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Influences of sudden changes in discharge and physical stream characteristics on transient storage and nitrate uptake in an urban stream

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Abstract:

Changes in the physical structure of urban streams can occur abruptly due to flashy high-flow events and subsequently alter stream processes, including transient storage and nitrate uptake. We examined temporal variability in transient storage and nitrate uptake by exploring the effects of altered physical characteristics resulting from a single high-flow event in three reaches of Spring Creek, an urban stream in Fort Collins, Colorado, USA. Study reaches of varying geomorphic and hydraulic characteristics were chosen to represent distinct geomorphic settings in terms of substrate size, sinuosity, bed slope, and degree of rehabilitation and structural controls. We performed detailed physical characterizations and multiple nutrient injections of Br^- and NO_3^- to estimate transient storage and nitrate uptake in each reach. A comparison of pre-flood and post-flood data indicates that transient storage and nitrate uptake are highly context specific and mediated by interactions between geomorphic setting and flood discharge. In the two reaches that showed significant post-flood increases in transient storage (250% to 350% increases in $F_{med}{}^{200}$), the pool-riffle reach exhibited a significant increase in uptake velocity, while the channelized reach did not. In contrast, transient storage decreased post-flood in the third reach containing hydraulic structures. These complex responses likely reflect reach-specific differences in hyporheic versus in-channel storage. This study shows that repeat injections are necessary to describe nutrient dynamics because transient storage and nitrate uptake can be highly variable over time (showing changes on the order of 100%) due to variation in discharge and geomorphically influential flow events.
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KEY WORDS ecohydraulics; nitrate uptake; transient storage; flashy urban stream; solute transport modelling

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BACKGROUND

Human alteration of landscapes through urban development influences the ecological functions of streams through hydrologic modifications, nutrient enrichment, sedimentation, clearing of riparian vegetation, nonpoint input of pollutants and other factors (Poff *et al.,* 1997; Allan, 2004). Anthropogenic land-use changes associated with urbanization can decrease the geomorphic complexity of streams (Booth and Henshaw, 2001; Jacobson *et al.,* 2001), thereby potentially reducing transient storage and biogeochemical cycling (Gooseff *et al.*, 2007). Urbanization can also dramatically alter flow regimes (Roesner *et al.*, 2001), and typically leads to increased magnitude and frequency of moderate to high discharges and increased flashiness, or flow magnitude rate of change (Poff *et al.,* 2006). In relating flashy flow regimes to nutrient transport, Konrad and Booth (2005) showed that the movement of organic matter and nutrients in flashy flow regimes with high storm discharges mainly occurs in brief periods of rapid movement with limited retention. Urban streams often have both flashier hydrographs and elevated levels of nutrients, as well as reduced efficiency of nutrient retention (Walsh *et al.,* 2005). At the same time, elevated nitrogen inputs can markedly affect patterns of seasonal and storm-related nitrate loading from the landscape into streams (Poor and McDonnell, 2007) and increase the risk of eutrophication in downstream water bodies (Peterson *et al.,* 2001).

Quantifying nitrate uptake rates in natural systems is complex due to coupled processes of biogeochemical reactions, which are influenced by microbial communities, organic carbon content and hyporheic exchange as affected by discharge and substrate characteristics (O'Connor and Harvey, 2008). Retention of water and solutes through hyporheic exchange can be a primary control on nutrient uptake and biogeochemical processes

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in streams, which further impacts solute dynamics (Bencala, 2005). As denitrification is a major biogeochemical process occurring in the hyporheic zone that removes nitrate from stream systems, promoting hydraulic connectivity between surface water and groundwater through the hyporheic zone increases the potential for biogeochemical processing of nitrogen (Hester and Gooseff, 2010). Variations in streambed topography (e.g. riffle-pool sequences) and in physical characteristics of the streambed (e.g. bed material size and mobility) promote exchange between surface water and hyporheic zone, thereby affecting solute retention and transport (Harvey and Bencala, 1993; Tonina and Buffington, 2009). Although bedforms such as riffle-pool sequences can promote hyporheic exchange, fine sediment can clog the interstices of gravels and cobbles in riffles and reduce exchange through the streambed (Kasahara and Hill, 2006). Hence, there is a complex interplay between substrate topography and permeability that controls the exchange of solutes in the hyporheic zone (Packman and Salehin, 2003).

Additionally, increases in nitrate concentrations and discharge can decrease nitrate removal efficiency (Alexander *et al.,* 2009). During these high discharges, streambeds are flushed of fine benthic organic matter (FBOM), which is associated with higher rates of nutrient uptake (Meyer *et al.,* 2005). Because high discharges can reconfigure substrate material and flush streambeds of algal biomass, hyporheic exchange can substantially influence nutrient uptake shortly after high-flow events (Orr *et al.,* 2009). As time passes after major flow events and algal biomass accumulates on streambeds, bed permeability decreases and nutrient uptake shifts from being limited by physical controls (hyporheic exchange) to biological controls (benthic interactions) (Orr *et al.,* 2009).

Because many nutrient cycling studies are conducted under base-flow conditions (e.g. Brookshire *et al.,* 2009; Stanhope *et al.,* 2009), the effects of hydrologic variability and geomorphically effective flow events on nutrient uptake are not yet well-understood. Conducting nutrient enrichment studies as individual injections under base-flow conditions is not adequate to fully characterize nutrient dynamics (i.e. provides information about conditions that represent only a snapshot in time and is subject to timing of the study among varying hydrologic conditions within a site and across sites). In contrast to the preponderance of nutrient uptake studies performed at a single discharge near base flow, Doyle (2005) and Doyle *et al.* (2005) included hydrologic variability in nutrient uptake modelling to posit an effective discharge responsible for the largest quantity of nutrient retention over time. However, this approach assumed a monotonic relationship between discharge and nitrate uptake and did not attempt to resolve temporal variation in geomorphic and biotic influences on nutrient uptake.

Although previous studies have explored nitrate uptake in urban streams (Meyer *et al.,* 2005; Walsh *et al.,* 2005), examining the effects of high-flow events on transient storage and nutrient uptake in streams is not always emphasized. Notable exceptions include a study that investigated the effects of a flood on channel morphology and hyporheic zones in mountain streams, where locations of upwelling and downwelling zones were altered by flood-induced channel change (Wondzell and Swanson, 1999), as well as a study that found changes in nitrate retention in a desert stream after a flood and attributed temporal changes in nitrate uptake to changes algal biomass (Marti *et al.*, 1997). Additional studies that investigated transient storage over time with changes in discharge (Morrice *et al.*, 1997; Hall *et al*., 2002) showed that discharge influences transient storage and nutrient uptake. Such studies underscore that nutrient uptake is a complex process mediated by dynamic processes, including both natural and human-induced changes to channel substrate and morphology as well as varying biogeochemical conditions. Accordingly, nutrient uptake in streams is likely to exhibit a complex response to variation in discharges that can alter the physical template of a stream.

In this study, we explored temporal variation in transient storage and nitrate uptake in an urban stream by comparing data collected from physical measurements and nutrient injections performed immediately before and after a flash flood in three distinct geomorphic settings. We hypothesized that increases in substrate size and removal of interstitial fine sediment and organic matter due to the flashy high-flow event would lead to greater potential for hyporheic exchange, increases in transient storage, and possibly enhanced nitrate uptake. Furthermore, we anticipated that responses to the flash flood would differ among a 'naturalized' (*sensu* Rhoads *et al.,* 1999) pool-riffle reach, a structurally stabilized reach and a channelized plane bed reach due to variations in geomorphic setting.

