Effects of in-stream structures and channel flow rate variation on transient storage

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Abstract

In-stream structures can potentially enhance surface and subsurface solute retention. They form naturally in small streams and their installation has gained popularity in stream restoration for multiple purposes, including improved water quality. Yet few studies have quantified the cumulative effect of multiple structures on solute transport at the reach scale, nor how this varies with changing stream flow. We built a series of weirs in a small stream to simulate channel spanning structures such as natural debris dams and stream restoration log dams and boulder weirs. We conducted constant rate conservative (NaCl) tracer injections to quantify the effect of the weirs on solute transport at the reach scale. We used a one dimensional solute transport model with transient storage to quantify the change of solute transport parameters with increasing number of weirs. Results indicate that adding weirs significantly increased the cross-sectional area of the surface stream (A) and transient storage zones (A_s) while exchange with transient storage (α) decreased. The increase in A and A_s is due to backwater behind weirs and

increased hydrostatically driven hyporheic exchange induced by the weirs, while we surmise that the reduction in α is due at least in part to reduced hydrodynamically driven hyporheic exchange in bed ripples drowned by the weir backwater. In order for weir installation to achieve net improvement in solute retention and thus water quality, cumulative reactions in weir backwater and enhanced hydrostatically driven hyporheic exchange would have to overcome the reduced hydrodynamically driven exchange. Analysis of channel flow variation over the course of the experiments indicated that weirs change the relationship between transient storage parameters and flow, for example the trend of increasing α with flow without weirs was reversed in the presence of weirs. Effects of flow variation were substantial, indicating that transient storage measurements at a single point in time typically cannot be extrapolated to estimate net annual effects. Thus, rigorous evaluation of water quality effects of stream restoration structures requires measurements at multiple channel flow rates.

1. Introduction

Human development such as agriculture and urbanization strongly affects streams (Wenger *et al.*, 2009), including loss of ecosystem function (FISRWG, 1998; USEPA, 2006) due to excess nitrogen and phosphorus, riparian disturbance, higher peak flow, and mobilized sediments (Howarth *et al.*, 2002). Excess nutrient delivery in turn causes eutrophication in downstream waters such as the Chesapeake Bay, Gulf of Mexico, and Long Island Sound (Breitburg *et al.*, 1999; Houde *et al.*, 1999; Kemp *et al.*, 2005; Scavia and Bricker; USEPA, 2010). Streams receive, assimilate, and transport nutrients (Bernhardt *et al.*, 2003, 2005), and can be a hotspot for excess nutrient removal (Seitzinger *et al.*, 2002).

The practice of stream restoration can improve habitat in degraded streams and benefit water quality by removing dissolved nutrients such as nitrogen (Baron *et al.*, 2002; van Driel *et al.*, 2006; Bukaveckas, 2007; Craig *et al.*, 2008; Lawrence *et al.*, 2013; Mueller *et al.*, 2014; Scott *et al.*, 2014; Veraart *et al.*, 2014; Johnson *et al.*, 2015). Stream restoration often entails stream channel modifications that reduce surface velocities and promote exchange with the subsurface (hyporheic exchange). Common structures used for this purpose include cross-vanes, J-hooks, channel spanning logs, boulder weirs, and root wads (Doll *et al.*, 1999; Roni *et al.*, 2006; Daniluk *et al.*, 2013; Miller and Kochel, 2013; Palmer *et al.*, 2014). These structures can also potentially improve water quality by regulating temperature (Arrigoni *et al.*, 2008; Hester *et al.*, 2009; Menichino and Hester, 2014), removing toxins (Bencala and Walters, 1983; Harvey and Fuller, 1998; Fuller and Harvey, 2000), and retaining excess dissolved and suspended nutrients (Craig *et al.*, 2008; Hester *et al.*, 2016). Regulatory bodies, such as the Chesapeake Bay Program (CBP) and the Western Oregon Stream Restoration Program, provide support and guidelines for

restoring water quality in regional water bodies. For example, the Chesapeake Bay program, which was formed to lead the restoration of water quality in the Chesapeake Bay region encourages structures like debris dams and brush sills for nutrient removal (Berg *et al.*, 2014).

Velocity reducing stream restoration structures can potentially modify transient storage, which has been defined as the temporary retention of flow and solute from the main channel (Bencala and Walters, 1983) that ultimately returns to the main channel. Transient storage can occur on the surface (exchange with off-channel dead zones – surface transient storage) and in the shallow subsurface (hyporheic transient storage). The latter, generally having more reactive surface area and longer residence time, is considered more conducive to chemical or biogeochemical reactions beneficial to water quality (Hester and Gooseff, 2010; Hester *et al.*, 2013). The transient storage model describes solute transport in a stream using the one dimensional advection dispersion equation augmented with terms representing exchange with immobile transient storage zones along the reach (Bencala and Walters, 1983). The size of the overall transient storage zone and exchange rate between main channel and transient storage zone can be estimated by fitting measured tracer breakthrough data, and provide a convenient way of measuring the “potential” of the stream to retain and process solutes (Bencala *et al.*, 1990; Workshop, 1990; D’Angelo *et al.*, 1993; Hall *et al.*, 2002; Ensign and Doyle, 2005; Lautz and Siegel, 2007; Gordon *et al.*, 2013; Zarnetske *et al.*, 2015).

