Relating transient storage to channel complexity in streams of varying land use in Jackson Hole, Wyoming

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[1] Transient storage processes are important to biogeochemical cycling in many streams and depend greatly upon stream fluvial structure. Fluvial geomorphic structure establishes patterns of surface water and subsurface head distributions, often driving hyporheic exchange through steps, riffles, and meanders, and controls the potential for in-channel dead zone storage in side pools, eddies, etc. We performed stream tracer experiments and geomorphological assessments (topographic thalweg surveys, channel dimension measurement, and sediment size analyses) in six streams in Jackson Hole, Wyoming, two agricultural streams, two urban streams, and two reference streams surrounded by native vegetation, to relate stream water transient storage to channel complexity. We propose that the inclusion of agricultural and urban streams increases the range of channel complexity and transient storage response over an assessment of numerous reaches within a single land use type. Stream tracer experiments were performed in each of the six reaches with slugs of Rhodamine WT (RWT). Downstream RWT breakthrough curves (BTCs) were simulated with a one-dimensional solute transport model, STAMMT-L, capable of simulating several transient storage residence time distribution types. As an indication of transient storage, relative BTC residence times were compared to timescale of advection, \( t_{adv} \) (taken to be the time of peak tracer concentration). Reference streams were geomorphically complex, agricultural streams were intermediate, and urban streams were least complex. Urban streams had the shortest total relative residence times (< 5\( t_{adv} \)) and short mean storage residence times (0.34 hour, n = 2), and reference streams consistently had the longest total relative residence times (13–20\( t_{adv} \)) and the longest mean storage residence times (1.82 hours, n = 2). These results indicate that increased geomorphic complexity increases the potential for transient storage, likely both in the channel and in the subsurface, as demonstrated in reaches in a range of land use settings.


1. Introduction

[2] Transient storage, the process by which water is stored in either stream channel dead zones (side pools, eddies) or exchanges through the hyporheic zone, influences stream biogeochemical cycling. Transient storage increases the residence time of stream solutes and the opportunity for contact time with microbial communities. Both in-channel and subsurface transient storage processes depend upon channel geometry and substrate [Harvey and Bencala, 1993; Kasahara and Wondzell, 2003; Cardenas et al., 2004; Gooseff et al., 2005]. Additionally, fluvial geomorphic form influences nutrient transport and retention [Doyle et al., 2003; Gucker and Boechar, 2004].

[3] There have been a number of studies addressing transient storage as a function of stream morphology and stream hydraulic condition. D’Angelo et al. [1993] documented reduced transient storage in artificial streams (flumes) and generally increasing transient storage (as determined by transient storage model simulations) from first- to fourth-order natural streams. Certainly, along the geomorphic continuum from first- to fourth-order streams studied by D’Angelo et al. [1993], there existed a general increase in fluvial bed form size and spacing, such as that documented by Anderson et al. [2005]. Wondzell [2006] documented increased transient storage, which he interpreted as due to hyporheic exchange, in streams with a few large steps compared to reaches with more, but smaller steps. Harvey et al. [2003] showed that hydraulic retention increases with increased macrophyte and vegetation density in a semiarid stream over a timescale of many years. Similarly, Salehin et al. [2003] found that seasonal vegetation increased stream solute retardation in a Swedish agricultural stream, as a consequence of modified flow and turbulence regimes within the channel.

[4] Much of the recent research on stream transient storage processes has been in streams in natural settings,
typically in high-gradient mountain streams. However, streams flowing through modified land use types (e.g., agricultural and urban) are subject to channel constraint, reduced input of sediment, anthropogenic augmentation (and even creation), and altered flow regimes [Paul and Meyer, 2001]. Gergel et al. [2002] note that a number of landscape indicators, such as proportion of contributing impervious area and riparian buffer extents, can greatly inform assessment of human impacts on rivers. Salehin et al. [2003] found that channel excavation, resulting in a simplification of channel bed form sequence and spacing, and subsequent lining with clay were responsible for longer timescale transient storage, largely because of reduced hydraulic conductivity of the streambed. Building upon that work, we contend that fluvial geomorphic alterations, and characteristics of anthropogenically influenced streams, are likely to impact transient storage by restricting in-stream dead zones, armoring streambeds, and reducing channel geomorphic forms that establish head gradients driving groundwater-surface water exchange, and therefore transient storage of stream water and solutes.

[5] One recent study of biogeochemical cycling in urban streams, which at least in part, should depend upon transient storage, have shown that urban streams are capable of processing N at rates comparable to and higher than nearby forested reference reaches [Grootman et al., 2005]. Grimm et al. [2005] compared differences in N spiraling in arid urban and reference streams, and qualitatively observed that channel complexity and transient storage were diminished in the urban streams, coincident with elevated concentrations of dissolved-nitrogen species. Thus alteration of channel form has been shown to drive changes in stream ecosystem function.