METHODOLOGY

We selected three reaches of varying geomorphic and hydraulic characteristics in Spring Creek (Figures 1 and 2), an urban stream in Fort Collins, Colorado, USA, to investigate changes in physical characteristics, transient storage and nitrate uptake due to a geomorphically effective high-flow event. On 2 August 2007, a summer convective storm dropped 5–6 inches of precipitation in the 9 mi^2 watershed resulting in a peak discharge of 30 m^3/s (approx a 10-year event) (Anderson Consulting Engineers, Inc., 2008). Just days prior to the flash flood, physical characterizations and nutrient injections were completed on the three study reaches of Spring Creek. Following the storm event, physical changes were visually

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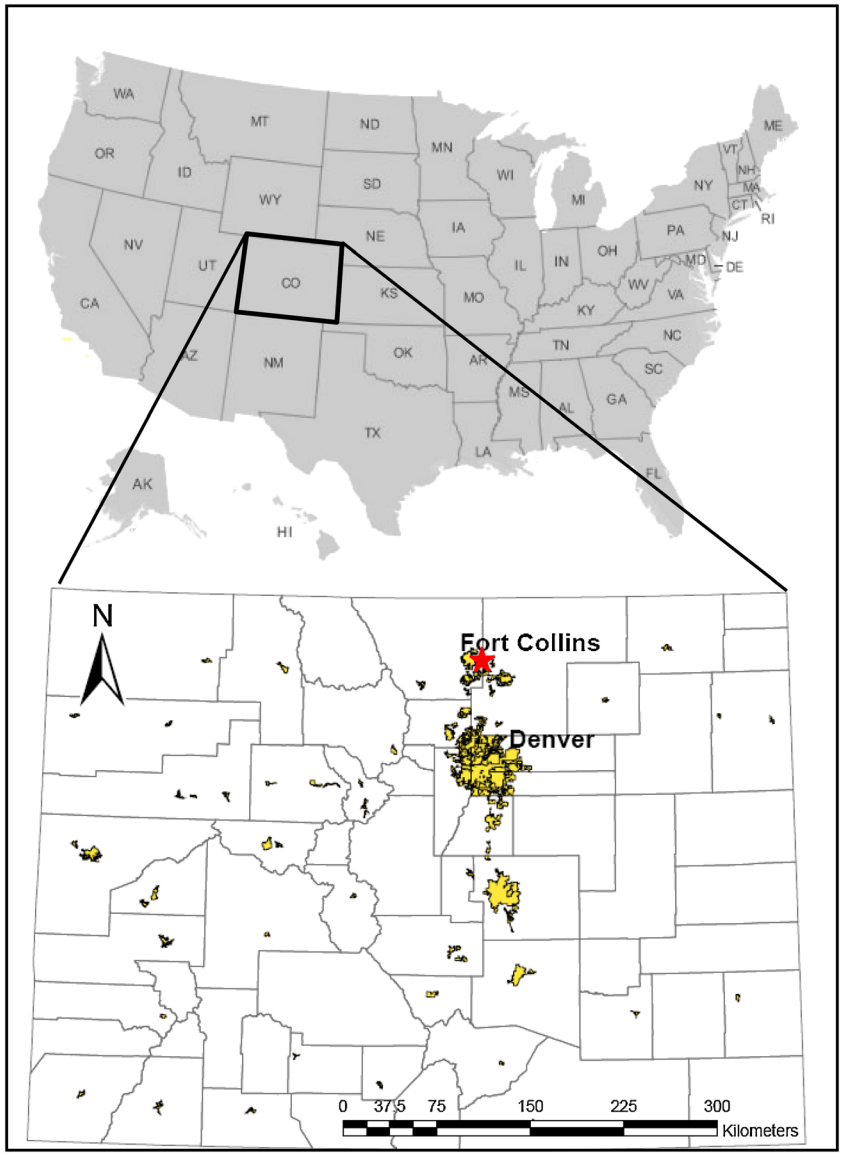

Figure 1. Location of Spring Creek

observed in the reaches, including coarser substrates and bank failures. Another set of physical characterizations and nutrient injections was performed on each study reach within 4 to 6 days of the flash flood to explore the extent of physical changes caused by the sudden increases in discharge and how they influence transient storage and nitrate uptake. A third set of physical characterizations and nutrient injections was performed on each study reach at the end of July 2008, nearly one year after the flash flood, to examine whether stream characteristics and behaviour returned to pre-flood conditions or remained similar to post-flood conditions. During the one year period between the flash flood and the third set of data collection, no other substrate mobilizing flow event of magnitude similar to the 2 August 2007 storm occurred along Spring Creek.

Site selection

Spring Creek is one of the primary stormwater drainages within Fort Collins (see star in Figure 1). The discharge in Spring Creek is regulated by stormwater retention facilities yet retains a flashy flow regime. Due to flooding history and urban encroachment, several sections of the stream have undergone channelization, bank and bed stabilization, and alteration of riparian vegetation. Other reaches are more 'naturalized' (*sensu* Rhoads *et al.,* 1999) and have connected floodplains with patches of riparian forest, and lack conspicuous channel armoring features. The chosen reaches along Spring Creek (Figure 2) vary substantially in their overall physical characteristics and exhibit various styles of management that provide a range of geomorphic complexity and

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(a) Edora Park

(b) Stuart

(c) Railroad

Figure 2. Photos of study reaches along Spring Creek contrasting the geomorphic setting in each reach: (a) naturalized pool-riffle reach at Edora Park that is located in a city park and has reduced woody riparian vegetation due to lawn maintenance and mowing close to the stream banks, most sinuous with median gradient and grain size of the three reaches; (b) structurally stabilized reach at Stuart that is highly modified with grouted bank stabilization and grade-control structures, median sinuosity with highest gradient and grain size of the three reaches; and (c) channelized plane bed reach at Railroad that is highly modified through straightening and channelization and has banks covered with dense, tall grasses, least sinuous with lowest gradient and grain size of the three reaches

potential influences on nitrate uptake. The study reaches are characterized based upon their geomorphic setting as a naturalized pool-riffle reach (Edora Park), a structurally stabilized reach (Stuart) and a channelized plane bed reach (Railroad). Each approx 180 m reach was divided by 21 equally spaced transects, positioned perpendicular to the flow, for the purpose of cross-sectional channel geometry surveys and physical characterization (see Section 2.4).

Nutrient injections

The protocol for nutrient injection and sample collection was developed to provide the data needed for modelling both transient storage and nitrate uptake (Baker *et al.,* 2012). We prepared an injection solution of a conservative tracer, sodium bromide (NaBr) and a reactive solute, potassium nitrate (KNO_3). We selected injection concentrations to elevate the background concentration of NO_3^--N by a factor of four and to elevate the background concentration of Br^-, assumed to be negligible in the study reaches, to 2–3 mg/L. Pump injection rates were calibrated to the discharge on the day of injection, as measured at two cross sections using the velocity-area method (Harrelson *et al.,* 1994).

Prior to injection, we collected water samples for background NO_3^--N and Br^- concentrations at the upstream end (T1), middle (T11) and downstream end (T21) of each reach. All aqueous samples were collected with a syringe, filtered (0.7 μm) in the field and stored on ice. We injected the KNO_3 and NaBr solution as a 60 min steady-rate input into the stream in a turbulent mixing zone approximately 20 m upstream of each reach. Samples were collected at 3 min intervals at T21 for downstream breakthrough curves (BTCs) of NO_3^--N and Br^-. Sample collection began 10 min before the injection started and continued for 1 h and 50 min after the injection stopped, totaling 3 h of sample collection, to obtain the background, rising limb, plateau and tail of the BTCs. The 20 ml BTC samples were collected in the same manner as background samples. All water samples collected were analysed by Stewart Environmental Consultants, Inc. (Fort Collins, CO). Concentration in mg/L NO_3^-–N and Br^- were analysed using U. S. Environmental Protection Agency (EPA) Method 300.0 on an ion chromatograph (Pfaff, 1993). The method detection limit (MDL) is 0.1 mg/L. Any samples with concentrations less than the MDL were reported as 'Not Detected'. Duplicates were collected and analysed on a frequency of approximately one duplicate in every thirteen samples for quality assurance.

Benthic organic matter collection

Benthic organic matter (BOM), a source of carbon and energy for nitrogen-processing microbial communities, was measured on the day of injection. Six to ten BOM samples per reach were collected at transects corresponding to the areal distribution of habitat units (see Section 2.4). Samples were divided between fine BOM (FBOM; <0.5 mm) and coarse BOM (CBOM; >0.5 mm) and collected in a manner adapted from Golladay *et al.* (1989) using a cylinder driven into the stream bed and agitating the substrate within the cylinder for collection. FBOM was microfiltered in accordance with Wallace *et al.* (2007), and all BOM samples were dried, weighed and incinerated following Steinman *et al.* (2007) for ash free dry mass (AFDM) content.