Studies have shown that in-stream structures drive hyporheic exchange (Lautz and Siegel, 2006; Hester and Doyle, 2008; Daniluk *et al.*, 2013), yet fewer studies have evaluated transport of nutrients that impair water quality. Studies of individual structures such as log dams have shown that they increase biogeochemical or thermal heterogeneity in the subsurface thereby

creating biogeochemical hotspots (Kasahara and Hill, 2006; Lautz and Fanelli, 2008; Menichino and Hester, 2014), but fewer studies have evaluated cumulative reach scale effects. Briggs et al. (2013) found that hyporheic zones induced by beaver dams can create localized hotspots for nutrient processing but their net effect on nutrient removal at the reach scale was minimal. Gordon et al. (2013) studied cross-vanes and similarly concluded insignificant reach scale impact. Hines and Hershey (2011) did not find significant difference in ammonium uptake across completed restoration structures like cross-vanes. In modeling studies, Azinheira et al. (2014) and Hester et al. (2016) found insignificant impact of hyporheic exchange induced by two in-stream weirs in a 90 m reach. Zimmer and Lautz (2015) studied the addition of a single cross vane and concluded that if head gradient across the structure is too large, it may induce hyporheic exchange with residence times that are too short to promote significant nutrient processing.

The cumulative effect of a series of structures has shown greater potential than single structures to increase transient storage. Jin et al. (2009) found that transient storage area increased with the number of beaver dams. Ensign and Doyle (2005) observed higher ammonium and phosphate uptake velocity after adding a series of flow baffles in a stream. Roberts et al. (2007) observed that adding a series of flow-obstructing logs enhanced transient storage and ammonia uptake. Transient storage parameter estimation is strongly dependent on channel flow, as shown by multiple studies (Valett *et al.*, 1996; Hall *et al.*, 2002; Ward *et al.*, 2013a, 2013b). Yet, to the best of our knowledge, no studies so far have systematically related the presence or number of instream structures to transient storage parameters (e.g., cross-sectional area, transient storage size) while simultaneously evaluating the effects of varying channel flow rate. Yet, such

relations are key to understanding the impact of stream restoration structures on solute transport and may allow better prediction of their effects on water quality.

The overall aim of this study was to measure the effect of multiple small channel spanning structures (representing typical restoration structures such as log dams and boulder weirs) on solute transport and transient storage characteristics of a stream. Our main objective was to test the effect of increasing number of in-stream structures on transient storage. Specific expectations were that: 1) weir construction would increase surface transient storage by creating pools and zones of slow moving water; 2) weir construction would enhance hyporheic transient storage zone size and exchange by creating hydrostatic head gradient across the weirs; and 3) increasing the number of weirs would correspondingly enhance transient storage parameters. A secondary objective was to quantify the hydrologic transport effects of structures across a range of channel flow rates.

2. Methods

2.1 Study Site and Background Hydrologic Monitoring

The field site is a second order (field observation and USGS topo maps) stream dominated by riffle-pool and step-pool (log dam) features located in the Jefferson National Forest in southwestern Virginia (37°20'N 80°21'W). The stream drains a catchment of about 1 km² (Figure 1) and eventually flows to the James River and the Chesapeake Bay. Stream flow at the project reach is highest during the winter and sometimes becomes intermittent during late summer and early autumn. Background specific electrical conductance increases with decreasing

flow and ranges between 15 and 25 uS/cm. Experiments were conducted during the late spring baseflow recessions between May 11 and June 9, 2015 with flow declining from 14 to 4 L/s.

Our experiments utilized a control reach (MS1 to MS2) and a treatment reach (MS2 to MS3) downstream of the control reach (Figure 1). The two reaches were both 80 m in length (measured along the thalweg) and are contiguous with very similar geomorphology and bed material. The primary purpose of the control reach was to help interpret changes in the treatment reach, allowing us to better distinguish effects of experimental manipulation from those due to natural channel flow variability. The control reach has an average slope of 0.056 m/m and the treatment reach has an average slope of 0.066 m/m (both have a measurement error of ± 0.001 m). The upper half of the control reach lies adjacent to the end of a steep hill slope, while the remaining portion of the control reach and the entire treatment reach had comparatively flat floodplains on both banks. The channel is typically about 2 m wide and 0.5 m deep with near vertical banks. Based on visual observation, winter high flows were generally contained within the channel.

We also installed a stilling well in the stream channel at the upstream end of the treatment reach. We measured absolute pressures in the stilling well (surface water), and in the air with HOBO pressure transducer sensor-loggers (Onset, Bourne, MA). Water depths were calculated by subtracting atmospheric pressure from the absolute pressures and dividing by the specific weight of water. The HOBOs logged pressure continuously in the stream at 15 min intervals starting in July 2014.

2.2 Stream Tracer Injection and Weir Construction

We performed six experiments (E1 through E6) that differed in terms of number of in-stream structures and/or flow rate in the channel (Table 1). We installed a series of structures (weirs) in

the treatment reach to simulate natural debris dams as well as stream restoration structures such as log dams, boulder weirs, w-weirs, and upstream v's (Bilby and Likens, 1980; Brooks *et al.*, 2004; Roni *et al.*, 2006; Bhuiyan *et al.*, 2007; NRCS, 2007; Miller and Kochel, 2013). We varied the number of structures from 0 to 10 and installed them in stages between E1, E2, E3, and E4 to test the effect of weir number/density on transient storage parameters. Each weir entailed a single 5x20 cm wooden board ranging in length from 2.4 m to 3.6 m installed perpendicularly across the channel and buried on average 2.5 cm to 5 cm into the channel bottom. For each experiment, we waited from 2-7 days between structure construction and tracer injection for the disturbed sediments to settle. We repeated the 10-weir experiment twice (three events in total) to study the effect of changing channel flow on the estimation of transient storage parameters.

