Environ. Sci. Technol. **2007**, *41,* 1570−1576

Effects of Channel Restoration on Water Velocity, Transient Storage, and Nutrient Uptake in a Channelized Stream[†]

PAUL A. BUKAVECKAS*

Center for Environmental Studies, Department of Biology,
Virginia Commonwealth University,
Richmond, Virginia 23111

Channel design is an important component of stream restoration, but little is known of the interplay between hydrogeomorphic features and ecosystem processes within designed channels. Water velocity, transient storage, and nutrient uptake were measured in channelized (prerestoration) and naturalized (postrestoration) reaches of a 1-km segment of Wilson Creek (KY) to assess the effects of restoration on mechanisms of nutrient retention. Stream restoration decreased flow velocity and reduced the downstream transport of nutrients. Median travel time was 50% greater in the restored channel due to lower reach-scale water velocity and the longer length of the meandering channel. Transient storage and the influence of transient storage on travel time were largely unaffected except in segments where backwater areas were created. First-order uptake rate coefficients for N and P were 30- and 3-fold higher (respectively) within the restored channel relative to its channelized state. Changes in uptake velocities were comparatively small, suggesting that restoration had little effect on biochemical demand. Results from this study suggest that channel naturalization enhances nutrient uptake by slowing water velocity. Solute injection experiments revealed differences in the functional properties of channelized, restored, and reference streams and provided a means for quantifying benefits associated with restoration of ecosystem services.

Introduction

Streams and their associated riparian ecotones provide important ecosystem goods and services through their role in the cycling of water, energy, and materials (*1*). Vital services include water storage, maintenance of biodiversity, and mitigation of downstream nutrient transport through nutrient retention. Habitat alteration can be accompanied by loss of services and has led to widespread efforts to restore degraded streams and identify metrics that quantify benefits associated with restoration (*2*). Measures of restoration success typically rely on biotic attributes (e.g., fish and macroinvertebrate indices) while metrics related to ecosystem function are less commonly used (*3*, *4*). Nutrient retention is of particular concern due to adverse effects associated with nutrient delivery to downstream and coastal ecosystems (*5*, *6*). At present, there is little quantitative information for assessing potential benefits of stream restoration in mitigating nutrient transport.

In low-order streams, nutrient removal is principally a benthic process carried out by algae and bacteria that colonize the surfaces of substrates which comprise the stream bed (inclusive of the hyporheic zone; *7*, *8*). The hyporheic zone is a subsurface feature within which water from the active (flowing) channel mixes with water held in interstitial spaces before returning to the channel (*9*). Streams by virtue of their high ratio of bottom area to overlying water are thought to account for a large fraction of nutrient retention in river networks (*10*). Nutrient removal can occur through short-term storage (e.g., in algal and bacterial biofilms) or, in the case of nitrogen, through loss to the atmosphere (conversion to N_2 gas via denitrification). Streams vary in their nutrient retention capacity owing to variable rates of biological activity (algal and bacterial metabolism; *11*) and to differences in their hydrologic and geomorphologic characteristics (*12*). In temperate regions, biotic activity is principally constrained by seasonal cycles in water temperature although other factors can influence the growth of algae and bacteria. These include light limitation of photosynthesis due to riparian shading and constraints on bacterial production imposed by variable quantity and quality of organic matter inputs. Hydrologic and geomorphologic influences are principally those that determine the length of time that water resides within a stream segment and its contact with reactive surfaces (mineral and biofilm). Water velocity is a useful metric for gauging the potential for biotic−abiotic mechanisms to influence stream nutrient concentrations. High water velocity limits opportunities for nutrient removal while reduced velocity favors greater nutrient retention. Transient storage is a related hydrologic property that refers to the short-term retention of water (and solutes) within a stream segment (*9*). Transient storage zones include features within the active channel ("in-stream storage") as well as below the stream channel (hyporheic exchange). Morphological features (e.g., backwater areas) and channel structures (e.g., debris dams) enhance transient storage and have been shown in some studies to increase nutrient retention (*12*, *13*). Other factors that influence transient storage are those related to the composition of streambed materials (*14*). Coarse materials (sand, gravel) allow the movement of water through interstitial spaces thereby increasing water exchange with transient storage zones. Fine materials (silt, clay) have low hydraulic conductivity which limits opportunities for water exchange.