[6] There have been several studies focused on transient storage processes in relation to stream geomorphic form, though there has been little focus on transient storage in streams in a range of land use settings. We hypothesize that transient storage residence time, storage zone size, and exchange are reduced in streams that have reduced stream channel complexity. We tested this hypothesis by performing geomorphic surveys and stream tracer experiments in six streams in urban, agricultural, and reference land use settings in Jackson Hole, Wyoming. Geomorphic surveys, which included topographic surveys, channel width and depth measurements, and substrate characterization, were used to characterize channel complexity while transient storage in each stream reach was characterized by simulations and analysis of stream tracer experiment data. We expect that more complex stream channels will be found in reference reaches, those least impacted by anthropogenic changes to land use in the contributing area. In turn, we expect that the more complex a channel, the greater the potential for transient storage. We test these expectations by comparing transient storage parameter values, from optimized simulations of stream tracer transport, with channel characteristics. Our assessment of streams in varying land use settings extends the range of variability in geomorphic and transient storage variables than would be found by analyzing pristine streams alone, which have been the focus of many transient storage studies in the past.

2. Site Description

[7] The Jackson Hole area of Wyoming contains a wide array of land use types ranging from undisturbed land in Grand Teton National Park and surrounding National Forests, to urban/suburban in and around the towns of Jackson and Teton Village, to agricultural land use on the several ranches in Jackson Hole. We studied six stream reaches, 305–550 m in length, with equal representation among agricultural, urban, and reference land use settings (Table 1). Land use characterizations for each reach in this study were determined from personal observation of the dominant land use for the contributing area to each reach, and specifically, of the riparian lands adjacent to each stream. The two agricultural streams studied, Giltnner Spring Creek in 2003 and Headquarters Stream in 2004, flow through privately managed, irrigated grazing lands. Giltnner Spring Creek originates as a spring, and Headquarters Stream is partly an irrigation canal return, though both channels largely consist of irrigation return waters. These two streams were surrounded by pasture, and vegetation consisted of extensive grasses and sparse trees. In both channels, grasses grew along the channel margins, within the water column. The two urban/suburban streams are anthropogenic in design, origin, and operation. In 2003, we studied Golf Stream which flows through the Jackson Hole Golf and Country Club. It is an irrigation ditch that flows through the golf course and associated suburban houses on the downstream end. Immediately adjacent to the channel, vegetation was mixed: native grasses and trees in some locations, and lawns or golf course cover in other locations. This stream reach included a section ~50 m in length that flowed in a culvert under a fairway. In 2004, we studied Teton Pines Stream,
which is an artificial stream originating as pumped groundwater that flows through a lawn at the Teton Pines Townhomes. Adjacent to the channel, planted lawns, shrubs and a few trees contributed to the land cover, as did impervious surfaces. The reference streams were Ditch Creek studied in 2003, and Two Ocean Lake Creek studied in 2004, located in Grand Teton National Park, both surrounded by native vegetation. Two Ocean Lake Creek is a lake outlet.

This work was performed in coordination with the Lotic Intersite Nitrogen eXperiment II (LINX II) that occurred simultaneously in these streams. The LINX II project is assessing the influence of land use on dissolved N dynamics in streams set within reference, urban, and agricultural landscapes in eight biomes, and Wyoming represents the intermountain shrub-steppe biome in the project.

3. Methods

3.1. Channel Surveys

We performed topographic surveys of stream channel thalwegs and water surface profiles in each stream reach using a Topcon GS 226 total station (Topcon, Inc., Pleasanton, California). Our objective was to characterize planform and longitudinal profiles of the thalweg of the channel and water surface. Thus the choice of survey points was determined by the location of slope breaks and curvature of the stream [e.g., Anderson et al., 2005]. To assess channel complexity, we compute three metrics from the thalweg surveys. The first metric is the channel planform sinuosity, $s$, computed as

$$ s = \frac{L}{L_s} \quad (1) $$

where, $L$ is the downstream length of the channel (m), and $L_s$ is the straight line distance from the top to the bottom of the channel (m). The streambed slope ($S$) was calculated using survey data from the furthest upstream and downstream streambed locations in the thalweg. We also compute the longitudinal roughness, $\varepsilon$, as

$$ \varepsilon = \frac{1}{n} \sum_{i=1}^{n} \left| z_{obs,i} - z_{pred,i} \right| \quad (2) $$

where, $i$ is an incremental topographic survey point of the streambed, along the thalweg, $z_{obs,i}$ is the observed elevation of a point on the streambed (m), and $z_{pred,i}$ is the predicted observation of that point along the thalweg, assuming the mean slope of the streambed. Finally, we also computed Average Water Surface Concavity (AWSC) of each reach from the thalweg survey of the water surface [Anderson et al., 2005]. The AWSC describes the hydraulic expression of the streambed forms, longitudinally, and is computed as