We injected NaCl as a conservative tracer 40 m upstream of the upstream end of the control reach ("Injection" in Figure 1) to allow for mixing of tracer before measurement at MS1. We mixed NaCl with stream water on the day of the injection in quantities which would increase the specific electrical conductance by about 150 $\mu\text{S}/\text{cm}$. Injection duration ranged from 3.0 to 4.8 hours depending on stream flow to ensure steady state concentration was achieved. We measured specific conductance (as a surrogate for Cl⁻) with YSI Pro Plus Multiparameter conductivity probes (YSI Incorporated, Yellow Springs Ohio) at the upstream end of the control reach (MS1), the downstream end of the control reach (MS2), and the downstream end of the treatment reach (MS3) (Figure 1). We also measured background specific conductance with a Solinst LTC (Ontario, Canada) probe 20 m upstream of the injection location ("Background" in Figure 1). Specific conductance was automatically recorded at 5 second intervals at MS1-MS3, and 1 min

intervals at “Background”. The background specific conductance remained relatively constant during each experiment with changes less than $2 \mu S/cm$. The average of the background specific conductance was subtracted from the tracer breakthrough curves at the three monitoring stations, before parameter estimation. We calculated channel flow rate using specific conductance values at MS1 after specific conductance had plateaued and assuming complete recovery of tracer.

2.3 Transient Storage Modeling and Data Analysis

We analyzed our conservative tracer data using the one dimensional advection dispersion equation with exchange with a well-mixed off-channel transient storage zone, as described in Bencala and Walters (1983). The model is known as the transient storage model (TSM) and is implemented in the software OTIS:

$$\frac{\partial C}{\partial t} = -\frac{Q}{A} \frac{\partial C}{\partial x} + \frac{1}{A} \frac{\partial}{\partial x} \left(AD \frac{\partial C}{\partial x} \right) - \alpha(C - S) \quad (1)$$

$$\frac{\partial S}{\partial t} = \alpha \frac{A}{A_s} (C - S) \quad (2)$$

where C and S are solute concentration [ML^{-3}] in the main channel and in the transient storage zone, respectively; t is time [T], A and A_s are cross-sectional areas [L^2] of the main channel and the transient storage zone, respectively; Q is the stream channel flow rate [L^3T^{-1}]; D is the dispersion coefficient [L^2T^{-1}]; x is the distance downstream of the injection [L], and α is the exchange rate coefficient [T^{-1}] with the transient storage zone.

We used the inverse modeling version of the OTIS software known as OTIS-P (Runkel, 1998), to estimate the transport parameters D , A , A_s and α . Transport parameters for the control

reach (MS1-MS2) were estimated by fitting modeled specific conductance (SPC) to observed SPC at MS2, using observed SPC at MS1 as the upstream boundary condition. Similarly, parameters for the treatment reach (MS2-MS3) were estimated by fitting modeled SPC to observed SPC at MS3, using observed SPC at MS2 as the upstream boundary conditions. Even though the two reaches are contiguous, natural variability between the reaches made direct comparison of transport parameters difficult. We therefore, calculated the percent change in each parameter (during E2 through E6) relative to their initial values during E1, and compared those between the two reaches. This approach better distinguishes the impact of the weirs on the transport parameters. Identical changes in the control reach and treatment reach parameter values would imply that the weirs did not have measurable impact on the estimates of the transport parameters. We also report the propagated 95% confidence interval (CI) of the normalized transport parameters. The actual 95% CI was obtained from OTIS-P, which uses the non-linear regression routine STARPAC to calculate the approximate variance of the parameters in the vicinity of the parameter estimate (Runkel 1998).

We calculated the Damköhler (*Dal*) [--] number to assess the suitability of the length of the two reaches for transient storage parameter estimation (Wagner and Harvey, 1997):

$$Dal = \alpha \left(1 + \frac{A}{A_s}\right) \frac{L}{u} \quad (3)$$

where, L is the length [L] of the reach and u is the average stream velocity [LT^{-1}], calculated as Q/A . We also calculated the metric F_{med}^{200} [--] (Runkel, 2002), defined as the fraction of median travel time (t_n) attributable to the retention caused by exchange with transient storage, for a standardized reach of 200 m. Median travel time, t_n , for a reach is the time required for half the

tracer molecule (from a pulse injection) to pass the downstream end of the reach, which can be approximated for a constant rate injection by measuring the time elapsed for the achievement of half of the plateau concentration. The metric F_{med}^{200} incorporates the role of advective and non-advective movement of water and mass in the reach travel time calculation and was calculated using the approximate function presented in Runkel (2002):

$$F_{med}^{200} \approx \left(1 - e^{-L \frac{\alpha}{u}}\right) \frac{A_s}{A + A_s} \quad (4)$$

2.4 Statistical Analysis

To analyze the impact of the weirs on the transport parameters, first we calculated the percentage change in the transport parameters, Δp_i from their initial values (i.e. E1) for each experiment and reach (i.e., $\Delta p_i = (p_i - p_{E1})/p_{E1}, i = E2, \dots E6$). Weirs were added in stages in the treatment reach but nothing changed besides flow in the control reach. Then, we tested the null hypothesis that the changes in parameter values (with respect to their values from E1) were identical in both reaches, using Student's t distribution. This is identical to testing the hypothesis that a set of samples d_i is t-distributed with a population mean of zero and standard deviation equal to sample standard deviation, where $d_i = \Delta p_{i,cont} - \Delta p_{i,treat}, i = E2, \dots E6$. Identical changes in control and treatment reach parameter values (i.e., d_i indeed has a mean of zero), will imply that the weirs did not have measurable impact on the parameter values. A high p-value indicates support for the null hypothesis, whereas a low p-value indicates insufficient evidence to support the null hypothesis.

3. Results

3.1 Flow Variation

Our experiments had two principal independent variables, the number of weirs and stream flow (Q). Even though we had control over the number of weirs, Q variation was uncontrolled and followed the seasonal recession trend. During the 29-day experimental period, channel flow (Q) dropped by 70% (from 14.6 L/s to 4.4 L/s, Table 1). This variability in Q was relatively low compared to the full annual range (as represented by variation in measured stream stage, Figure 2). Although we assumed constant Q during each individual experiment, Q actually varied over the course of each experiment, primarily due to the diel cycle of evapotranspiration. The two experiments with the lowest Q (E4 and E6) had the highest relative sub-daily Q variability (4.4 and 11.4%, respectively, Figure 3). For the rest of the experiments, Q variation was 2.1% or less. This sub-day variability for E4 and E6 also manifested in the breakthrough curves (BTC) in the form of an upward sloping specific conductance plateau (Figure 4d, f).