Channel modifications alter the hydrologic and biological properties of streams and may thereby influence nutrient retention. Naturally curved channels create complex flow environments which enhance hyporheic exchange (*15*). Channelization reduces the natural diversity of velocity and substrate conditions and would be expected to diminish transient storage and nutrient retention (*4*). Deployment of in-stream structures (e.g., flow baffles, woody debris) has been shown to increase water travel time and nutrient uptake (*16*, *17*), but the application of hydrogeomorphic approaches has yet to be tested in a designed channel. This paper describes a restoration effort in which a stream was rerouted from its straightened and incised channel into a constructed channel designed to mimic morphologic features of natural streams. Pre- and postrestoration data are used to characterize the functioning of channelized, naturalized, and reference channels and to examine the interplay between design features and the biotic−abiotic mechanisms regulating nutrient retention.

---

* Corresponding author phone: 804-828-0168; e-mail: pabukaveckas@vcu.edu.

[†] This paper is dedicated to the memory of Jeff Jack, friend and colleague.

10.1021/es061618x CCC: $37.00

© 2007 American Chemical Society
Published on Web 01/24/2007

Materials and Methods

Site Description. The study sites are located in an unglaciated area of low hills distributed across northwestern Kentucky and southeastern Indiana (*18*, *19*). Like many streams in this region, Wilson Creek was channelized and relocated to the margin of its floodplain (adjacent to the valley hillslope) ca. 100−150 years ago to facilitate bottomland agriculture. As a consequence, the stream channel became incised, entrenched, and confined with bankful capacity comparable to a 10-year flood. The 1-km reach selected for restoration was composed almost entirely of runs while pools and riffles represented less than 10% of the total length. Substrate was exposed bedrock (dolomitic limestone) with isolated patches of gravel and cobble. In recent decades, management of the remnant floodplain (6.5 ha within the restoration zone) has shifted from crops for wildlife (e.g., millet) to warm season grasses (fescue) that are mowed for hay production. Harts Run shares a similar history of agricultural impacts in the floodplain, but an important distinction is that its upper section was not relocated to the margin of the floodplain. Secondary resorting of bank and floodplain materials during the past 60−100 years resulted in a meandering channel that was dominated by riffles and pools with gravel and cobble substrate (little exposed bedrock). Its selection as a reference site serves to quantify the condition attained by a stream that has recovered to a more natural state rather than to typify conditions occurring prior to European settlement. Both Wilson Creek and Harts Run were shaded by a narrow riparian buffer of mature (50+ years) sycamores (*Platanus occidentalis*) and white oaks (*Quercus alba*).

Stream Restoration. Channel design and construction is briefly summarized here (see also Supporting Information). The purpose of the restoration was to (1) provide a diversity of flow conditions within the constructed channel and (2) to reconnect Wilson Creek with its former floodplain. Stream−floodplain connectivity was established by relocating the channel to its floodplain and reducing its bankful capacity. Channel meanders and constructed pools and riffles were used to create diverse flow conditions. The design of the restored channel followed parameter ranges for bank-full dimensions, meander belt width, meander radius, and channel slope obtained from reference streams within the region (*20*). The morphometry and location of the constructed channel was determined in part by historical considerations (as revealed by underlying deposits and microtopography of the floodplain) and the desire to achieve a profile that would sustain long riffles with short runs into deep pools. The engineered channel was narrower (5.5 m) and deeper (0.14 m) relative to the channelized segment (width = 6.8 m, depth = 0.09 m) to accommodate a pool−riffle structure. The meandering form of the channel resulted in a total stream length of 944 m (vs 823 m prior to restoration).