$$ \text{AWSC} = \left( \frac{1}{n} \right) \left( \sum_{i=1}^{n} \frac{d^2 z_i}{dx^2} \right) \quad (3) $$

where $x$ is the along-thalweg distance (m), $z$ is the elevation of the streambed (m), and $i$ is a measurement point index. AWSC is calculated by averaging the absolute values of the concavity measured at every survey point ($i$) within the longitudinal water surface profile and has units of m m$^{-2}$. Increases in values of each of these four metrics suggest increased variability in the geomorphic form of the stream, which is important in establishing variable head gradients that drive hyporheic exchange through streambeds and banks.

We also measured channel width dimensions and channel substrate size. Mean stream width ($w$) was calculated from width measurements made every 10 m throughout each reach. Mean stream depth ($d$) was determined as the quotient of discharge (measured by the wading method) by the product of mean velocity and $w$. Mean velocity was taken to be the time to peak of the arrival of a salt pulse peak (arbitrary NaCl mass injected). Mean substrate size was determined from randomly gathered substrate samples throughout each reach. Substrate size in each sample was measured with a gravimeter.

3.2. Stream Tracer Experiments

We conducted pulse stream tracer experiments using Rhodamine WT (RWT) in each of the six experimental reaches. During the design of each experiment, the mass ($M$) of RWT injected in the stream was determined using the following empirically derived formulae with a target peak concentration ($C_{0pk}$) at the sampling site of 100 $\mu$g L$^{-1}$:

$$ M = C_{0pk} A \sqrt{4 \pi D_L t_{\text{transport}}} \quad (4) $$

$$ D_L = \frac{0.11 v w}{d} \quad (5) $$

where, $D_L$ is longitudinal dispersion ($m^2 s^{-1}$), $A$ is the cross-sectional area of the stream ($w \ast d$), $v$ is the mean velocity of the stream flow, and $t_{\text{transport}}$ is the time of transport for the experimental reach (quotient of reach length by $v$), as recommended by Fisher et al. [1979]. Parameters $w$, $d$, and $v$ were determined from stream discharge measurements and empirical estimates. Stream tracer (RWT) concentrations were measured at the end of each reach with a Turner Designs 10-AU field fluorometer (Turner Designs, Sunnyvale, California), outfitted with a flow-through cell and battery operated pump. Rhodamine WT is not a perfectly conservative tracer, and is known to sorb to bed sediments [Bencala et al., 1983]. However, we were able to account for mass loss of tracer when simulating solute transport.

3.3. Stream Tracer Simulations

To facilitate quantitative comparisons among stream reaches, stream tracer data was simulated with a one-dimensional solute transport model that accounts for reach-averaged advection, dispersion, and transient storage, and best fit parameter quantities, and metrics (i.e., mean storage residence time) were evaluated. The STAMMT-L model applies a user-specified residence time distribution (RTD) to a general one-dimensional advection-dispersion transport equation [Haggerty and Reeves, 2002]. For system with no longitudinal inputs, the transport equation is

$$ \frac{\partial C}{\partial t} = -\nu \frac{\partial C}{\partial x} + D_L \frac{\partial^2 C}{\partial x^2} - \beta_{aw} \frac{\partial}{\partial x} \int_0^t C(\tau)g^4(t - \tau) d\tau \quad (6) $$
where \( \nu \) is the mean advection velocity (m s\(^{-1}\)), \( \beta_{tot} \) is the ratio of storage to stream volumes, \( C \) is the solute concentration in the stream (\( \mu g \) L\(^{-1}\)), and \( \tau \) is a lag time (s). In the last term of equation (6), \( g(t) \) is convolved with the stream concentration to represent exchange with the transient storage zone following an appropriate RTD. This would be formulated as

\[
g(t) = \alpha e^{-\alpha t} 
\]

(7)

for an exponential RTD where \( \alpha \) is the first-order rate coefficient (s\(^{-1}\)). This is the same as the standard first-order model [e.g., Bencala and Walters, 1983], though this \( \alpha \) value is equivalent to the product of the \( \alpha \) of the standard first-order model and \( \beta_{tot} \). The \( g(t) \) for a power law residence time distribution in the storage zone is expressed as

\[
g(t) = \frac{(k-2)}{(\alpha_{max}^2 - \beta_{min}^2)} \int_{\alpha_{min}}^{\alpha_{max}} \alpha^k e^{-\alpha t} d\alpha
\]

(8)

where \( k \) is the power law exponent, which corresponds to the slope of late time concentration tail after a pulse injection [Haggerty et al., 2000, 2002]. Equation (8) defines a power law function with cutoffs at \( \alpha_{max} \) and \( \alpha_{min} \), with behavior \( g(t) \sim t^{-2} \) between the inverse of those limits. These limits are determined by bracketing the timescales of the solute breakthrough curve (BTC) from the tracer experiment; \( \alpha_{max} \) is always chosen to be \( 10^{-1} \) s\(^{-1}\), and \( \alpha_{min} \) is always chosen to be the last time of data acquisition in the field, since the injection. Thus we accept that the late-time window of detection [Harvey and Wagner, 2000] of our stream tracer experiment approach is the timescale of the latest arrival of detectable tracer concentrations in the stream.