3.2 Transport Parameters

3.2.1 Effect of Channel-Spanning Structures

We focus in this section on experiments E1 through E4, where the number of weirs was successively increased from 0 to 10 (Table 1). Streamflow (Q) also decreased during the first four experiments, and since Q can have significant impact on solute transport, we also discuss how such variation in Q can explain some of the observed variation in transport parameters during these first 4 experiments. We focus on trends of transport parameters relative to the first experiment (E1) (Figure 5) rather than the absolute differences among reaches, although the latter is available in Table 2.

The dispersion coefficient (D) decreased both in the control and treatment reaches with the greatest drop occurring from E1 to E2 (Figure 5a). The decrease was slightly greater in the

treatment reach, but this was not statistically significant (p-value = 0.14). Dispersion coefficient is often estimated as function of average velocity (u), and also square of u (Chapra, 1997). The trend of D with u (Figure 6a) was approximately linear for the treatment reach.

Channel flow cross-sectional area (A) in the treatment reach increased approximately linearly with increasing number of weirs, despite simultaneously decreasing Q (experiment E2, E3 and E4, Figure 5b). By contrast, A decreased across the experiments in the control reach, and was significantly different (p-value of 0.003) than in the treatment reach. Transient storage zone cross sectional area (A_s) for the treatment reach monotonically increased during the first four experiments except for E3 and ranged between approximately 125 and 190% of the first experiment (p-value of 0.006, Figure 5c). In the control reach A_s oscillated among different experiments with perhaps a small increasing trend, ranging from 11 to 72% of the first experiment. The transient storage exchange rate coefficient (α) decreased in both reaches, but the decrease was significantly higher in the treatment reach (p-value = 0.004, Figure 5d).

The ratio A_s/A generally increased in the control reach due to increases in A_s and simultaneous decreases in A (Figure 5e). Similarly, A_s/A increased in the treatment reach as an increase in A (maximum increase of about 75%) was overwhelmed by the relatively larger increase in A_s (maximum increase of about 240%). Despite the substantial increase in A_s in the treatment reach, the simultaneous increase in A in the treatment reach led to moderate increases in A_s/A . In the two reaches, changes in A_s/A were not significantly different (p-value = 0.93).

To account for the effect of changes in Q , and therefore to isolate the effects of the different treatments, we normalized the treatment reach parameter with the control reach parameter (Figure 5f). Dispersion decreased in the treatment reach from about 90% to 40% of its value in

the control reach, A increased from about 80% to about 150%, A_s oscillated (but generally increased with the number of weirs) and ranged between 30% and 80%, and α decreased from about 80 to 40%. These trends confirm the trends seen in Figures 5a-d.

F_{med}^{200} increased in both reaches by $\sim 160\%$ (Table 2, Figure 7a) indicating no significant difference for weirs. On the other hand, the addition of weirs substantially increased the median travel time (t_n) in the treatment reach ($\sim 325\%$) relative to the control reach ($\sim 125\%$) (Figure 7b). Except for the first experiment, t_n was higher in the treatment reach for all experiments and increased with the number of weirs (Table 2). The absolute values of the part of t_n attributable to transient storage (estimated by multiplying t_n and F_{med}^{200}) were higher for the control reach for all experiments. However, the changes in this parameter relative to the first experiment were larger in the treatment reach than in the control reach (Figure 7c).

3.2.2 Effect of Flow Variation

Since flow Q was the main independent variable in the control reach, delineating the effect of Q variation in the control reach is straightforward. By contrast, coupled changes in both Q and number of weirs in the treatment reach make the interpretation of the impact of Q more difficult for experiments E1 through E3 (Table 1). Hence, for the treatment reach we primarily focus on the last three experiments, E4 through E6, when the number of weirs was not changing. Nevertheless, we do gain insight where we can from the changes observed in E1 through E3, conscious of the fact that the number of weirs was not constant but rather gradually increasing, with the control reach observations helping us to partially isolate the effects of Q .

In the control reach, A and α had a clear positive correlation with Q across all six experiments (Figure 8a, c), while A_s was negatively correlated (Figure 8b). D in the control reach was positively correlated with Q (Figure 8d; $r = 0.84$), although this correlation clearly depended on the large value of D from E1 (Figure 8d) and exclusion of this data point would make the correlation slightly negative.

In the treatment reach, during the last three experiments (E4–E6), changes in A_s and α differed from that in the control reach (Figure 8). By contrast, trends in A and D were similar in both reaches during these experiments. Changes in α and D with Q were milder in the treatment reach than in the control reach during E4 through E6. By contrast, in the first three experiments (E1–E3, when numbers of weirs varied), A increased with concurrent decreases in Q in the treatment reach. Transient storage area, A_s , increased both in the control reach and the treatment reach during E1 through E3, but the increase was relatively higher in the treatment reach. Both α and D decreased in the two reaches during the first three experiments, but the rate of change was steeper in the treatment reach. The trends of transport parameters with Q show consistent behavior in the control reach but no such consistent trend was observed in the treatment reach. Overall, Figure 8 shows how most parameter trends with Q were altered by the weirs.