Study Design. Injection experiments were performed during mid-April to mid-June to characterize stream functioning over a range of discharge and temperature conditions. The range of discharge on dates when injection experiments were performed (10−300 L s^{-1}) corresponded to 58% (by calendar year) of the daily mean discharge observed at this site and 53% of the mean annual discharge (based on historical USGS gauging data). Prerestoration data were collected in 2002 and 2003, and postrestoration data were collected in 2004 and 2005 (reference site data collected throughout the 4-year study). Fixed study reaches were established at the reference (Harts Run), channelized (Wilson Creek, prerestoration), and naturalized (Wilson Creek, postrestoration) streams. Subreach lengths were fixed across experiments despite changing discharge and travel time in order to obtain reach-specific measurements that were comparable through time. At Harts Run, the two subreaches (length = 110 and 150 m) were located in a meandering channel that was dominated by riffles and pools with gravel and cobble substrate (little exposed bedrock). Because discharge (and therefore velocity) was higher at Wilson Creek, I used longer subreaches so that travel times would be comparable. At Wilson Creek, two subreaches (length = 185 and 240 m) were located near the top and bottom of the 1-km section that was selected for restoration. These reaches were characterized by a greater prevalence of bedrock substrate and lack of riffles or pools. In the restored channel, two subreaches (length = 180 and 210 m) were delineated in the lower half of the 1-km restored section to characterize the functioning of the constructed channel. A third subreach (length = 100 m) was added in the upper section of the restored segment where the new channel was routed through a remnant of the old channel (see map; Supporting Information). Experiments conducted on this subreach (hereafter, 'merged' channel) served to assess the functioning of the old channel where it had been incorporated into the new channel. A total of 44 experiments were performed at the reference ($N = 13$), channelized ($N = 14$), and restored ($N = 17$) streams during the 4-year study. No significant differences in measured properties were observed between the two replicate subreaches in each stream, and therefore all experiments were pooled to characterize average values for each site. An exception was the 'merged' subreach which differed from the two subreaches that were not connected to the old channel. These data were treated separately in subsequent analyses.

Injection Experiments (see also Supporting Information). The introduction of conservative (nonreactive) tracers is a well-established method to determine the rate at which water moves through a stream channel (median travel time) and the exchange of water between the active channel and surface/subsurface storage zones (transient storage; *21*). The simultaneous addition of nonconservative solutes (nutrients) is used to quantify their downstream loss relative to the conservative tracer. Injection experiments were performed by simultaneously adding a solution of salt (NaCl) and nutrients (N, P) to a well-mixed section of stream. Ammonium is the more biologically active form of N (*22*, *23*), whereas nitrate is the dominant form of N associated with anthropogenic loading (*24*, *25*). I used nitrate for injection experiments since the focus was on mitigation of downstream transport. To avoid confounding effects, pre- and postrestoration experiments were conducted at comparable levels of nutrient addition (*26*). Increases in conductivity due to salt injection were large (typically 30−60 μS cm^{-1}) relative to background variation (<3 μS cm^{-1}). Once conductivity readings reached a plateau (ca. 45 min after start of injection), water samples were collected for salt and nutrient analyses at six to eight locations spaced at 20−30 m intervals over the length of the subreach. Nutrient analyses followed standard methods (*27*) using filtered samples and automated procedures (Skalar San Plus) for the determination of NO_3 (cadmium reduction) and soluble reactive phosphorus (SRP; ascorbic acid). Chloride analyses were performed manually using the ferricyanide method (*27*).

Data Analyses. Hydrodynamic properties were quantified using a one-dimensional advection-dispersion, transient storage model that has previously been used in similar studies (*28*). The model assumes uniform flow conditions during the injection experiment, and therefore we avoided periods immediately following rain events. For each injection, model-derived estimates of water velocity (v, m min^{-1}), the exchange rate of water between the channel and transient storage (k_1, min^{-1}), and the exchange rate of water between transient storage and the main channel (k_2, min^{-1}) were obtained. Parameter estimates were derived iteratively by solving for a least-squares best fit between modeled and measured conductivity values. A metric of transient storage is derived