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Physical characterization

Physical habitat units. We classified each reach into repeating sets of habitat units to visually characterize its physical condition. Channel types were assigned following Montgomery and Buffington (1997), with further descriptions of channel modifications, such as drop structures, toe protection and bank stabilization. Subreaches were classified by specific habitat units, including distinct combinations of geomorphic unit (Hawkins *et al.,* 1993), sediment classification and substrate condition, to characterize spatial heterogeneity or patchiness (Pringle *et al.,* 1988; Cooper *et al.,* 1997).

Substrate distribution. Pebble counts (Bunte and Abt, 2001a) were performed at each transect. A sampling grid frame was used for clast selection to reduce selection bias (Bunte and Abt, 2001a). Pebble counts were distributed by physical habitat unit, with 100 clasts required for each unit and a minimum of 300 clasts for the entire reach. Bed substrate distribution was described as percent fines, d_{16}, d_{50} and d_{84} (Bunte and Abt, 2001b).

Channel geometry survey. Longitudinal profile and cross-section surveys at each transect were performed to characterize reach geometry. To measure cross-sectional area, survey points were taken at least every 0.5 m across each transect. Additionally, intermediate points of the thalweg and the left and right edges of water were surveyed between each transect at least at 3 m intervals to characterize any breaks in slope, meanders, contractions or expansions.

Modelling transient storage and nitrate uptake

The One-dimensional Transport with Inflow and Storage (OTIS) model was used to model the shape of the BTC to estimate parameters describing transient storage and nitrate uptake (Runkel, 1998). We operated OTIS through a universal inverse modelling code (UCODE), using nonlinear regression for optimizing parameter estimates (Poeter and Hill, 1999). Using the OTIS-UCODE models to parameterize transient storage and nutrient uptake is a two phase operation (Scott *et al.,* 2003). First, we modelled transient storage using the BTCs of the conservative tracer, Br^-. The upstream boundary condition was set at the injection point, based on the pump start and stop times and the actual in-stream concentration (normalized by background levels), as calculated from a mass balance of discharge measured on the injection day, actual pump flow rate and concentration of the solutes in the injection solution. The continuous field data of the downstream BTC were filtered using a three-point moving median filter (Tukey, 1977) to remove outliers. Output data from OTIS include parameter estimates of main channel area (A), area of storage zone (A_s), dispersion (D) and storage zone exchange coefficient (α), which were optimized in UCODE (Poeter *et al.,* 2005). These parameters were used with average velocity (u) and reach length (L) to calculate the fraction of median travel time along the reach due to exchange with storage, F_{med} (Runkel, 2002):

$$F_{\text{med}} = \left(1 - e^{-L\frac{\alpha}{u}}\right)\frac{A_S}{A + A_S} \tag{1}$$

By normalizing to a reach length of 200 m, ${F_{\text{med}}}^{200}$ can be calculated as a way to compare reaches of various lengths. The ratio A_s/A normalizes the size of the storage zone to allow for comparisons of water and solute retention in streams (Morrice *et al.,* 1997).

Next, building upon the estimated transient storage parameters, we modelled uptake using the BTCs of the reactive solute, NO_3^-. Output from this simulation yielded first-order uptake coefficients of the main channel (λ) and storage zone (λ_s). Uptake velocity (v_f) was then calculated as $v_f = \lambda h$, where h = average flow depth (Stream Solute Workshop, 1990; Runkel, 2007). A measure of uptake length (S_w), based upon the mean distance that a nutrient atom travels in a stream before uptake by biota (Newbold *et al.,* 1981), was calculated as $S_w = \frac{u}{\lambda}$ (Stream Solute Workshop, 1990; Runkel, 2007).

Monte Carlo simulations were also performed to investigate the compounded uncertainty when estimates of A, A_s, D, α, λ and λ_s were used to calculate the parameters A_s/A, ${F_{\text{med}}}^{200}$, S_w and v_f (Hanafi *et al.,* 2007). Using UCODE output statistics to define an assumed normal distribution, ranges of values for each output parameter were then obtained through 1000 calculated iterations. The Monte Carlo simulations were used to estimate mean values, standard deviations, quartiles, and 10$^{\text{th}}$ and 90$^{\text{th}}$ percentiles describing the range of values for each modelled and calculated parameter.

We developed a correlation matrix, including all parameters of physical characteristics, transient storage and nitrate uptake, to assess whether storage and uptake parameters are more closely related to discharge measurements or physical stream characteristics. Metrics describing flow (Table I), including unit discharge and unit stream power, were compared with transient storage parameters (${F_{\text{med}}}^{200}$ and A_s/A) and nitrate uptake parameters (v_f and S_w) for significant Pearson correlation coefficients ($p < 0.10$). In the same way, metrics describing physical stream morphology (Table I), including grain size, longitudinal roughness and cross-sectional area variability, were compared with transient storage and nitrate uptake parameters.

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Table I. Variables describing physical conditions of each reach

Variable	Equation	Reference
Unit discharge, q[a]	$q = Q/w$	Garcia (2008)
Unit stream power, ω[a,b]	$\omega = \gamma Q S_o / w$	Garcia (2008)
Longitudinal roughness, LR[c]	$LR = \frac{\left(\sum_{i=1}^{n} \left\lvert z_{\mathrm{obs},i} - z_{\mathrm{pred},i} \right\rvert\right)}{n}$	Gooseff *et al.* (2007)
Width variability, ε_w[d]	$\varepsilon_w = \frac{\left(\sum_{i=1}^{n} \left\lvert w_{\mathrm{avg}} - w_i \right\rvert\right)}{n}$	adapted from Baker *et al.* (2012)
Variability in cross-sectional area, ε_A[e]	$\varepsilon_A = \frac{\left(\sum_{i=1}^{n} \left\lvert A_{\mathrm{avg}} - A_i \right\rvert\right)}{n}$	adapted from Baker *et al.* (2012)
Gradation coefficient[f]	$\left[\frac{1}{2}\left(\frac{d_{84}}{d_{50}} + \frac{d_{50}}{d_{16}}\right)\right]$	Bunte and Abt (2001b)
Relative submergence[f,g]	R/d_{84}	Garcia (2008)

[a] Q = discharge; w = channel width
[b] γ = specific weight of water, S_o = bedslope
[c] Average residual between measured thalweg elevation at each point ($z_{\mathrm{obs},i}$) and predicted thalweg elevation based on bed slope ($z_{\mathrm{pred},i}$)
[d] Average residual between each measured wetted width (w_i) and average wetted width of the reach (w_{avg})
[e] Average residual between each measured cross-sectional area (A_i) and average cross-sectional area of the reach (A_{avg})
[f] d_{84} = 84th percentile bed sediment size; d_{50} = median bed sediment size; d_{16} = 16th percentile bed sediment size
[g] R = hydraulic radius

RESULTS

Post-flood responses in channel characteristics, transient storage and nutrient uptake were mediated by geomorphic setting and varied appreciably among reaches. Shortly after the storm, visual observations of changes in physical stream attributes were noted, including coarser substrates in all three reaches. Deposition was prominent downstream of the grade-control structure along Stuart, and bank failure was evident near the downstream end of the Edora Park reach (Figure 3). Due to the various geomorphic settings of the three study reaches, they exhibited differences in geomorphic complexity and ecological condition among the sampling intervals before, immediately after and one year after the flash flood (Table II). Consequently, mean values of transient storage and nitrate uptake parameter estimates followed varying patterns as well (Table III). To observe uncertainty in the parameter estimates and determine significance ($p < 0.10$) in changes among parameter estimates, we display transient storage and nitrate uptake parameter estimates visually as statistical ranges of values (Figures 4 and 5). In the following paragraphs, we first discuss comparisons of pre-flood to post-flood conditions, then conditions one year after the flood to pre-flood conditions and finally conditions one year after the flood to post-flood conditions. Changes that are noted as significant are based on $\alpha = 0.10$.

Analyses of the physical attributes from pre-flood to post-flood conditions showed that substrate size and variability in cross-sectional area increased, as percentage of fine sediment, relative submergence (based upon the discharge on the date of injection) and BOM decreased. Increases in cross-sectional area variability were likely due to the 25% to over 200% higher discharges among the reaches when data were collected for post-flood compared to pre-flood conditions. Longitudinal roughness, bed slope and sinuosity were not substantially altered by the high-flow event.