3.3 Parameter Reliability

Experimental Damköhler number (Dal) is an indicator of the reliability of the estimated transient storage parameters and ideally should be 1.0, but a range that is considered reasonable is between 0.5 and 5 (Harvey and Wagner, 2000). For the control reach, Dal ranged between 0.40 and 0.64 while for the treatment reach Dal ranged between 0.43 and 0.84 (Table 3). In

general, the treatment reach had slightly better *Dal* (average of 0.68) than the control reach (average of 0.54). The only *Dal* less than 0.5 were for the treatment reach for E5 and the control reach for E6. Wagner and Harvey (1997) suggested designing experiments based on *Dal*, but it was impractical for us to change reach lengths with Q given the type of manipulations we performed. Nevertheless, *Dal* of the different experiments gives us a metric to weigh the results of each experiment according to their respective reliability. In terms of model fitness, the modeled tracer BTC matched the observed data well (Figure 4) for all experiments except for E4 and E6. The mean squared residuals (total squared residuals normalized by number of observation) were less than 2 for all experiments, except for E4 (around 4.5 for the two reaches) and E6 (around 6) (Table 3).

4. Discussion

4.1 Effect of Channel-Spanning Stream Restoration Structures

4.1.1 Effect on Transport Parameters

Weir construction creates obstruction to flow and dissipates energy, changing local flow conditions and in turn affecting solute transport locally and potentially downstream. The parameters of the one dimensional transient storage model give a highly simplified representation of the actual processes that solutes undergo. Yet the transient storage model gives us valuable (albeit implicit) information as to the fate and transport of solutes. Here we refer to the latter effect as reach scale transport effects. The most important effect of the weirs that we observed was the reduction of channel flow velocity due to added resistance from the weirs, which subsequently caused an increase in channel flow cross-sectional area, A . The increase in A

can be understood by applying a uniform open channel flow equation at the reach scale (i.e. encompassing multiple weirs). For example, in the Manning's equation ($Q = n^{-1}R^{2/3}S_0^{1/2}A$), weirs would increase the roughness coefficient n (consequently increasing A to route the same Q , assuming slope S_0 remains constant).

The increase in A from the addition of weirs in turn led to a decrease in u , which in turn would explain the associated decrease in exchange rate parameter α (Figure 6b). Average stream velocity is also positively correlated with Q and therefore we also observed lowering of α in the control reach over time. Positive correlation between α and u has been observed in multiple prior studies collated by Johnson et al. (2014). Reduced u decreases exchange with surface transient storage through decreased turbulence (D'Angelo *et al.*, 1993; Phanikumar *et al.*, 2007). In terms of hyporheic transient storage, reduction in u leads to reduced turbulent hyporheic exchange with the shallowest/coarsest sediments (Nagaoka and Ohgaki, 1990; Elliott and Brooks, 1997; Packman and Brooks, 2001; Boano *et al.*, 2011; Blois *et al.*, 2014), and also reduced form-drag induced hyporheic exchange by ripples, dunes, and bars (D'Angelo *et al.*, 1993; Zarnetske *et al.*, 2007; Jin *et al.*, 2009). By contrast, dispersion was less sensitive to stream manipulation than the other transport parameters. Still, the modest observed decline in D (Figure 5a) most likely was due to the reduction of turbulent diffusion and therefore reduction in longitudinal plume spreading as u decreased (e.g., Ward *et al.*, 2013). Contrary to our observation, Becker *et al.* (2013) reported increases in velocity and α in reaches restored using natural channel design method (Rosgen, 1994). Even though their flow obstructing structures also created pools, the authors attributed increased flow velocity to the reduced conveyance area around restoration

structures. Thus their structures may have had different impacts to surface water hydraulics, with corresponding transient storage effects.

Increases in both the number of weirs and Q in our study appeared to lead to increases in the size of the transient storage zone A_s , probably due to increased surface transient storage volume behind the weirs and increased volume of hydrostatically driven hyporheic flow paths beneath the weirs. These effects are consistent with increases in surface dead zones (a contributor to surface transient storage, Ensign and Doyle, 2005; Roberts *et al.*, 2007; Jin *et al.*, 2009) and hyporheic flow paths (e.g., Azinheira *et al.*, 2014, Hester and Gooseff, 2011, Hester *et al.*, 2009) due to in-stream structures as reported in the literature. Nevertheless, A_s/A , which is often considered an indicator of the potential of the transient storage to impact solute transport/processing (Runkel 2002), increased in both reaches (Figure 5e), such that there was little comparative increase in the treatment reach (Figure 5f). In other words, the relatively significant increase in A_s was masked by the concurrent increase in A , which supports the contention by Runkel (2002) that these parameters cannot be used on their own to compare different reaches (or streams) without simultaneously accounting for other parameters, such as α and u . The simultaneous increase in A_s and decrease in α with weir installation may cancel each other out in terms of net effect on pollutant or nutrient processing. While increased A_s is considered beneficial for solute processing, a decrease in α can be interpreted as both advantageous and disadvantageous (Runkel, 2002). For example, as α decreases, the metric representing average flux through storage zone per unit length, $q_s (= \alpha A)$, decreases. On the other hand, the metric representing average time in storage, $T_{sto} (= A_s \alpha^{-1} A^{-1})$, will increase.

Median travel time t_n is not affected by extreme values, and provides another perspective of how transient storage affects solute transport. We partitioned median travel into two parts, one that is due to main channel transport and the other due to transient storage. The increase in t_n could be explained by the increase in surface transient storage area (with relatively low exchange) and increased hydrostatically driven hyporheic exchange near the weirs. At the same time that the weirs were installed, Q also decreased due to seasonal recession, which would also increase t_n due to lowered u in the channel, as observed in the control reach. Yet, the greater increase in t_n in the treatment reach where there were also increases transient storage (Figure 7c) shows that solutes are being retained longer where weirs are present.