There is no perfect physical explanation of the difference between the exponential and power law models of transient storage, except to note that the exponential model is associated with a single, general timescale of exchange \( \alpha \), whereas the power law model characterizes a distribution of timescales of exchange. Marion et al. [2003] noted that the exponential model did not accurately simulate hyporheic exchange of solutes in flume studies. In line with the findings of Marion et al. [2003], one would expect that the power law model of transient storage would characterize more complex exchange dynamics between storage zones and the stream.

The governing equations of the STAMMT-L model do not include a direct mass loss term for nonconservative solutes. Instead, a mass loss factor is used

\[
m_{rec} = \frac{M}{\varphi}
\]

(9)

where \( m_{rec} \) is the mass recovered, as simulated, at the end of the reach \( g \) and \( \varphi \) is the mass loss factor (unitless) due to irreversible sorption or unsampled tracer in bypassing hyporheic flow. Thus we depend upon stream discharge measurements to determine whether \( m_{rec} \) is less than \( M \), the mass of RWT injected.

Parameters were estimated within STAMMT-L using a nonlinear least squares algorithm [Marquardt, 1963] that minimized the sum of square errors on the logarithms of concentrations. For all simulations we report root mean squared error (RMSE) as defined by Bard [1974, p. 178], in which a value of 0 indicates a perfect fit of the simulated values to the observations. Depending on the RTD type, parameters \( \nu, D_s, \beta_{tot}, k, \alpha, \) and \( \varphi \) were optimized. During optimization simulations, STAMMT-L also provides the standard error of each parameter estimate. We report those values as an indication of relative confidence in estimated parameter values.

For additional comparison of transient storage in each reach, we calculated mean storage residence times \( t_{res} \) from the optimized solute transport simulations. Mean storage residence time \( t_{res} \) is computed as \( 1/\alpha \) for exponential simulations, and as the inverse of the harmonic mean of \( \alpha_{min} \) and \( \alpha_{max} \) for power law simulations.

4. Results

4.1. Comparison of Stream Geomorphic Characteristics

We compared the geomorphic characteristics of all six stream reaches because channel morphology largely controls both in-channel and hyporheic transient storage. The two urban reaches were least sinuous (1.02, 1.11), had the narrowest channels (2.57 m, 2.29 m), low \( w/d \) ratios (15.1 and 25.2), yet had intermediate slope (0.005, 0.006) and mean substrate size (36.9 mm, 96.5 mm) compared to agricultural and reference stream reaches (Table 1 and Figure 1). Because the urban streams were anthropogenic in origin and maintenance, discharge and sediment transport regimes did not fluctuate naturally. Furthermore, in the case of these particular reaches, hydrologic contributing areas were narrow strips of land near the streams, rather than catchments with appreciable area and relief. Reference streams were the steepest (0.010, 0.019) and intermediate to most sinuous (1.39, 1.76) of all reach types, though they had intermediate channel widths (3.01 m, 4.73 m), high \( w/d \) ratios (43.0 and 31.0 for Ditch and Two Ocean Lake Creeks, respectively), and had mean substrate size similar to urban streams (34.7 mm, 98.8 mm) (Table 1). The two agricultural streams, both in pasture, were composed of appreciable irrigation return flow, had the lowest slopes (0.003, 0.004), intermediate sinuosity (1.26, 1.50), smallest mean substrate sizes (17.9 mm, 24.7 mm), widest channels of all stream types (5.16 m, 5.71 m) and intermediate \( w/d \) ratios (22.4 in Headquarters Stream and 40.8 in Gilnert Stream) (Table 1). The two urban streams had low \( w/d \) ratios: 15.1 in Golf Stream, and 25.2 in Teton Pines Stream (Table 1).