For Edora Park, median travel time due to transient storage was higher in post-flood compared to pre-flood conditions. The $F_{\mathrm{med}}{}^{200}$ parameter showed a significant increase of nearly threefold at Edora Park, which coincided with increased nitrate uptake, as shown in faster v_f (significant threefold increase). Conversely, Railroad showed no significant changes. Furthermore, Stuart demonstrated the opposite pattern of median travel time due to transient storage decreasing in post-flood conditions from pre-flood conditions with a significant decrease in $F_{\mathrm{med}}{}^{200}$ of nearly 70%. Nitrate uptake values at Stuart were inconclusive as both v_f and S_w increased in post-flood conditions compared to pre-flood conditions. The uptake coefficients (λ) of post-flood and pre-flood conditions at Stuart remained nearly constant, while the discharge more than doubled in post-flood compared to pre-flood conditions. Because v_f was calculated using flow depth, and S_w was calculated using flow velocity, both uptake variables increased with discharge in post-flood conditions. This shows that changes in discharge itself, not just physical attribute changes induced by the flood event, may be influencing changes in uptake.

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(a) Edora Park

(b) Stuart

Figure 3. The sudden increase in discharge in Spring Creek during the flash flood led to (a) geomorphic changes of bank erosion at Edora Park and (b) deposition below a grade-control structure at Stuart

Variability in the magnitude of change in transient storage and nitrate uptake among the three study sites demonstrate how the effects of discharge fluctuation are complex and relate to the geomorphic context of each site. When examining characteristics of the study reaches one year after the flood, the degree to which parameter values returned to pre-flood conditions was also variable among sites. Data collected one year after the flood at Edora Park showed a significant increase of greater than 260% in v_f and a significant decrease of nearly 80% in S_w, compared to pre-flood conditions. At Edora Park, the substrate remained coarser (decreases of % fines and increases of d_{50} and d_{84}) one year after the flood when compared to pre-flood conditions. Conversely, the substrate of Railroad returned to the finer grain sizes that were characteristic of the reach before the flash flood, and so no detectable changes in the percentage of fines and median grain size were observed. Data collected at Railroad one year after the flood showed a significant threefold increase in $F_{\text{med}}{}^{200}$, a significant decrease in v_f by an order of magnitude and a significant increase in S_w, compared to pre-flood conditions. Although the percentage of fines measured at Stuart one year after the flood was less than that measured during pre-flood conditions, d_{50} only showed a slight (2 mm) increase and d_{84} decreased from pre-flood conditions. Changes in transient storage and nitrate uptake one year after the flood compared to pre-flood conditions at Stuart were not significant.

When comparing conditions one year after the flood with post-flood conditions, the percent changes were substantially larger than in comparisons with pre-flood conditions. Edora Park showed an increase nitrate uptake with a significantly shorter S_w of nearly 70%. Conversely, Railroad showed a decrease in nitrate uptake, with significantly lower v_f of 90%, when comparing conditions one year after the flood to post-flood conditions. $F_{\text{med}}{}^{200}$ significantly increased by a factor of four at Stuart, while nitrate uptake results were inconclusive as both v_f and S_w decreased, around 30% and 20%, respectively, when comparing conditions one year after the flood to post-flood conditions. For BOM and percent fines, all three study reaches showed large increases one year after the flood compared to post-flood conditions (when values were relatively low) even though these values one year after the flood were not as markedly different from pre-flood conditions.

The physical characterizations of the reaches indicated differences in geomorphic complexity. Edora Park and Railroad have vegetated boundaries, as well as stagnant areas near the vegetated banks, which allow for more

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Table II. Summary of Spring Creek physical and ecological parameters

	Pre-flood: Edora Park 7-30-07	Post-flood: Edora Park 8-8-07	After 1 year: Edora Park 7-21-08	Pre-flood: Stuart 7-31-07	Post-flood: Stuart 8-9-07	After 1 year: Stuart 7-22-08	Pre-flood: Railroad 8-1-07	Post-flood: Railroad 8-8-07	After 1 year: Railroad 7-24-08
Reach length (m)	178	180	176	180	181	181	181	181	186
Discharge (L/s)	72	152	66	46	107	57	17	21	21
Unit discharge, q (m^2/s)	0.017	0.037	0.015	0.011	0.026	0.014	0.007	0.010	0.008
Ambient [NO_3^--N](mg/L)	0.74	0.71	0.64	0.72	0.66	0.64	1.07	1.60	0.93
Sinuosity	1.16	1.18	1.15	1.05	1.05	1.05	1.01	1.02	1.04
Bed slope, S_o	0.0046	0.0044	0.0050	0.0108	0.0108	0.0109	0.0025	0.0024	0.0024
Unit stream power, ω (W/m^2)	0.78	1.58	0.73	1.18	2.75	1.47	0.18	0.23	0.19
Longitudinal roughness (m)	0.13	0.13	0.14	0.11	0.10	0.12	0.05	0.04	0.05
Width variability (m)	1.0	1.13	1.20	0.96	0.83	0.86	0.45	0.48	0.62
XS area variability (m)	0.22	0.40	0.37	0.24	0.49	0.46	0.04	0.05	0.10
Percent fines (<2 mm)	34%	1%	9%	25%	0.4%	7%	75%	33%	75%
d_{16} (mm)	4	13	8	9	17	13	< 2	< 2	< 2
d_{50} (mm)	14	28	21	26	41	28	< 2	5	< 2
d_{84} (mm)	40	65	63	84	129	72	4	14	7
Gradation coefficient	3.1	2.3	2.8	3.1	2.8	2.4	1.7	2.9	2.6
Relative submergence, R/d_{84}	3.1	2.8	2.7	1.7	1.6	3.2	22.9	6.2	22.2
FBOM AFDM (g/m^2)	320	98	207	389	79	316	120	101	209
CBOM AFDM (g/m^2)	26	10	63	107	7	171	48	24	97

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changeable channel structure and greater changes in storage, while Stuart has bank stabilization throughout. Edora Park and Stuart each consisted of seven different physical habitat units, while Railroad consisted of one continuous habitat unit. Edora Park and Stuart have more longitudinal reach scale complexity, with varying substrate size and physical habitat units. Although Railroad had less longitudinal complexity (only one designated habitat unit), this did not always lead to less transient storage or nitrate uptake when compared to the more longitudinally diverse reaches of Edora Park and Stuart. The results at Railroad were strongly influenced by dense bank vegetation, a different type of physical complexity compared to Edora Park and Stuart. Vegetation encroachment into the channel at Railroad generated lateral variability and ineffective flow regions (in-channel storage) near the banks depending on protrusion and position of tall grasses standing upright versus flattened by high flows in post-flood conditions.

DISCUSSION

This study explored how high-flow spates could modify physical stream characteristics and associated nutrient uptake processes in a small urban stream spanning three geomorphic settings. Changes in transient storage and nitrate uptake in response to the flash flood and changes in discharge, as well as responses one year after the event, were not consistent among sites and appear to be strongly mediated by the unique geomorphic setting of each study reach. This indicates that temporal changes resulting from sudden increases in discharge, as often experienced in urban streams, can lead to distinct responses and fluctuations in transient storage and nitrate uptake over time. Although this spate was estimated as a 10-year event, such geomorphic changes can occur much more frequently, as shown in observations one year after the event, especially in fine-grained, labile channels. This finding supports the importance for future studies to monitor changes in transient storage and uptake over time because individual injections that represent a snapshot in time are not fully representative of nutrient dynamics in streams. Urban streams are also highly spatially variable (Chin and Gregory, 2005), as shown by distinct responses to the flood and differences in physical characteristics among the three reaches, which are in close proximity to each other along the stream. The most prominent changes that resulted from sudden high-flow conditions among all three study reaches was the flushing of fines and BOM, supporting previous findings (Meyer *et al.,* 2005; Orr *et al.,* 2009). This suggests that the factors controlling uptake vary with time, a further limitation of using individual injections to describe nutrient dynamics, as substrate conditions and biotic influences change after a disturbance such as high flows (Orr *et al.,* 2009). The results of this study extend this conceptual framework by underscoring the site-specific nature of bed material dynamics and biomass flushing and their dependence upon the particular geomorphic setting of a stream reach. After a disturbance, the starting point of biomass growth and decline of hyporheic exchange is a function of the antecedent interaction between discharge and substrate characteristics in a particular stream context, which demonstrates that the timing of individual injections affects the intersite and intrasite comparison of nutrient dynamics.