An increase in t_n due to transient storage would be potentially beneficial in terms of time available for solute processing. However, the importance of this enhanced retention depends on whether it is surface or subsurface storage (Stewart *et al.*, 2011; Gomez-Velez *et al.*, 2015), in that surface processing can be quite slow compared to that in the sediment or hyporheic zone (Hall *et al.*, 2002; Haggerty *et al.*, 2008; Hester and Gooseff, 2010, 2011). We surmise that the weirs caused a switch from short hyporheic flow paths through shallow coarse sediment, due to turbulence and form drag over ripples (which would give low A_s and high α), to sluggish exchange with dead zones on the surface and some longer hyporheic flow paths induced by hydrostatic head drop over weirs (which would give high A_s and low α , with higher likelihood to remain undetected by the current tracer method due to its limited window of detection). Thus, in order for weir installation to achieve net improvement in water quality, cumulative processing in the backwater surface transient storage zones behind weirs and greater hydrostatically induced hyporheic exchange around weirs would have to overcome the loss of processing capacity from

reduced hydrodynamically induced hyporheic exchange and surface dead zone exchange rate. This is consistent with recent studies which show that cumulative hyporheic exchange through smaller geomorphic forms (e.g., ripples) can be greater than that induced by larger structures such as weirs (Gomez-Velez and Harvey, 2014; Gomez-Velez *et al.*, 2015).

The transient storage model is relatively less representative of deeper hyporheic fluxes, due to the limited window of detection of the tracer method, such that the longer portion of the hyporheic flow paths created by the weirs might have remained “unobserved” (Zaramella *et al.*, 2003; Briggs *et al.*, 2009; Ward *et al.*, 2013b). Deeper hyporheic flow paths are often less important than relatively shallow hyporheic exchange, due to their low flow rate (hence, low reactant delivery) compared to the stream flow (Gomez-Velez and Harvey, 2014; Gomez-Velez *et al.*, 2015). Hence, the longer time scale exchanges that weirs enhance most likely have lower impact on solute processing. Depending on geology, deeper hydraulic flow paths could become constrained due to bed rock and in extreme eliminate hyporheic flow entirely. Streams with minimal hyporheic exchange could potentially benefit relatively more from any surface transient storage induced by weirs.

4.1.2 Implications for Stream Restoration

Reduction in u by channel-spanning structures can be consequential for stream restoration since any gain in A_s might ultimately be overcome by the effect of lower α . Stewart *et al.* (2011) illustrated that the relative importance of A_s and α is determined by the biological/chemical process being considered where a highly reactive process (e.g., chemical oxidation) will be controlled by α and a less reactive process (e.g., denitrification) will be controlled by the size of

A_s . Reducing u with flow obstructing structures might shift the spatial structure of transient storage giving more importance to less reactive surface transient storage and less importance to highly reactive hyporheic transient storage (although some reactions like photochemical breakdown is only possible on the surface). Simultaneously, within the hyporheic transient storage, we may be shifting from shorter residence time hydrodynamically-induced hyporheic transient storage that favors rapid reactions to longer residence time hydrostatically-induced hyporheic transient storage that favors slower reactions. This shift toward longer residence times may in turn increase the fraction of hyporheic flow paths that experience anoxia and hence reactions that are enhanced in such conditions, e.g., denitrification. Nevertheless, conclusions drawn from this stream might not be generally applicable to other streams because hyporheic exchange is heavily controlled by geology (Baker *et al.*, 2012, Zarnetske *et al.*, 2007). Our study therefore highlights the importance of assessing each stream separately when evaluating the impact of reach scale restoration.

Our results also illustrate the need for methods that are capable of reliably separating surface transient storage from hyporheic transient storage and the need to consider the impact of restoration structures on surface and hyporheic transient storage separately (Briggs *et al.*, 2010). It is possible that an optimum condition exists where hyporheic transient storage lost from reduced hydrodynamic exchange can be overcome by increased hydrostatic exchange but evaluation of such optimal condition is not possible using the conservative tracer method employed here. Additional information from reactive tracer (e.g., Argerich *et al.*, 2011) or subsurface sampling (e.g., Harvey *et al.*, 2012, 2013; Stonedahl *et al.*, 2012; Zimmer and Lautz, 2015) might aid in separating the impact on surface and hyporheic transient storage.

4.2 Effect of Flow Variation

4.2.1 Effect on Transport Parameters

The trends of transient storage parameters with Q in the control reach (Figure 8) were not surprising, as similar observations have also been reported in the literature (e.g., Schmid *et al.*, 2010). Of the various parameters in the treatment reach, stream cross-sectional area (A) in particular behaved similarly to the control reach, increasing with Q when the number of weirs was held constant.

However, for some parameters, we observed markedly different responses to Q in the treatment reach. For example, the general trend of decreasing A_s with increasing Q in the absence of weirs, i.e. in the control reach from E1 through E6 and to some extent in the treatment reach during E1 through E4, can be explained by surface transient storage zones being relatively smaller compared to the channel cross sectional area during higher flows. By contrast, the opposite trend of increasing transient storage area (A_s) with increasing Q observed in the treatment reach during E4 through E6 might be explained by higher flows creating larger pools behind the weirs. Dynamic hyporheic transient storage should increase with Q in the control reach, but this was not sufficient to overcome the loss in surface transient storage area in the control reach.

The minimal change in exchange rate (α) with decreasing Q (and hence u) in the last three experiments (E4 through E6) in the treatment reach compared to the control reach (Figure 8c) is most likely due to the fact that α has already been reduced extensively by the drop in velocity near the weirs, such that it has become less responsive to further lowering of u . As can

be seen from the trend in the control reach, α is strongly nonlinear with Q (i.e., u) with a stronger relationship/steeper trend at lower Q . By contrast, in the treatment reach, weir-induced backwater strongly suppressed α , which is an order of magnitude less than in the control reach (Table 2), and became less responsive to further change in Q during E4 through E6. Gradual addition of weirs directed α towards this less responsive state, as seen from E1 through E3.

