across a range of flow states. (B) Pre- and post-realignment RTDs observed after injected solute traversed approximately 500 m of valley length in a pre-realignment and a post-realignment channel segment. RTDs are displayed in normal and semi-log space.

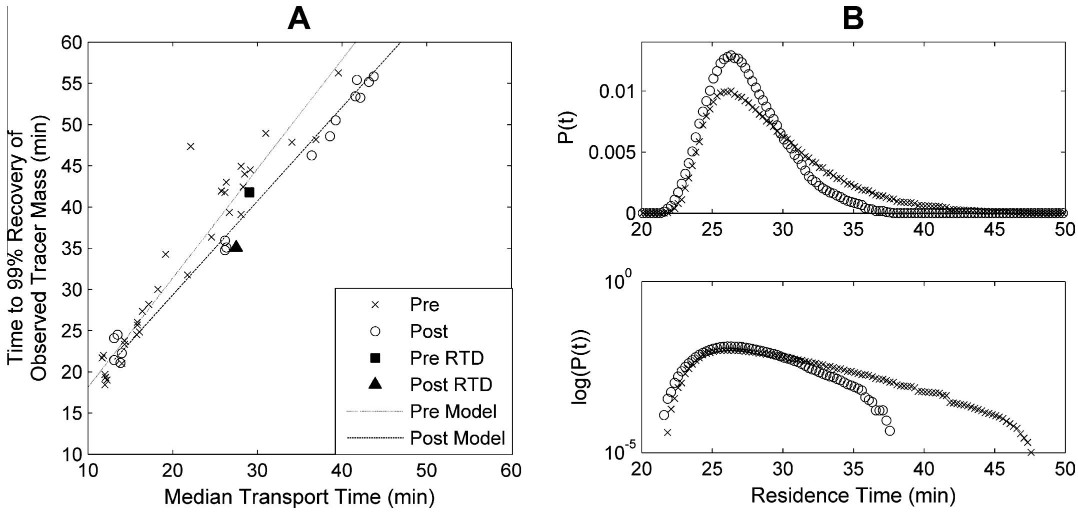

Fig. 8. (A) Index of transient storage as a function of average channel residence time in pre- and post-realignment channels. (B) RTDs observed after approximately 27 min of downstream transport in a pre-realignment and a post-realignment channel segment. RTDs are displayed in normal and semi-log space.

median hydrologic loss on pre-realignment reaches (12%, $n = 35$) was significantly greater than median loss on post-realignment reaches (3%, $n = 23$) (two-sided p-value = 0.022). Similarly, the median hydrologic gain on pre-realignment reaches (14%, $n = 35$) was significantly greater than median gain on post-realignment reaches (3%, $n = 23$) (two-sided p-value = 0.009). Thus, our work indicated that a larger fraction of stream water in pre-realignment reaches either: (1) interacted with the alluvial aquifer at spatio-temporal scales greater than that of individual stream tracer experiments, or (2) bypassed the downstream observation point by moving through streambed sediments. Our methodology occasionally produced mass recovery estimates greater than 100% (Fig. 9). While this finding suggested some caution is necessary during interpretation of mass recovery data from individual tracer experiments, the consistent patterns we observed across multiple experiments suggested that fundamental differences in reach-scale patterns of stream/aquifer interactions existed between pre- and post-realignment channels. Compounded error from individual discharge measurements at the upstream and downstream ends of a given reach and small errors in tracer concentration measurements recorded by individual probes may explain mass recovery estimates greater than 100%. Alternatively, incomplete solute mixing due to channel geometry and hydraulics may have produced some erroneous measurements; although field observation of fluorescent dye tracers indicated adequate horizontal and vertical mixing over the reach lengths typical to our experiments.