Agricultural streams had the largest and smallest longitudinal roughness values \( \varepsilon \) (0.06 m, 0.43 m) of the range determined for the study streams, whereas urban stream \( \varepsilon \) values were fairly low (0.08 m, 0.13 m), and reference \( \varepsilon \) values were also intermediate (0.13 m, 0.25 m) (Table 1). In all streams, roughness values were larger than the mean substrate size. However, in the two urban streams and in Gilnert Spring Creek (agricultural), \( \varepsilon \) values were within the standard deviation of the substrate sizes, indicating that in these streams, individual grains may play a larger role in driving streambed elevation variance than bed form development.
We propose the following equation as a metric of geomorphic complexity, directly relevant to transient storage:

\[ \chi = S e d \]  \hspace{1cm} (10)\

Slope provides for the potential for vertical variability in head distributions, sinuosity provides the potential for both in-channel bed form variability and out-of-channel exchanges, and the longitudinal roughness characterizes bed form variability. Thus the product of these three is an equally weighted, albeit simple, metric of geomorphic complexity. Using this metric, reference streams were the most complex with Ditch Creek having a value of \( 6.60 \times 10^{-3} \), and Two Ocean Lake Creek having a value of \( 2.29 \times 10^{-3} \). The other four agricultural and urban streams had lower values with a range of \( 0.36 \times 10^{-3} \) to \( 1.63 \times 10^{-3} \) (Table 1).

[20] AWSC determinations for the six reaches displayed variability between and within land use settings. Agricultural stream reaches displayed the most consistent AWSC values among stream types \( (0.11 \times 10^{-3} \text{ m}^{-1}, 0.13 \times 10^{-3} \text{ m}^{-1}) \), whereas one urban and one reference stream had negative AWSC values, indicating a generally convex shape to the streambed longitudinal profile (Table 1). The convex shape of Ditch Creek (reference) is likely due to a single large step that dominates the vertical loss along the length of the experimental reach, whereas the convex shape of Golf Stream (urban) is engineered, with intermittent steps. The urban Teton Pines Stream had the highest AWSC of all.

Figure 1. (left) Longitudinal profiles and (right) plan views of channel thalwegs from experimental reaches surveyed in 2004: (a) and (b) Teton Pines Stream, (c) and (d) Headquarters Stream, and (e) and (f) Two Ocean Creek. Northing and easting are relative to a local horizontal angle datum. Surveys represent only a portion of the entire experimental reach because of obstructions that limited line of sight.
streams, with a value of $1.9 \times 10^{-3} \text{ m}^{-1}$, while the reference Two Ocean Lake Creek had an AWSC value of $0.71 \times 10^{-3} \text{ m}^{-1}$ (Table 1).

4.2. Stream Tracer Experiments and Simulations

[21] Observed RWT stream BTCs were simulated with both power law and exponential RTDs. For clarity, only the best fit simulated RTD, as determined by a comparison of RMSE values for optimized simulations, for each observed BTC, is presented in Figure 2. For the agricultural streams, Giltner Spring Stream BTC was best simulated by an exponential RTD, and a power law RTD for Headquarters Stream. Both urban streams BTCs were best fit by exponential RTDs, and both reference stream BTCs were best simulated by power law RTDs (Table 2 and Figure 2).
simulation fits to observed data were quite good, as evidenced by all RMSE values being 0.25 or less. Optimized values of model parameters allowed for some comparison among the three reach types. The streams with exponential RTD dynamics had the lowest $\beta_{tot}$ values (<0.4) and the lowest $t_{stor}$ values (<0.70 hour), and those displaying power law behavior had higher $\beta_{tot}$ values (>0.5), and longer $t_{stor}$ values (>0.90 hour) (Table 2). Among the exponential RTD reaches, there was no clear pattern of $\alpha$ values, as the Giltner Stream $\alpha$ value ($4.96 \times 10^{-4}$ s$^{-1}$) was between the two urban stream $\alpha$ values (Table 2). Similarly, among the power law RTD reaches, the Headquarters Stream $k$ value (1.87) was between those of the two reference streams (Table 2). These results suggest that the urban streams and Giltner Spring Stream (agricultural) had the least complex transient storage dynamics, while those BTCs best simulated with a power law RTD demonstrated a greater range of transient storage zone residence times.

As a separate comparative assessment of the transient storage dynamics among these reaches, we plotted the observed RWT BTCs relative to $t_{adv}$, which we take to be the time of the peak concentration of the BTC (Figure 3). This allows for the explicit comparison of time of travel for the entire BTC to the advection timescale. Regardless of whether transient storage occurred in the channel or in the hyporheic zone, transient storage is interpreted as a timescale of transport separate from advection and dispersion. The two urban streams had the lowest transient storage, compared to the advection timescales as RWT BTCs flushed through in less than $5t_{adv}$ (Figure 3). Reference streams had the highest transient storage in both years, with BTCs that took as long as 20$t_{adv}$ to move through them, and agricultural reaches fell in between (6–7$t_{adv}$) (Figure 3). These results do not agree perfectly with the reach-type comparison of $t_{stor}$, however, this is likely because Giltner Spring Stream has the slowest stream velocity of the six reaches (Table 2). However, as a normalized comparison to advection, the timescales of transport in the urban streams were shorter, with less transient storage, than agricultural and reference streams.