TABLE 1. Average Values for Metrics Used To Characterize Water Quality, Hydrology, and Nutrient Uptake at the Channelized (Wilson Creek − Prerestoration), Naturalized (Wilson Creek − Postrestoration), and Reference (Harts Run) Sites. Superscript Letters and p Values Denote Statistical Significance Based on Repeated-Measures ANOVA and Planned (*a priori*) Comparisons of Reference vs Channelized and Restored vs Channelized Data ('ns' Denotes $p > 0.10$)

	channelized	restored	reference	p
water quality parameters				
temperature (°C)	14.0^a	19.2^b	13.9^a	<0.001
P-SRP (μg L^{-1})	10.8^a	7.2^b	6.7^b	0.03
N-NO$_3$ (μg L^{-1})	375^a	456^a	63^b	<0.001
hydrologic parameters				
stream discharge (Q_s; L s^{-1})	125^a	109^a	62^b	0.03
lateral inflow (L; s^{-1} m^{-1})	0.204	0.165	0.188	ns
velocity (V; m s^{-1})	11.9^a	8.7^b	6.1^c	<0.001
normalized storage zone area (A_S/A; m^2 m^{-2})	0.281^a	0.405^b	0.550^b	<0.001
median travel time due to transient storage ($F_{med}{}^{200}$; %)	14^a	17^a	30^b	0.001
dispersion (D; m^2 min^{-1})	22.3^a	14.4^b	8.4^c	0.002
Damköhler values (DaI)	5.7	4.2	4.9	ns
nutrient uptake parameters				
N rate coefficient (k_N; m^{-1})	0.00005^a	0.00162^b	0.00012^a	0.04
P rate coefficient (k_P; m^{-1})	0.00073^a	0.00263^b	0.00193^b	0.03
N uptake velocity (V_f; mm min^{-1})	0.13^a	1.26^b	0.03^a	0.09
P uptake velocity (V_f; mm min^{-1})	1.54	2.40	2.21	ns

from the ratio of the exchange coefficients (k_1:k_2) whereby larger values denote greater transient storage. This value is equivalent to the ratio of storage zone cross-sectional area to stream cross-sectional area (hereafter, A_S/A). The fraction of median travel time that is due to transient storage was derived for a standardized reach length of 200 m ($F_{med}{}^{200}$; *29*). Damköhler values were calculated for each experiment to determine whether the length of the subreach was suitable for measuring transient storage (*30*; see Supporting Information). The median travel time was derived for the entire restored segment to integrate variable velocity responses among the subreaches and the effect of channel lengthening.

Several parameters are commonly used to describe nutrient uptake in streams based on downstream changes in N and P concentrations. The first-order uptake rate coefficient (k_N, k_P, m^{-1}) is calculated as the slope of the regression for the natural logarithm of concentration (NO$_3$−N or PO$_4$−P corrected for background and dilution) versus distance. Background correction was based on an average value of samples collected prior to and after the injection experiment. Dilution rates were determined from downstream declines in the conservative tracer (Cl). Rate coefficients were used as the primary response variable to assess differences among the reference, channelized, and restored sites. Uptake lengths (S_w; the average distance traveled by a nutrient ion before uptake) are reported for comparison to other studies. The uptake length was calculated as the inverse of k_N or k_P. Uptake velocities (V_f; the vertical velocity at which nutrients move to the stream bottom) were calculated as the product of water velocity and stream depth divided by the uptake length (depth derived from discharge and width; *21*). This parameter normalizes for differences in water velocity across experiments and is used to discern postrestoration changes in nutrient demand from those arising from changes in water velocity. Statistical analyses of data from individual experiments were based on least-squares regression which yielded an estimate of the probability that the uptake rate coefficient (k_N, k_P) was significantly different from zero. Meta-analyses were based on repeated-measures ANOVA with specific comparisons for *a priori* (reference vs channelized and restored vs channelized) and *a posteriori* (among subreaches within the restored channel) tests.

Results

Water temperature was higher and velocity was lower in the restored channel relative to the channelized segment (Table 1). Water temperatures in the restored segment were on average 5.2 °C warmer relative to the channelized segment. At the reference site, stream temperatures were generally similar for periods corresponding to pre- (mean = 14.2 °C) and post- (mean = 14.7 °C) restoration. Regressions of velocity against discharge yielded similar predictive power for the restored and channelized segments (R^2 = 0.65 and 0.57, respectively) but with higher slope and intercept for the channelized segment (Figure 1). Water velocity at Harts Run was lower than that measured at Wilson Creek due to overall lower discharge from the smaller, reference catchment. Among subreaches in the restored channel, water velocities were lowest in the 'merged' subreach (segment of the new channel that was routed through the old channel). To integrate velocity effects over the length of the restored segment, values for specific subreaches were weighted according to the proportion of the channel they represented. Using the length and average water velocity for the merged reach and applying the average value for the two remaining subreaches (that did not include the old channel) to the rest of the restored segment yielded a median travel time of 104 min (at mean discharge observed during the injection experiments). By comparison, the median travel time of Wilson Creek in its channelized state was 69 min (at similar discharge).