Due to natural and anthropogenic flow variation in the system, the nutrient injections were performed at different discharges, which also influence transient storage and nutrient uptake (Hall *et al.,* 2002). For Edora Park and Stuart reaches, the discharges during injections under post-flood conditions were more than twice as large as the discharges during injections at pre-flood conditions and during injections one year after the flash flood (Table II).

To examine the question of whether differences in transient storage and nitrate uptake parameters were likely due to flash flood-related morphological changes in the study reaches versus their dependence on varying discharge, we developed a correlation matrix of physical, storage and uptake parameters among all study reaches. This matrix revealed a significant inverse correlation between FBOM and the storage nitrate uptake coefficient ($r = -0.59$, $p = 0.09$). This relationship is plausibly due to FBOM clogging pore space in the streambed, reducing hyporheic exchange (Rehg *et al.,* 2005) and nitrate uptake in the storage zones of the channel. While statistical inferences in our study are limited by a small sample size ($n = 9$), the correlation supports the findings at Edora Park where nitrate uptake increased while FBOM was reduced following the flash flood. However, this finding is in contrast to Meyer *et al.* (2005), in which FBOM was directly related to uptake velocity. It is plausible that both changes in discharge and morphological conditions from the flash flood are driving factors for nutrient processing and transient storage along a reach. Future study should investigate the relative influence between the two and if the measured effects are more influenced by variation in discharge or morphological changes in pre-flood and post-flood conditions.

All three study reaches exhibited context-specific responses to the flash flood owing to inherently different geomorphic characteristics. Physical habitat complexity in Edora Park and Stuart are associated with both hydraulic and geomorphic heterogeneity. Although channelized and geomorphically homogeneous, Railroad is hydraulically complex due to bank vegetation encroachment that results in substantial ineffective flow areas. Increases in nitrate

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Table III. Summary of Spring Creek transient storage and nitrate uptake parameters

	Pre-flood: Edora Park 7-30-07	Post-flood: Edora Park 8-8-07	After 1 year: Edora Park 7-21-08	Pre-flood: Stuart 7-31-07	Post-flood: Stuart 8-9-07	After 1 year: Stuart 7-22-08	Pre-flood: Railroad 8-1-07	Post-flood: Railroad 8-8-07	After 1 year: Railroad 7-24-08
A (m^2)	0.54 (5.1E−03)	0.74 (2.9E−02)	0.49 (2.3E−01)	0.62 (4.2E−03)	0.91 (7.1E−03)	0.62 (4.4E−02)	0.15 (4.5E−03)	0.11 (4.8E−02)	0.20 (2.0E−03)
A_s (m^2)	0.08 (3.6E−03)	0.20 (2.6E−02)	0.12 (2.8E−01)	0.17 (2.8E−03)	0.14 (1.2E−02)	0.21 (4.6E−02)	0.04 (7.3E−03)	0.06 (3.6E−02)	0.05 (1.1E−03)
D (m^2/s)	0.44 (2.2E−02)	0.45 (2.1E−01)	0.67 (1.0E+00)	0.05 (7.7E−03)	0.27 (4.0E−02)	0.03 (7.3E−02)	0.49 (1.3E−01)	0.30 (2.1E+00)	0.08 (1.5E−02)
α (s^{-1})	1.6E−04 (8.4E−06)	5.9E−04 (2.1E−04)	8.3E−04 (2.8E−03)	7.1E−04 (6.0E−05)	3.3E−04 (1.8E−05)	6.1E−04 (3.8E−04)	1.6E−04 (4.6E−05)	2.1E−03 (1.1E−03)	8.1E−04 (1.2E−05)
λ (s^{-1})	3.2E−05 (4.1E−06)	6.5E−05 (1.1E−05)	9.1E−05 (3.0E−05)	4.4E−05 (8.8E−06)	4.3E−05 (2.2E−06)	2.6E−05 (4.3E−05)	1.1E−04 (7.8E−06)	1.3E−04 (3.7E−05)	6.3E−06 (1.9E−05)
λ_s (s^{-1})	2.3E−10 (4.7E−02)	7.0E−05 (2.2E−05)	6.8E−05 (1.2E−04)	6.0E−09 (9.2E−06)	7.7E−05 (4.3E−05)	−1.6E−04 (−1.1E−04)	7.4E−05 (8.7E−06)	2.6E−09 (2.8E−05)	−3.8E−05 (−7.0E−05)
A_s/A	0.15 (6.8E−03)	0.27 (3.5E−02)	0.25 (6.6E−01)	0.27 (4.8E−03)	0.16 (1.3E−02)	0.33 (7.9E−02)	0.29 (4.8E−02)	0.52 (1.7E+00)	0.27 (5.9E−03)
F_{med}^{200}	0.03 (1.6E−03)	0.09 (2.6E−02)	0.17 (4.1E−01)	0.18 (5.8E−03)	0.06 (4.6E−03)	0.22 (1.2E−01)	0.07 (2.1E−02)	0.33 (1.1E+00)	0.20 (3.5E−03)
S_w (m)	4,350 (700)	3,120 (510)	980 (360)	1,740 (430)	2,950 (150)	2,300 (2200)	700 (51)	920 (430)	8,190 (54,000)
v_f (m/s)	4.7E−06 (6.4E−07)	1.4E−05 (2.2E−6)	1.7E−05 (5.6E−06)	7.9E−06 (1.6E−06)	1.1E−05 (5.3E−07)	7.1E−06 (1.1E−05)	1.3E−05 (9.2E−07)	1.3E−05 (3.7E−06)	1.2E−06 (3.1E−06)

Note: Mean values are displayed with standard deviations in parentheses

uptake parameters of Edora Park were accompanied by increases in transient storage parameters, suggesting that transient storage in the hyporheic zone may be associated with nitrate uptake. We hypothesize that a large portion of transient storage increase in the Edora Park reach may have been due to increased hyporheic exchange from flushing of fines and coarsening of bed material, which would lead to more potential for nitrate processing and uptake. On the other hand, increases of transient storage parameters at Railroad and Stuart were not consistently accompanied by increased nitrate uptake. It could be inferred that the primary mechanisms responsible for these changes are entirely different; i.e. increased uptake in Edora Park corresponds with an increase in hyporheic exchange (more potential for nitrate processing, including denitrification) as a major portion in the transient storage increase, whereas increased transient storage at Railroad is likely due to increased amounts of stagnant water (in-channel storage) from flattened grasses (stems of approx 1 m length) that protruded into the channel. It is not likely that hyporheic exchange increased much at Railroad because the streambed was still composed of fine sediment, with more than 30% of the bed material being fines (<2 mm). Hyporheic exchange may be limited at Railroad due to a streambed of predominantly fine substrate, as compared to a streambed consisting of coarser and more heterogeneous substrate as observed at Edora Park. Additionally, Railroad is a plane bed stream with little variation in hydraulic gradients, while Edora Park has pool and riffle sequences that lead to greater hydraulic gradients to drive hyporheic exchange.

At Railroad, the flood flows temporarily caused bank vegetation, mainly tall grasses, to lie flat and drift into the channel. Decreased transient storage and uptake velocity at Railroad one year after the flood were likely due to less vegetation encroachment into the channel (as was visually observed during field investigations that the tall grasses were standing straight and no longer drifting into the channel), which is hypothesized to have been a major source of increased in-channel storage immediately after the high-flow event. Furthermore, Stuart demonstrated the opposite pattern of transient storage decreasing in post-flood conditions from pre-flood conditions, which could be due to substantial aggradation below the grade-control structure (Figure 3) that filled in the pool and reduced in-channel storage. Increases in transient storage one year after the flood compared to post-flood parameters may have resulted in relatively greater in-channel storage as particles that had been deposited below the grade-control structure began to be transported further downstream, resulting in partial removal of the pool deposits. At Stuart, uptake via hyporheic exhange may have been constrained by a shallow concrete apron extending approximately 20 m downstream of the grade-control structure, and so a large portion of transient storage is likely due to in-channel storage.