Table 2. Optimized Simulation Results of Stream Tracer Experiments

<table>
<thead>
<tr>
<th>Stream Reach</th>
<th>BTC Type</th>
<th>$Q$, L s$^{-1}$</th>
<th>$\beta_{tot}$ $^b$</th>
<th>$k^b$ or $\alpha$ (s$^{-1}$)</th>
<th>$v$, m s$^{-1}$</th>
<th>$D$, m$^2$ s$^{-1}$</th>
<th>$\phi^b$</th>
<th>$t_{stor}$, hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jackson Hole Golf Stream</td>
<td>exponential</td>
<td>97.4</td>
<td>0.38 (0.007)</td>
<td>$9.29 \times 10^{-3}$ 6 $\times 10^{-5}$</td>
<td>0.26 (0.001)</td>
<td>0.01 (0.09)</td>
<td>0.57 (0.01)</td>
<td>0.03</td>
</tr>
<tr>
<td>Teton Pines Stream (u)</td>
<td>exponential</td>
<td>10.0</td>
<td>0.24 (0.009)</td>
<td>$4.36 \times 10^{-4}$ 2 $\times 10^{-7}$</td>
<td>0.05 (0.002)</td>
<td>0.20 (0.006)</td>
<td>1.84 (0.004)</td>
<td>0.64</td>
</tr>
<tr>
<td>Giltner Spring Stream</td>
<td>exponential</td>
<td>236.2</td>
<td>0.18 (0.01)</td>
<td>$4.96 \times 10^{-4}$ 2 $\times 10^{-7}$</td>
<td>0.17 (0.002)</td>
<td>1.24 (0.008)</td>
<td>1.07 (0.008)</td>
<td>0.56</td>
</tr>
<tr>
<td>Headquarters Stream (a)</td>
<td>power law</td>
<td>161.8</td>
<td>23.8 (0.07)</td>
<td>1.87 (0.002)</td>
<td>0.26 (0.002)</td>
<td>0.67 (0.01)</td>
<td>1.04 (0.04)</td>
<td>0.97</td>
</tr>
<tr>
<td>Ditch Creek (r)</td>
<td>power law</td>
<td>59.3</td>
<td>0.55 (0.04)</td>
<td>1.74 (0.002)</td>
<td>0.17 (0.004)</td>
<td>0.27 (0.01)</td>
<td>1.21 (0.01)</td>
<td>1.80</td>
</tr>
<tr>
<td>Two Ocean Creek (r)</td>
<td>power law</td>
<td>64.4</td>
<td>25.6 (0.01)</td>
<td>1.89 (&lt;0.001)</td>
<td>0.68 (0.007)</td>
<td>0.38 (0.02)</td>
<td>1.00 (&lt;0.001)</td>
<td>1.84</td>
</tr>
</tbody>
</table>

$^a$Standard errors of the optimized values are noted in parentheses. Abbreviations are $a$, agricultural stream; $u$, urban stream; and $r$, reference stream. $^b$Parameters $\beta_{tot}$, $k$, and $\phi$ are unitless.

[23] We attempted to link each geomorphic characteristic ($S$, $s$, mean substrate size, $e$, $\chi$, AWSC) to each transient storage characteristic ($\beta_{tot}$, $\alpha$, $k$, and $t_{stor}$), and there were significant relationships (for $p < 0.10$) between $s$ and $t_{stor}$ (Figure 4a), and $\chi$ and $t_{stor}$ (Figure 4b). Though constrained by only 3 power law BTC fits, the lowest observed $k$ (1.74) at Ditch Creek corresponded to the highest mean substrate size (98.8 mm ± 27.5 mm, Table 1). From these analyses, $s$ explained 54% of the variance in $t_{stor}$ in all six reaches, and

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![Figure 3](image-url)

**Figure 3.** RWT stream tracer breakthrough curves normalized to time of advective transport ($t_{adv}$), taken to be the time of the peak tracer concentration, for streams studied in (a) 2003 and (b) 2004. Data have been culled for clarity.
the geomorphic complexity metric $\chi$ explained 59% of the variance in $t_{stor}$.