Transient storage values were higher among restored and reference reaches relative to the channelized segment. Differences in transient storage between the restored and channelized sites were statistically significant whereas differences between the restored and reference sites were not. Greater transient storage in the restored segment was largely due to higher transient storage (mean = 0.918) in the 'merged' subreach relative to the two subreaches that were confined to the newly constructed channel (mean = 0.191). Transient storage in the merged subreach was consistently high over a range of discharge conditions ($A_S/A > 0.5$) and included the two highest values measured in this study ($A_S/A > 1.0$; Figure 1). A weighted average (as for travel time, above) for the restored segment ($A_S/A = 0.260$) did not differ appreciably from that of the channelized segment ($A_S/A = 0.281$), and both were well below those observed in the reference stream ($A_S/A = 0.550$). The influence of transient storage on travel time ($F_{med}{}^{200}$) was greatest at the reference site with lower values observed among channelized and restored reaches. Within the restored segment, the fraction of median travel

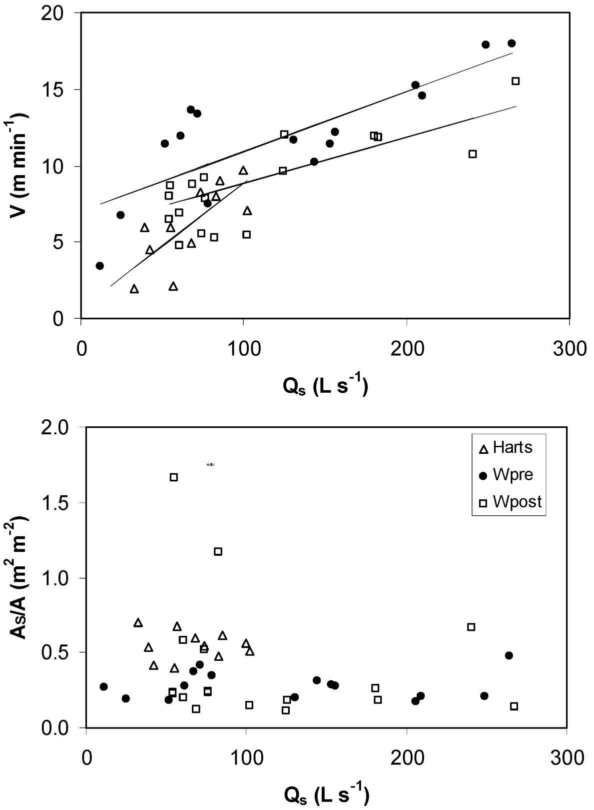

FIGURE 1. Water velocity (upper panel) and transient storage (lower panel) as a function of stream discharge at the reference (Harts Run), channelized (Wpre), and restored (Wpost) streams. Discharge and velocity were derived independently using the measured increase in stream Cl concentrations and the speed with which Cl traveled downstream during injection experiments. Lines shown are for least-squares regression ($R^2 = 0.57-0.65$; $p < 0.01$).