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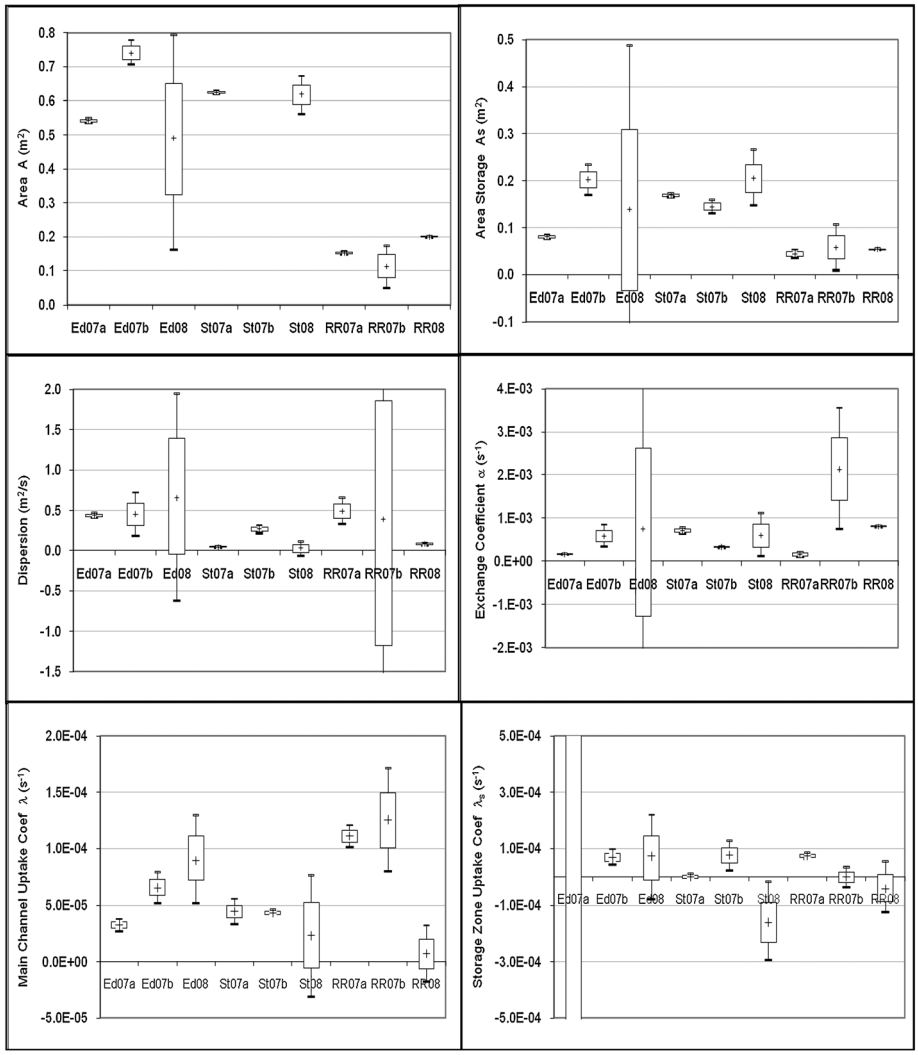

Notes : Ed07a = Pre-flood Edora Park; Ed07b = Post-flood Edora Park; Ed08 = Edora Park after one year. whiskers = 10th and 90th percentiles, box = 25th and 75th percentiles, crossbar = median. The variances of highly uncertain parameters are visually truncated, as the ends of the boxes and/or whiskers extend beyond the plot, to allow comparison of all parameters, including those with narrower distributions.

Figure 4. Estimates of output data from OTIS model

The findings of this study support the complexity of interpreting the measured results of nutrient enrichment studies to describe nutrient uptake as being primarily controlled by physical changes resulting from a flash flood, discharge variability among injections, or other differences in characteristics among the study reaches. A further limitation of nutrient enrichment is that nutrient uptake has been found to not always follow a linear relationship with concentration, where nutrient enrichment could lead to saturation (Dodds *et al.,* 2002) and values of v_f and S_w may not be representative of ambient conditions. Although we added nitrate to achieve a consistent fourfold increase of in-stream concentrations, the ambient nitrate concentrations varied among reaches and injection dates, leading to differences in the absolute amount of nitrate added to the stream during each injection.

Further research in partitioning hyporheic exchange and in-channel storage is important to fully describe the transient storage and nutrient uptake behaviour. Additionally, it should be noted that the transient storage results in this study are only quantifying the effects of shorter hyporheic flowpaths along each study reach (3 h sample period for a 60 min injection) as hyporheic flowpaths can have residence times ranging from minutes to days (Gooseff *et al.*, 2003). Hence, this study supports the concept that transient storage and uptake are highly heterogeneous along streams traversing varied geomorphic settings and sensitive to the temporal sequence of flow events that alter substrate, vegetative and longitudinal characteristics. In working towards models that incorporate hydrologic variability in estimating an effective discharge that accounts for the largest quantity

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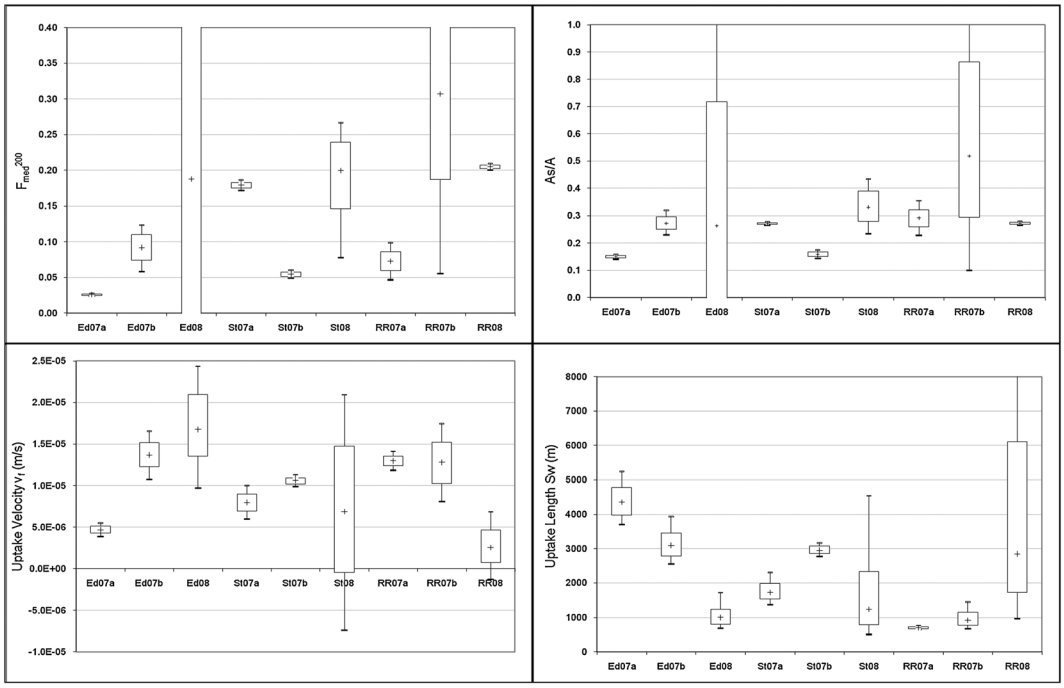

Notes : Ed07a = Pre-flood Edora Park; Ed07b = Post-flood Edora Park; Ed08 = Edora Park after one year. whiskers = 10th and 90th percentiles, box = 25th and 75th percentiles, crossbar = median. The variances of highly uncertain parameters are visually truncated, as the ends of the boxes and/or whiskers extend beyond the plot, to allow comparison of all parameters, including those with narrower distributions.

Figure 5. Results of Monte Carlo simulations of transient storage and nitrate uptake parameters

of nutrient retention, we suggest that the relationship between nitrate uptake and discharge may not be well-represented by simplistic relationships that do not account for resetting events that can occur rather frequently in some geomorphic settings. Processes of transient storage and nitrate uptake are sensitive to the distinct physical setting of a particular reach, individual events and antecedent conditions. Characteristics and behaviour of urban streams are highly variable in space (Chin, 2006), as demonstrated by the distinct responses to the high-flow event among study reaches in Spring Creek, and in time due to flashy urban hydrology.