The observed change in parameter response to flow variation in presence of weirs is most likely due to the nature of the resistance provided by the weirs. Unlike channel perimeter roughness, weirs provide point roughness and create large pools that dissipate energy via sudden expansion. An analogous situation for weirs in piped flow would be a large minor loss due to sudden expansion at pipe junctions, whereas channel roughness would be analogous to pipe roughness. Our three experiments with constant number of weirs are not statistically definitive, yet our results do suggest that transport parameters of stream reaches with dense channel spanning weirs might respond differently to Q variation than reaches without them.

More fundamentally, our work shows the complication of dealing with Q variability in analyzing transient storage data. Unless Q variability can be eliminated, there will always be conflation of observed changes in transient storage parameters among experimental treatments with changes in Q . From this perspective our Q variability was at an annual minimum (represented by variation in stream stage, Figure 2) and therefore unusually well suited for such experiments yet Q still declined by ~70% over the course of our six experiments. Given that it is impossible to predict Q variability ahead of time with any accuracy, it is reasonable to assume that our relatively low Q variation is not easily repeatable, and our site is not unique in this regard. This joins earlier concerns expressed about the sensitivity of the transient storage

approach to Q variation (Harvey *et al.*, 1996; Wondzell, 2006; Ward *et al.*, 2013b) and warrants caution. Harvey *et al.* (1996) in particular found that with increasing Q the transient storage model becomes increasingly insensitive to hyporheic exchange due to the shrinking of window of detection at high u . In our treatment reach, shorter/faster hydrodynamically driven hyporheic flow paths were likely reduced by the weirs, while longer hydrostatically driven hyporheic flow paths were likely enhanced. Any shift toward hydrostatically induced hyporheic exchange could yield a reduction in ability of the transient storage approach to fully characterize that exchange, complicating the comparison between different experiments. These issues may have ramifications beyond physical hydrology. For example, Ye *et al.* (2012) coupled a hydrologic model with the transient storage model to compute nitrogen retention in river networks with assumed transient storage parameters. The uncertainties discussed here would have produced uncertainties in the estimates of nitrogen retention.

Flow variation was also evident during individual experimental days from the upward sloping plateaus of most BTCs, particularly E4 and E6 (Figure 4). We expect that this was mostly due to evapotranspiration during daylight hours. This led to a poorer fit (Table 3) of the modeled transport for E4 and E6 compared to the rest of the experiments. Such non-ideal flow conditions meant greater uncertainty in the parameter estimation of E4 and E6 but from inspection of the plots we conclude that the uncertainty is well within the bounds that is typical in transient storage model literature, and regardless does not impact our conclusions.

4.2.2 Implications for Stream Restoration

The high sensitivity of the transient storage approach to Q variation raises a potential quandary for assessing the water quality impacts of stream restoration. Quite a bit of trust has been placed in stream restoration to play a significant role (e.g., in reducing nutrient pollution to Chesapeake Bay, Berg *et al.*, 2014), and practitioners are already widely using this approach. Yet these existing approaches are generally silent on how much specific stream restoration practices will reduce water quality impairment or pollutant loading, and how that varies in time and space (Veraart *et al.*, 2014). In the case of in-stream structures, an example question is how many structures are needed to remove 50% of the excess N? And how does that vary with parameters such as N concentration, channel slope, and of course stream channel flow rate? The transient storage approach has significant appeal in quantitatively testing the efficacy of these BMPs because it is relatively quick and inexpensive, yet still integrates the net effect of a whole reach into a single quantification. This contrasts with point measurements such as hyporheic piezometers. Yet the main weakness of the transient storage approach is that Q variation affects the answers substantially even when Q variation is minimized as much as is reasonably possible. For example, a recent study by Mueller Price *et al.* (2016) observed that nitrogen removal capacity gained by stream restoration/manipulation can potentially be overwhelmed by flow variation. These issues can be addressed to some extent using control reaches and duplicate experiments over time as we have, but these techniques substantially increase the data collection effort in both time and space. Thus, there is great incentive for future development and improvements in this area, for both scientific and applied reasons.

5. Conclusions

There is increased interest in stream restoration for its potential to improve water quality. In this study we tested the effect of common in-stream restoration structures (weirs representing channel-spanning structures such as log dams and boulder weirs), in a small forested stream. We tested their impact on transient storage in surface dead zones and the hyporheic zone, as measured by constant rate injection of conservative tracer. We experimentally added 10 weir-type structures along an 80 m reach and compared the effects with an un-manipulated control reach.

The weirs significantly increased channel flow cross-sectional area (A) due to creation of backwater. The weirs also enhanced cross-sectional area of the transient storage zone (A_s), likely both in surface water (backwater behind weirs) and in the hyporheic zone (due to the induced hydrostatic gradient across the weirs), although the transient storage modeling approach cannot distinguish these components. Simultaneous with an increase in A_s was a decrease in exchange rate with the transient storage zone (α) thus making the overall impact of the weirs on water quality complicated. The reduction in α is likely due to the increase in A which increases residence time in the reach (t_n) and reduces channel flow velocity (u). Reduced u reduces hydrodynamically driven hyporheic exchange due to reduced turbulence and form drag across existing bedforms such as ripples, and similarly reduces exchange with surface transient storage due to reduced turbulence. The impact of increased hydrostatically driven hyporheic exchange by the weirs was either overcome by the losses in hydrodynamically driven exchange or was “unobserved” due to the limited window of detection of the tracer method. Our results are thus consistent with weirs causing a switch from short fast moving hydrodynamically driven hyporheic flow paths through shallow coarse sediment (which would give low A_s and high α) to

long slow moving hydrostatically driven hyporheic flow paths (which would give high A_s and low α).

These results have substantial implications for efforts to harness in-channel stream restoration structures to improve water quality. The various effects of these structures are complicated and potentially mutually cancelling, such that assuming greater connectivity with hyporheic zones from instream structures (e.g., cross-vanes or J-hooks) may not have the intended water quality effect.