5. Discussion

[24] Geomorphic structure of streams strongly controls hyporheic exchange patterns and fluxes [Harvey and Bengala, 1993; Kasahara and Wondzell, 2003; Cardenas et al., 2004; Gooseff et al., 2006]. One conclusion from this growing body of literature is that streams with more complex geomorphic architecture are likely to have enhanced hyporheic exchange, depending on streamed hydraulic conductivity characteristics. Furthermore, streams with complex planforms are also likely to accommodate more in-channel dead zone storage. Thus it is expected that geomorphically simplified streams, whether they are of anthropogenic origin (e.g., Teton Pines Stream) or natural streams that have been specifically managed to efficiently move irrigation return flows off of pastures (our agricultural streams), are less likely to provide transient storage to stream solutes compared to reference streams. One potential consequence of reduced transient storage (as hydraulic retention) in streams is the reduction of the buffering capacity of streams to alter stream dissolved nutrient loads, assuming storage is linked to nutrient uptake.

[25] The geomorphic metrics used to assess complexity of channel structure in this study did not show a clear ranking of complexity among the reach types. However, if only slope $S$ and sinuosity $s$ were considered as the driving components that influence head gradients between the stream and near stream subsurface environments, then the reference streams were the most complex with the largest $S$ and largest average $s$ values, compared to the urban and agricultural streams. Despite the fact that these urban streams represent simplified channels, but not necessarily urban streams that are degraded from a reference state because of urban pressures, these urban streams were the least sinuous of the six reaches studied, and also had low slopes similar to those of the agricultural streams, suggesting that they were the least complex. With regard to dead zone storage, $\varepsilon$ and channel width variation were the factors that we predicted would be most influential. Thus the agricultural reaches had the highest likelihood potential for dead zone storage with the highest channel width variation and wide ranging $\varepsilon$ values; the urban reaches were intermediate, displaying the most consistent widths (smallest channel width variations) and had intermediate $\varepsilon$ values; and the reference streams were the least likely to have significant dead zone storage with intermediate channel width variability and intermediate $\varepsilon$ values (Table 1). We recognize that this evaluation does not account for compound dead zone and hyporheic storage dynamics within a reach. However, these comparisons of geomorphic characteristics may assist us in interpreting the dominant transient storage mechanisms reflected in the relative BTCs of Figure 3. Reference stream reaches were likely dominated by hyporheic transient storage with some dead zone storage. Agricultural stream BTCs likely represented a larger proportion of dead zone storage and appreciable, but less, hyporheic exchange. Urban reaches, with short total breakthrough times, confined channels, and in the case of Teton Pines Stream, a cement-lined channel (at depth), more likely reflected a dominance of dead zone storage with little or no hyporheic exchange. This is a consequence of the anthropogenic factors constraining urban reaches, namely substrate and channel planform designs.

[26] Our findings suggest that there is little transient storage occurring in the urban reaches, the most heavily anthropogenically impacted or managed streams in this study. This finding is not in agreement with those of Salehin et al. [2003] who noted an increase in transient storage due to reduced hydraulic conductivity of bed material, compared to reference reaches. Together, though, these results and those of Salehin et al. [2003] suggest that the anthropogenic or management practices that impact urban streams result in potentially varied transient storage responses. Twin Pines Stream, which was lined at depth, will have minimal potential for transient storage, whereas Golf Stream had a more natural bed material, but also showed minimal transient storage, compared to the more geomorphically com-

Figure 4. Relationships between (a) sinuosity ($s$) and (b) geomorphic complexity ($\chi$) to mean storage residence time for all six reaches. Abbreviations are GSS, Giltnner Spring Stream; HQS, Headquarters Stream; Golf, Jackson Hole Golf Stream; TPS, Teton Pines Stream; DC, Ditch Creek, and TOC, Two Ocean Creek. Coefficient of determination ($R^2$) and the significance index ($p$) are noted on each plot.
plex channels in the study. Both Groffman et al. [2005] and Grimm et al. [2005] have suggested that channel complexity is important in driving nutrient retention in urban streams. The urban stream reaches studied here were the least geomorphically complex of the six study reaches, and transient storage was minimal. If we presume that nutrient retention is positively correlated to transient storage, then we would expect these reaches to be less retentive of nutrients than the agricultural and reference reaches.

27 Previous studies that have attempted to link reach morphology to transient storage dynamics have sometimes failed to show that the stream tracer approach is sensitive enough to detect these differences [e.g., Gooseff et al., 2003]. Yet the stream tracer approach has proven useful to compare tracer dynamics in reaches of drastically different reach morphology, such as bedrock versus alluvial reaches [Gooseff et al., 2005]. Group by group, the reaches studied here are found in land use types that are common, though the reaches do not represent the entire range of morphologies within each group. Our small sample size limits our ability to generalize about streams in each land use type, though the range of these reaches does provide a wide range of channel complexity conditions and transient storage responses (Figure 3). More importantly, these six streams represent a greater range of channel complexity than is considered by focusing on streams of a single land use setting.