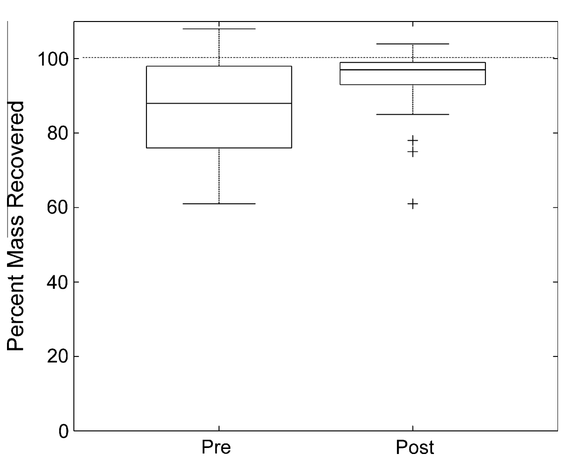

Fig. 9. Comparison of mass recovery during tracer experiments on pre-realignment ($n = 35$) and post-realignment ($n = 23$) study reaches. Values greater than 100% (dashed line) result from compounded discharge and tracer concentration measurement error.

5. Discussion

Research investigating the relationships between elements of stream structure and the movement of water and solutes throughout stream corridors (Anderson et al., 2005; Cardenas, 2008; Harvey and Wagner, 2000; Packman et al., 2004; Poole et al., 2006; Wondzell, 2006) largely informed recent work exploring the effects of anthropogenic modification of the streambed on measures of hydrologic and biogeochemical function (Bukaveckas, 2007; Gooseff et al., 2007; Knust and Warwick, 2009) and guided the development of our research questions on SBC. Our work illustrates the importance of the interplay between restoration activities, stream/floodplain structure, and channel hydraulics in governing patterns of water and solute transport.

5.1. Channel form and patterns of water and solute movement

Restoration of Silver Bow Creek replaced relatively straight channels exhibiting low channel-unit variability with highly sinuous channels exhibiting regular channel-unit spacing. Surprisingly, restoration increased bedform variability at the channel-unit scale (10^0–10^1 m) while somewhat reducing it at the bedform scale (10^{-2}–10^0 m). This change was noted in depth semivariograms at lag distances less than 10 cm (Fig. 5) and in the field as the dominant bed material shifted from large embedded cobbles in pre-realignment channels to sands and gravels in post-realignment channels. We expect that the semivariogram-derived differences in channel bed roughness are conservative because large absolute changes in depth occurring in the relatively smooth transition zones between channel units likely produced a significant portion of the observed semivariance at lag distances less than 1 m in realigned channels.

The strong relationships observed between semivariograms of channel bed structure and velocity fields (Fig. 5) indicated a tight coupling between streambed topography to velocity field structure. Legleiter et al. (2007) utilized a similar geostatistical approach to identify correlations between stage, streambed topography and the organization of overlying velocity fields. The shallow channel and relatively large roughness elements present in pre-realignment channels produced velocity fields with very short correlation lengths (Fig. 2), while increases in stage and discharge reduced the relative size of roughness elements and increased spatial correlation lengths (Fig. 5). Conversely, the regular channel-unit spacing, a hydraulically efficient channel geometry (Table 1), and smaller roughness elements present in post-realignment channels strengthened spatial correlations in velocity fields up to the scale approximating the average spacing of pool-riffle sequences. Thus, our findings support Legleiter's et al. (2007) conclusion that channel geometry—specifically, stream depth relative to the height of roughness elements in the streambed—is a fundamental control on velocity field structure. It follows from these results that: (1) the physical structure of the streambed is a critical control on the arrangement of surface-water flowpaths and (2) multi-scale alteration of streambed topography via stream restoration is an important mechanism influencing patterns of water and solute movement.

We utilized stream tracer data to present three frames of reference for considering restoration-induced changes in water and solute transport: (1) the stream length perspective (transport characteristics for a given stream channel length), (2) the valley length perspective (transport characteristics for a given downstream valley length), and (3) the residence time perspective (transport characteristics for a given advective transport time along the steam channel). Characterization of RTDs from each of the above perspectives led to different conclusions about hydrologic transport dynamics on pre- and post-realignment reaches, highlighting the need for caution when considering the implications of results produced by any single perspective. We posit that the richest understanding of patterns of water and solute movement, especially when relating those patterns to physical alterations of the stream channel, relies on the integration of all three perspectives.