CONCLUSIONS

Describing nitrate uptake in natural systems involves understanding complex interactions among hydrogeomorphic characteristics and biogeochemical processes. In this study, repeat injections at individual sites suggested that nitrate uptake and transient storage were mediated by complex interactions between geomorphic attributes and discharge variability. Few studies have performed multiple nutrient injections along the same stream reach, yet repeat injections allowed us to investigate flow variability over time in addition to geomorphological changes. Nitrate uptake responses to flow variability were not consistent among reaches of varying geomorphic context, as demonstrated in the unique responses of each Spring Creek reach to a single high-flow event. However, the difficulty of obtaining a larger sample size precluded a more robust statistical analysis that could potentially disentangle these complex responses. Despite its limitations, this study suggests that transient storage and nitrate uptake are highly dynamic and spatially heterogeneous along streams traversing varied geomorphic settings and styles of management as temporal sequences of flow events alter substrate, vegetative and longitudinal characteristics. This has important implications for investigating transient storage and uptake over time to capture these temporal changes in discharge and physical characteristics so that nutrient uptake behaviour can be more completely described.

A single geomorphically effective discharge appears to have the capacity to substantially alter the magnitudes and relative proportions of hyporheic versus in-channel storage, which are both components of transient storage. Nitrate uptake behaves differently in the hyporheic zone (potential nitrate removal due to denitrification) (Hester and Gooseff, 2010, 2011) compared to in-channel storage (retention of nitrate) (Craig *et al.,* 2008). Thus, it is recommended that future research be focused on differentiating between in-channel storage and hyporheic storage, as in Briggs *et al*. (2009, 2010), to more fully understand nitrate uptake and other biogeochemical

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processes occurring within stream ecosystems. As temporal sequences of flow events effectively reset both the physical template and biological processes controlling nitrate uptake, nutrient processing is variable in both space and time and does not lend itself to simple monotonic relationships with discharge. This presents ongoing challenges for upscaling these processes using techniques, such as magnitude-frequency analysis, and supports the importance of repeat injections and quantifying uncertainty to describe nitrate uptake.

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REFERENCES

Alexander R, Böhlke J, Boyer E, David M, Harvey J, Mulholland P, Seitzinger S, Tobias C, Tonitto C, Wollheim W. 2009. Dynamic modeling of nitrogen losses in river networks unravels the coupled effects of hydrological and biogeochemical processes. *Biogeochemistry* **93**(1): 91–116. DOI: 10.1007/s10533-008-9274-8

Allan JD. 2004. Landscapes and riverscapes: the influence of land use on stream ecosystems. *Annual Review of Ecology, Evolution, and Systematics* **35**: 257–284. DOI: 10.1146/annurev.ecolsys.35.120202.110122

Anderson Consulting Engineers, Inc. 2008. Flood documentation report. Chapter 8, City of Fort Collins, CO, Flood of August 2, 2007, March 2008.

Baker DW, Bledsoe BP, Mueller Price J. 2012. Nitrate uptake and transient storage over a gradient of geomorphic complexity, north-central Colorado, USA. *Hydrological Processes* **26**(21): 3241–3252. DOI: 10.1002/hyp.8385

Bencala KE. 2005. Hyporheic exchange flows. In *Encyclopedia of hydrological sciences,* Anderson MG (ed). John Wiley and Sons: Chichester, UK; 1733–1740.

Booth DB, Henshaw PC. 2001. Rates of channel erosion in small urban streams. In *Land use and watersheds: human influence on hydrology and geomorphology in urban and forest areas*, Wigmosta M, Burges S (eds). Geophysical AGU Monograph Series, Water Science and Application. American Geophysical Union, Washington DC, **2**; 17–38.

Briggs MA, Gooseff MN, Arp CD, Baker MA. 2009. A method for estimating surface transient storage parameters for streams with concurrent hyporheic storage. *Water Resources Research* **45**: W00D27. DOI: 10.1029/2008WR006959

Briggs MA, Gooseff MN, Peterson BJ, Morkeski K, Wollheim WM, Hopkinson CS. 2010. Surface and hyporheic transient storage dynamics throughout a coastal stream network. *Water Resources Research* **46**: W06516. DOI: 10.1029/2009WR008222

Brookshire EN, Valett HM, Gerber S. 2009. Maintenance of terrestrial nutrient loss signatures during in-stream transport. *Ecology* **90**(2): 293–299.

Bunte K, Abt SR. 2001a. Sampling frame for improving pebble count accuracy in coarse gravel-bed streams. *Journal of the American Water Research Association* **37**(4): 1001–1014. DOI: 10.1111/j.1752-1688.2001.tb05528.x

Bunte K, Abt SR. 2001b. Sampling surface and subsurface particle-size distributions in wadable gravel- and cobble-bed streams for analyses in sediment transport, hydraulics, and streambed monitoring. US Department of Agriculture, Forest Service RMRS-GTR-74.

Chin A. 2006. Urban transformation of river landscapes in a global context. *Geomorphology* **79**(3–4): 460–487. DOI: 10.1016/j.geomorph.2006.06.033

Chin A, Gregory KJ. 2005. Managing urban river channel adjustments. *Geomorphology* **69**(1–4): 28–45. DOI: 10.1016/j.geomorph.2004.10.009

Cooper SD, Barmuta L, Sarnelle O, Kratz K, Diehl S. 1997. Quantifying spatial heterogeneity in streams. *Journal of the North American Benthological Society* **16**(1): 174–188.

Craig LS, Palmer MA, Richardson DC, Filoso S, Bernhardt ES, Bledsoe BP, Doyle MW, Groffman PM, Hassett B, Kaushal SS, Mayer PM, Smith SM, Wilcock PR. 2008. Stream restoration strategies for reducing river nitrogen loads. *Frontiers in Ecology and the Environment* **6**(10): 529–538. DOI: 10.1890/070080

Dodds WK, Lopez AJ, Bowden WB, Gregory S, Grimm NB, Hamilton SK, Hershey AE, Marti E, McDowell WH, Meyer JL, Morrall D, Mulholland PJ, Peterson BJ, Tank JL, Valett HM, Webster JR, Wollheim W. 2002. N uptake as a function of concentration in streams. *Journal of the North American Benthological Society* **21**(2): 206–220. DOI: 10.2307/1468410

Doyle MW. 2005. Incorporating hydrologic variability into nutrient spiraling. *Journal of Geophysical Research* **110**(G1): G01003. DOI: 10.1029/2005jg000015

Doyle MW, Stanley EH, Strayer DL, Jacobson RB, Schmidt JC. 2005. Effective discharge analysis of ecological processes in streams. *Water Resources Research* **41**: W11411. DOI: 10.1029/2005WR004222

Garcia MH. 2008. Sediment transport and morphodynamics. In *ASCE manual of practice 110—sedimentation engineering: processes, measurements, modeling and practice*, Garcia MH (ed). American Society of Civil Engineers: Reston, VA; 21–163.

Golladay SW, Webster JR, Benfield EF. 1989. Changes in stream benthic organic matter following watershed disturbance. *Holarctic Ecology* **12**(2): 96–105.

Gooseff MN, Wondzell SM, Haggerty R, Anderson J. 2003. Comparing transient storage modeling and residence time distribution (RTD) analysis in geomorphically varied reaches in the Lookout Creek basin, Oregon, USA. *Advances in Water Resources* **26**(9): 925–937. DOI: 10.1016/S0309-1708(03)00105-2

Gooseff MN, Hall RO, Jr, Tank JL. 2007. Relating transient storage to channel complexity in streams of varying land use in Jackson Hole, Wyoming. *Water Resources Research* **43:** W01417. DOI: 10.1029/2005WR004626

Hall RO, Bernhardt ES, Likens GE. 2002. Relating nutrient uptake with transient storage in forested mountain streams. *Limnology and Oceanography* **47**(1): 255–265.

Hanafi S, Grace M, Webb JA, Hart B. 2007. Uncertainty in nutrient spiraling: sensitivity of spiraling indices to small errors in measured nutrient concentration. *Ecosystems* **10**(3): 477–487. DOI: 10.1007/s10021-007-9031-1

Harrelson CC, Rawlins CL, Potyondy JP. 1994. Stream channel reference sites: an illustrated guide to field technique. US Department of Agriculture, Forest Service GTR-RM-245.