28 Comparison of stream solute travel times to mean advection time ($t_{adv}$) was useful in assessing comparative transient storage processes among reaches, which are, by definition, a longer timescale of transport. Reduced transient storage, identified by this approach, was confirmed by stream solute transport modeling, which suggested that shorter total residence time reaches, relative to $t_{adv}$, also had generally shorter mean storage residence times (Figure 3 and Table 2).

29 The BTC of Headquarters Stream showed some atypical behavior at very late time (Figure 2d), with a sudden increase in slope, which appears to be more accentuated in Figure 3b. This is likely either an indication of a separate timescale of transport, which appears to suddenly increase, or, possibly, a result of a stark change in the weather. At approximately the same time of the field tracer experiment, a storm moved through the area, reducing the air temperature and light reaching the stream. Little rain fell in the immediate catchment. Continued measurement of stream discharge did not show an appreciable increase after the start of the storm. Thus there was potentially a change to the stream tracer (a fluorescent dye) property or detection.

30 For the BTCs best characterized by power law behavior, a relationship between $k$, the slope of the late time BTC in logC vs logt space, and mean substrate size was largely driven by Ditch Creek (reference stream) being very different than Two Oceans Lake Creek and Headquarters Stream, and was not significant because of low statistical power ($n = 3$). However, the relationship was expected because the power law behavior of the solute transport, which we interpreted as an indication of greater hyporheic exchange, was more likely to be dependent upon mean substrate size, as a surrogate for hydraulic conductivity of the bed materials. Thus we interpret the negative relationship to suggest that higher $k$ values are likely associated with finer sediments because of reduced hyporheic penetration, whereas larger substrate allows for potentially longer hyporheic flow paths to develop. Of course, this explanation is somewhat speculative with only surface substrate characterizations.

31 We assumed that longer $t_{stor}$ values and temporally longer residence times of stream tracers were indicative of stream hyporheic exchange, and that the relationship of $t_{stor}$ to $s$ suggested that hyporheic flow paths cutting through meander bends were responsible for some hyporheic exchange. The minor increase in explanation of variability in $t_{stor}$ from 54% when regressed against $s$ to 59% when regressed against $\chi$, suggests that $s$ largely controls computed $\chi$ values. Furthermore, there was no statistically significant relationship found between $t_{adv}$ (as $v$) and $t_{stor}$, which suggests that although roughness elements (s) or slope may influence advection and transient storage, they do so independently.

32 The methods used in this study did not allow us to distinguish between in-channel and subsurface, hyporheic transient storage. However, it is likely that the long BTC tails observed in the reference reaches result from hyporheic exchange. Teton Pines Stream has no hyporheic zone, and therefore its transient storage is completely due to in-channel, dead zone storage. Thus dead zone storage accounts for $\geq$4 times the timescale of advective transport. We contend that streambed form directly influences both in-channel transient storage, increasing with increasing sizes of pools, side channels, etc. [e.g., Gooseff et al., 2005], and hyporheic transient storage by dictating the spatial pattern of stream-subsurface head gradients [e.g., Harvey and Bengala, 1993; Kasahara and Wondzell, 2003]. It is also possible that the late-time drop off of the RWT concentrations through time in the agricultural stream reaches (Figure 3) may be due to a change in transient storage type, from in-channel dead zone to hyporheic. However, the steeper slope of the BTC after these transitions would suggest that hyporheic transient storage had a faster flushing dynamic than dead zone storage, which is counter to previous findings of in-channel versus hyporheic transient storage [Gooseff et al., 2005]. Our results from six independent dye-injection experiments support the notion that channel complexity impacts transient storage processes in streams. Furthermore, reduced channel complexity was noted in channels that existed in lands that had been anthropogenically impacted. Reduced transient storage volumes and times are likely to reduce potential for biogeochemical processing in streams with simplified channels [Hall and Tank, 2003].

6. Conclusions

33 We investigated the influence of stream channel complexity on stream transient storage, in streams in a range of land use settings. Geomorphic assessment of urban, agricultural, and reference (natural setting) stream reaches showed that channels increase in geomorphic complexity from urban to agricultural to reference settings. Streambed substrate size in urban streams was largely dictated by anthropogenic design, but for streams in natural settings, reaches had larger substrate than agricultural streams. Urban streams were narrowest, whereas reference streams were intermediate, and agricultural streams were the widest (to
maintain irrigation return flows). Streams in both agricultural and urbanized settings showed significantly shorter transient storage residence times than reference streams. Thus we conclude that over a substantial variety of stream settings, channel complexity can affect transient storage processes, potentially as a function of the surrounding land use. The impacts of land use on stream transient storage function are important because of the associated potential for reduced biogeochemical cycling in streams that run through anthropogenically altered landscapes, though it is also possible that variability in related stream ecosystem response (i.e., primary production and benthic organic matter) in each of these stream types may be more important factors affecting biogeochemical cycling.

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