RTD comparisons based on stream channel length are typical to hydrologic transport studies. Restoration of channels on SBC increased advective transport time over a given channel length by an average of 17% across all observed flow states (Fig. 6). Synergies created by decreased channel slope and low thalweg velocities in frequent slow-moving pools provided a mechanism for slowing the average downstream advection of water in post-realignment channels. Our findings are consistent with those of Bukaveckas (2007) who noted that channel realignment on Wilson Creek reduced reach-averaged water velocity and increased the median transport time of conservative solutes by 50%. Increased in-channel transport time in restored reaches of SBC likely increased opportunities for solutes to be degraded, transformed, or removed from the system via biological or abiotic processes. Utilization of this channel length based comparative approach may be useful in studies of natural streams or cases where restoration does not alter channel length. However, in systems like SBC where restoration design entails modification channel length, additional information may be gleaned from valley-length based comparisons.

Assessment of down-valley hydrologic transport characteristics is well-suited to evaluating the impact of restoration on the movement of water and solutes across a floodplain or through a channel network. Many restoration designs alter the length of the stream channel within a set project boundary by enhancing sinuosity, thereby altering transport characteristics between pairs of upstream–downstream valley points. Restoration decreased down-valley solute advection rates by an average of 42% across all observed flow states (Fig. 7). Increases in channel sinuosity that lengthened the channel largely accounted for this difference. The reduction in water velocity per unit channel length due to reduced reach-averaged channel slope and the presence of frequent pools in restored channels enhanced the effect. Restoration was much more effective at retaining water and solutes when considering down-valley rates of solute transport than would otherwise be concluded when comparing advection rates along a given thalweg distance. While this result was not surprising, it convoluted interpretations of restoration's affect on biogeochemical processes and ecological function. Reduced interactions between the advective portion of flow and transient storage zones—where elevated rates of biogeochemical activity often occur—in restored channels further complicated predictions regarding biogeochemistry and stream ecology.

Restoration reduced transient storage for a given in-channel residence time (Fig. 8). If a positive relationship exists between transient storage and the retention and transformation of nutrients and other pollutants, then restoration activities on SBC reduced the stream's capacity for assimilating these solutes per unit time spent in the stream channel. However, increased hydrologic residence time across a given stream or valley length afforded by channel realignment likely counteracted this effect to some extent. Importantly, the physical arrangement of the system and the sensitivity of the employed methodology to various timescales of exchange likely affected observed differences in RTD tailing behavior.

It is probable that elements of channel design generated many of the observed differences in water and solute transport characteristics on our study reaches. Enhanced exchange with transient storage zones associated with streambed roughness elements may be directly tied to the pronounced RTD tailing behavior observed in pre-realignment channels. The relationship between bed structure and transient storage is reported by others. A meta-analysis of tracer experiments conducted on streams across the US showed transient storage was positively correlated with channel friction factor, a measure of bed roughness (Harvey and Wagner, 2000). Roughness can affect transport dynamics by creating opportunities for water and solute storage in boundary layer vortices and eddies located behind topographic irregularities in the streambed. On SBC, channel realignment re-oriented the flow to a primarily downstream direction over relatively smooth bed surfaces, which produced nearly laminar velocity fields characterized by long spatial correlation lengths. Conversely, the presence of large roughness elements (relative to channel depth) in shallow pre-realignment channels significantly shortened velocity field spatial correlation lengths (Fig. 5) and may have promoted transient storage in the stream channel. Irregular bed surfaces also facilitate advective pumping mechanisms that lead to surface–subsurface exchange (Wörman et al., 2002). Indeed, calculation of gross hydrologic gains and losses on SBC suggested that long spatio-temporal exchanges between the channel and the alluvial aquifer were more prevalent prior to restoration. The reduction of streambed slope and reduced bedform variability in restored channels likely weakened hydraulic head gradients at small spatial scales, limiting the frequency of hyporheic flow along short spatio-temporal subsurface flowpaths. Although the introduction of large pool-riffle sequences and meander bends likely produced an abundance of longer hyporheic flowpaths, the methodological sensitivities typical to our experiments and the ratio of stream discharge to the volume/rate of water conveyed along these flowpaths likely made their presence and influence on RTD tailing difficult to detect. Reductions in the size of the stream-streambed interface (i.e. wetted perimeter) relative to the volume of water conveyed through the stream channel at any given time and/or changes in the hydraulic properties of the streambed may have further reduced rates of exchange between the channel and subsurface storage zones.