Harvey JW, Bencala KE. 1993. The effect of streambed topography on surface–subsurface water exchange in mountain catchments. *Water Resources Research* **29**(1): 89–98. DOI: 10.1029/92WR01960

Hawkins CP, Kershner JL, Bisson PA, Bryant MD, Decker LM, Gregory SV, McCullough DA, Overton CK, Reeves GH, Steedman RJ, Young MK. 1993. A hierarchical approach to classifying stream habitat features. *Fisheries* **18**(6): 3–11.

Hester ET, Gooseff MN. 2010. Moving beyond the banks: hyporheic restoration is fundamental to restoring ecological services and functions of streams. *Environmental Science & Technology* **44**(5): 1521–1525. DOI: 10.1021/es902988n

Hester ET, Gooseff MN. 2011. Hyporheic restoration in streams and rivers. In *Stream restoration in dynamic fluvial systems: scientific approaches, analyses, and tools*, Simon A, Bennett SJ, Castro JM (eds). AGU Geophysical Monograph Series. American Geophysical Union, Washington DC, **194**; 167–187.

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Jacobson RB, Femmer SR, McKenney RA. 2001. Land-use changes and the physical habitat of streams. US Geological Survey Circular 1175.

Kasahara T, Hill AR. 2006. Effects of riffle-step restoration on hyporheic zone chemistry in N-rich lowland streams. *Canadian Journal of Fisheries and Aquatic Sciences* **63**(1): 120–133.

Konrad CB, Booth DB. 2005. Hydrologic changes in urban streams and their ecological significance. *American Fisheries Society Symposium* **47**: 157–177.

Marti E, Grimm NB, Fisher SG. 1997. Pre- and post-flood retention efficiency of nitrogen in a Sonoran Desert stream. *Journal of the North American Benthological Society* **16**(4): 805–819.

Meyer JL, Paul MJ, Taulbee WK. 2005. Stream ecosystem function in urbanizing landscapes. *Journal of the North American Benthological Society* **24**(3): 602–612. DOI: 10.1899/04-021.1

Montgomery DR, Buffington JM. 1997. Channel-reach morphology in mountain drainage basins. *Geological Society of America Bulletin* **109**(5): 596–611. DOI: 10.1130/0016-7606(1997)109<0596:CRMIMD>2.3.CO;2

Morrice JA, Valett HM, Dahm CN, Campana ME. 1997. Alluvial characteristics, groundwater-surface water exchange and hydrological retention in headwater streams. *Hydrological Processes* **11**(3): 253–267. DOI: 10.1002/(SICI)1099-1085(19970315)11:3<253::AID-HYP439>3.0.CO;2-J

Newbold J, Elwood JW, O'Neill RV, Van Winkle W. 1981. Measuring nutrient spiralling in streams. *Canadian Journal of Fisheries and Aquatic Sciences* **38**(7): 860–863.

O'Connor BL, Harvey JW. 2008. Scaling hyporheic exchange and its influence on biogeochemical reactions in aquatic ecosystems. *Water Resources Research* **44**: W12423. DOI: 10.1029/2008WR007160

Orr CH, Clark JJ, Wilcock PR, Finlay JC, Doyle MW. 2009. Comparison of morphological and biological control of exchange with transient storage zones in a field-scale flume. *Journal of Geophysical Research* **114**(G2): G02019. DOI: 10.1029/2008JG000825

Packman AI, Salehin M. 2003. Relative roles of stream flow and sedimentary conditions in controlling hyporheic exchange. *Hydrobiologia* **494**(1): 291–297.

Peterson BJ, Wollheim WM, Mulholland PJ, Webster JR, Meyer JL, Tank JL, Marti E, Bowden WB, Valett HM, Hershey AE, McDowell WH, Dodds WK, Hamilton SK, Gregory S, Morrall DD. 2001. Control of nitrogen export from watersheds by headwater streams. *Science* **292**: 86–90. DOI: 10.1126/science.1056874

Pfaff JD. 1993. Method 300.0: determination of inorganic anions by ion chromatography. US Environmental Protection Agency, Environmental Monitoring Systems Laboratory, Office of Research and Development.

Poeter EP, Hill MC. 1999. UCODE, a computer code for universal inverse modeling. *Computers & Geosciences* **25**(4): 457–462. DOI: 10.1016/S0098-3004(98)00149-6

Poeter EP, Hill MC, Banta ER, Mehl S, Christensen S. 2005. UCODE_2005 and six other computer codes for universal sensitivity analysis, inverse modeling, and uncertainty evaluation. US Geological Survey Techniques and Methods Report TM 6-A11.

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC. 1997. The natural flow regime. *BioScience* **47**(11): 769–784.

Poff NL, Bledsoe BP, Cuhaciyan CO. 2006. Hydrologic variation with land use across the contiguous United States: geomorphic and ecological consequences for stream ecosystems. *Geomorphology* **79**(3–4): 264–285. DOI: 10.1016/j.geomorph.2006.06.032

Poor CJ, McDonnell JJ. 2007. The effects of land use on stream nitrate dynamics. *Journal of Hydrology* **332**(1–2): 54–68. DOI: 10.1016/j.jhydrol.2006.06.022

Pringle CM, Naiman RJ, Bretschko G, Karr JR, Oswood MW, Webster JR, Welcomme RL, Winterbourn MJ. 1988. Patch dynamics in lotic systems—the stream as a mosaic. *Journal of the North American Benthological Society* **7**(4): 503–524.

Rehg KJ, Packman AI, Ren J. 2005. Effects of suspended sediment characteristics and bed sediment transport on streambed clogging. *Hydrological Processes* **19**(2): 413–427. DOI: 10.1002/hyp.5540

Rhoads BL, Wilson D, Urban MA, Herricks EE. 1999. Interaction between scientists and nonscientist in community-based watershed management: emergence of the concept of stream naturalization. *Environmental Management* **24**: 297–308.

Roesner LA, Bledsoe BP, Brashear RW. 2001. Are best -management-practice criteria really envionmentally friendly? *Journal of Water Resources Planning and Management* **127**(3): 150–154.

Runkel RL. 1998. One-dimensional Transport with Inflow and Storage (OTIS): a solute transport model for streams and rivers. US Geological Survey Water-Resources Investigations Report 98 – 4018.

Runkel RL. 2002. A new metric for determining the importance of transient storage. *Journal of the North American Benthological Society* **21**(4): 529–543. DOI: 10.2307/1468428

Runkel RL. 2007. Toward a transport-based analysis of nutrient spiraling and uptake in streams. *Limnology and Oceanography: Methods* **5**: 50–62.

Scott DT, Gooseff MN, Bencala KE, Runkel RL. 2003. Automated calibration of a stream solute transport model: implications for interpretation of biogeochemical parameters. *Journal of the North American Benthological Society* **22**(4): 492–510. DOI: 10.2307/1468348

Stanhope JW, Anderson IC, Reay WG. 2009. Base flow nutrient discharges from Lower Delmarva Peninsula Watersheds of Virginia, USA. *Journal of Environmental Quality* **38**: 2070–2083. DOI: 10.2134/jeq2008.0358

Steinman AD, Lamberti GA, Leavitt PR. 2007. Biomass and pigments of benthic algae. In *Methods in stream ecology,* Hauer FR, Lamberti GA (eds). Elsevier: London; 357–379.

Stream Solute Workshop. 1990. Concepts and methods for assessing solute dynamics in stream ecosystems. *Journal of the North American Benthological Society* **9**(2): 95–119.

Tonina DB, Buffington JM. 2009. Hyporheic exchange in mountain rivers. I: mechanics and environmental effects. *Geography Compass* **3**(3): 1063–1086. DOI: 10.1111/j.1749-8198.2009.00226.x

Tukey JW. 1977. *Exploratory data analysis*. Addison-Wesley: Reading, MA.

Wallace JB, Hutchens JJ, Grubaugh JW. 2007. Transport and storage of FPOM. In *Methods in stream ecology,* Hauer FR, Lamberti GA (eds). Elsevier: London; 249–271.

Walsh CJ, Roy AH, Feminella FW, Cottingham PD, Groffman PM, Morgan RP. 2005. The urban stream syndrome: current knowledge and the search for a cure. *Journal of the North American Benthological Society* **24**(3): 706–723. DOI: 10.1899/04-028.1

Wondzell SM, Swanson FJ. 1999. Floods, channel change, and the hyporheic zone. *Water Resources Research* **35**(2): 555–567. DOI: 10.1029/1998WR900047

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