Our results also provide a series of methodological insights. We emphasize the importance of the effect of channel flow rate (Q) variation on transient storage. Exchange rate, α , increased with u and hence Q in both control and treatment reaches. On the other hand, the trend of A_s with Q was different in the treatment reach than in the control reach, even with constant number of weirs. This may explain contradictory results in the literature that show both increases and decreases in transient storage characteristics in response to spatial and temporal variations in Q . Nevertheless, despite natural Q variation affecting our experimental results, we actually minimized such variation as much as possible, underlining the challenges of generating definitive data on the water quality effects of in-channel stream restoration practices using the transient storage model. This also emphasizes that hyporheic exchange (and consequently capacity for water quality reactions) is highly variable across time, and evaluation of stream restoration projects at one flow regime most likely cannot be used to estimate the aggregate effect across time. Even though the transient storage model is widely used to analyze solute transport, it alone cannot provide sufficient information about potential of stream restoration structures for water quality benefit.

In summary, using channel-spanning stream restoration structures could be promising in enhancing transient storage, but additional study is needed to sort out the mechanisms behind observed changes in transient storage model parameters. An optimal condition might exist that maximizes increases in A_s and minimizes decreases in α , which is an interesting topic for future research.

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Tables

Table 1. Experiment details and flows

Exp. ID	Date	Number of structures	Stream Flow (L/s)			Injection Start Time	Injection Duration (hrs)
			Min	Avg	Max		
E1	5-11-2015	None	14.3	14.6	14.9	10:40 am	3.67
E2	5-19-2015	3 weirs	8.6	8.7	8.8	3:14 pm	3.00
E3	5-22-2015	7 weirs	6.9	7.05	7.2	11:12 am	3.00
E4	5-30-2015	10 weirs	5.4	5.65	5.9	11:03 am	3.95
E5	6-03-2015	10 weirs	6.7	6.90	7.1	11:29 am	4.7
E6	6-09-2015	10 weirs	3.9	4.40	4.9	11:27 am	4.75

Table 2. Summary of conservative tracer parameters.

Exp	Reach	Q (L/s)	# of weirs	t_n (mins)	% F_{med}^{200}	u (m/s)	D (m ² /s)	A (m ²)	A_s (m ²)	α (s ⁻¹) $\times 10^{-4}$
E1	Cont.	14.6	--	10.2	0.53	0.131	0.417	0.105	0.030	2.0
	Treat.		0	8.2	1.80	0.162	0.329	0.082	0.009	1.7
E2	Cont.	8.70	--	15.6	0.60	0.085	0.236	0.099	0.041	2.0
	Treat.		3	16.5	4.25	0.081	0.216	0.102	0.022	1.2
E3	Cont.	7.05	--	17.3	0.64	0.077	0.231	0.087	0.033	1.8
	Treat.		7	24.5	2.90	0.054	0.160	0.124	0.021	0.63
E4	Cont.	5.65	--	20.6	0.50	0.065	0.246	0.082	0.051	1.6
	Treat.		10	36.4	4.60	0.037	0.106	0.144	0.028	0.63
E5	Cont.	6.90	--	17.9	0.58	0.075	0.208	0.087	0.040	1.8
	Treat.		10	27.8	3.40	0.048	0.129	0.135	0.031	0.51
E6	Cont.	4.40	--	22.7	0.40	0.059	0.260	0.076	0.049	1.1
	Treat.		10	35.1	4.56	0.038	0.109	0.114	0.022	0.65

Table 3. Damköhler numbers

Exp	<i>Dal</i> (--)		Mean Squared Error ($\mu\text{S}^2/\text{cm}^2$)	
	Control	Treatment	Control	Treatment
E1	0.53	0.74	0.195	0.046
E2	0.60	0.65	0.361	0.067
E3	0.64	0.60	0.730	0.742
E4	0.50	0.84	4.683	3.954
E5	0.58	0.43	1.500	0.451
E6	0.40	0.84	2.155	5.989

Figures

Figure 1. Map showing the stream location, watershed, monitoring and injection stations (background, injection, MS1, MS2 and MS3), groundwater wells (GW1 through GW4) and in-stream stilling well.

Figure 2. Stream water depth versus date at stilling well (see Figure 1 for location). Vertical lines correspond to the dates of the experiments.

Figure 3. Sub-daily channel flow rate (Q) variation (in percent) estimated from mean Q and specific conductance plateau slope during each experiment versus mean Q .

Figure 4. Modeled and observed specific conductance breakthrough curves at monitoring station 2 and 3 (MS2 and MS3) for E1 through E6 shown in panel (a) through (f).

SPC=specific conductance.

Figure 5. (a through e) Change of transient storage parameters relative to their values estimated in the first experiment versus experiment number along with propagated 95% confidence interval (note that, due to normalization with respect to E1, uncertainty for the E1 cannot be calculated); and (f) Parameters of the treatment reach normalized by the

corresponding parameter of the control reach versus experiment number. A = channel cross sectional area, A_s = transient storage zone cross sectional area, α = transient storage zone exchange rate, D = channel dispersion coefficient.

Figure 6. (a) Channel dispersion coefficient (D , $R^2 = 0.74$) and (b) and transient storage exchange rate (α , $R^2 = 0.47$) versus u for the six experiments.

Figure 7. Change in (a) F_{med}^{200} ; (b) channel median residence time (t_n); and (c) part of t_n that is due to transient storage ($t_{n,As}$), as a percentage of their initial values from experiment E1 versus experiment number. TS=transient storage.

Figure 8. Channel cross sectional area (A), transient storage zone cross sectional area (A_s), transient storage zone exchange rate (α) and channel dispersion coefficient (D) plotted against channel flow rate (Q) for the control reach and treatment reach. Filled markers indicate the last three experiments (E4 – E6) when the number of weirs remained constant. R^2 values are given only for the control reach. Trend lines for the control reach are for all six experiments while trend lines for the treatment are only for E4-E6.