Although construction of post-realignment channels occurred in the same alluvial material that pre-realignment channels flowed through, sufficient time may not have passed between channel construction and field observations for any meaningful sediment sorting to occur. Lower hydraulic conductivities in restored streambeds due to limited sorting of bed material would, thus, increase the residence time of hyporheic flow, while concurrently reducing the volume of water exchanged between the channel and hyporheic zones per unit time. These explanations are, of course, speculative as we did not collect subsurface solute concentration measurements or directly measure streambed hydraulic conductivity.

5.2. Implications for stream restoration

Our results may indicate pathways for improving the effect of stream restoration on hydrologic transport processes. Channel realignment on SBC increased advective transport times along a given channel length and a given downstream-valley length. These increases in water and solute retention should benefit biotic uptake of solutes, but decreased bed roughness and velocity fields exhibiting long correlation lengths are apt to at least partially offset the beneficial effects of slower advective velocities by limiting transient storage. Incorporation of roughness elements that produce turbulent velocity fields into channel designs that inherently slow water velocity through increased sinuosity, decreased channel slope, and enhanced channel-unit variability could further enhance contact time between solutes, bio-reactive streambed sediments, and microbial assemblages in surface-water storage zones. Such approaches could, thus, provide additional ecological benefits over traditional channel realignment techniques that frequently aim to enhance hydraulic conveyance by making channels narrower, deeper, and by reducing the roughness of the streambed.

While our work suggested that restoration activities on SBC had the immediate impact of decreasing transient storage, it is important to note that we did not investigate the temporal evolution of restored channels. In valley-bottom, low-gradient streams like SBC, measures of transient storage may increase as channels are exposed to a range of discharge events and natural geomorphic processes begin to reorganize and reshape sediments in the streambed. Wondzell and Swanson (1999) report that flood-induced changes in channel form are a significant control on the spatial organization of hyporheic flow at a variety of scales. A modeling study by Poole et al. (2006) supports these findings and concludes that cut and fill dynamics, channel avulsion, and the presence of paleo-channels on a floodplain are critical controls on the development and maintenance of subsurface transient storage zones. Furthermore, the deformation of channel banks is necessary for the formation of eddies and backwaters, locations that Bukaveckas (2007) and Ensign and Doyle (2005) note can play a large role in controlling reach-scale solute transport. Therefore, we predict that the degree to which hydrologic transport dynamics in restored systems can recover and surpass normative conditions is directly tied to the channel's ability to self-organize. Long-term monitoring and research designs built around this prediction will help inform discussions about the way that 'ideal' restorations look and behave over time and may provide a foundation for dialog regarding the role of deformable channels and planned design-failure in restoration efforts focused on enhancing ecological function. We anticipate that continued work relating the geomorphic evolution of restored stream channels to the condition and persistence of hydrologic retention and transient storage will be a valuable contribution to both restoration science and restoration practice.

6. Conclusion

Restoration of stream segments on SBC slowed advective transport velocities for a given stream length and across a given valley length by reducing average streambed gradient and increasing stream length. Restoration was more efficient at retarding transport across a given valley length than a given stream length, indicating that adding sinuosity to stream channels is an important component of restoration design where slowing the advective transport of water and solutes along the stream corridor is a stated or implied goal. Despite increased water and solute retention due to changes in advective velocities, channel restoration reduced the influence of transient storage on hydrologic residence time distributions in our study reaches. Our findings caution that the benefits of increased residence time associated with enhanced sinuosity and pool frequency may be offset to some extent by a loss in surface-zone storage and near-channel hyporheic exchange in restored channels. Considering stream-bed complexity and the hydrologic effects of channel roughness and topographic heterogeneity may be a critical but commonly overlooked factor in the design of those stream restoration projects that incorporate channel realignment.

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