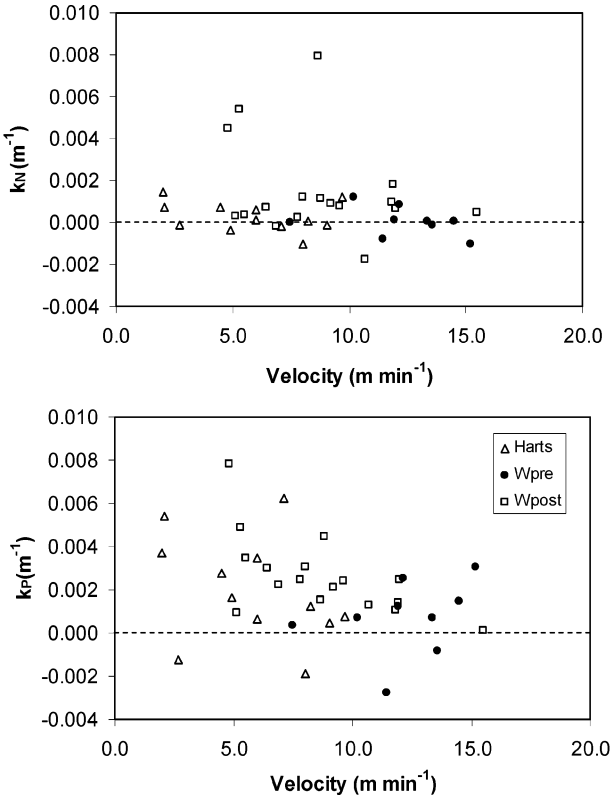

FIGURE 2. First-order N and P uptake rate coefficients as a function of water velocity for the reference (Harts Run), channelized (Wilson Creek, prerestoration), and naturalized (Wilson Creek, postrestoration) sites.

time due to transient storage was higher in the merged subreach (mean = 35%) relative to subreaches wholly within the newly constructed channel (mean = 8%). The fraction of median travel time due to transient storage was not significantly different between the restored and channelized segments.

Nutrient uptake was higher in the restored channel relative to the channelized segment (Figure 2). For P, all seventeen experiments in the restored channel yielded positive uptake rates (net retention) and fourteen of these were statistically significant. Three of the four highest uptake rates were obtained in the merged subreach. Seven of nine experiments at the channelized stream revealed net retention and two indicated net release (all significant). Experiments performed at the reference stream showed net retention on ten of twelve dates and net loss of P (negative uptake rates) on two dates (all statistically significant). Rate coefficients for P in the restored segment were on average 3-fold higher and were significantly different from those of the channelized segment (Table 1). P coefficients for the restored segment were not significantly different from those of the reference stream. The average P uptake length for the restored segment (380 m) was comparable to that of the reference site (518 m), and these were approximately one-third of the uptake length in the channelized segment (1370 m). P uptake velocities were on average 50% higher at the restored and reference sites relative to the channelized segment but differences were not statistically significant (Table 1).

For N, fifteen of the seventeen experiments performed in the restored segment exhibited positive uptake rates and eleven of these were statistically significant (Figure 2). Similar to P, highest uptake rates were measured in the merged subreach which yielded the three highest N uptake rates measured in this study. At the reference site, nitrate injections yielded significant uptake rates on only six dates (from twelve experiments) of which five were positive values (net retention). Similarly low uptakes rates were measured in the channelized segment where six of nine experiments yielded positive uptake values but only two were statistically significant. Two of the three experiments that yielded negative uptake rates were significant. N coefficients in the restored segment were on average 10-fold higher relative to the channelized segment and the reference stream (Table 1). Values for restored reaches were significantly different from those of the channelized and references streams. Average N uptake lengths were 617 m in the restored segment (178 m in the merged subreach) whereas uptake lengths in the reference stream and channelized segment exceeded 8 and 20 km (respectively). N uptake velocities in the restored segment exceeded those of the reference stream and channelized segment although differences were marginally significant.

Discussion

The restored channel exhibited lower water velocities over a range of discharge conditions relative to the channelized segment. Lower water velocities are attributed to the influence of constructed pools and channel meanders (*30*). Reduced water velocities combined with the greater length of the meandering channel resulted in a 50% increase in the median travel time of the restored segment relative to the channelized segment. Transient storage and its influence on median travel time was unaffected by restoration except in a single subreach connected to a backwater area. It was anticipated that use of gravel and cobble to line constructed riffles would increase transient storage in the restored channel since prior work has shown that constructed riffles exhibit high hyporheic exchange (*31*). A confounding factor may have been the presence of predominantly clay materials underlying portions of the restored channel as these have low hydraulic conductivity. Uptake rates were higher in the restored segment relative to the channelized segment despite the narrower designed channel (lower volume to benthic area ratio) and the fact that transient storage was largely unaffected. Effects on uptake coefficients were most apparent in the subreach of the restored channel connected to a backwater area. However, rate coefficients were generally higher throughout the naturalized segment and suggest that restoration reduced downstream nutrient transport.

Proportional increases in rate coefficients were large (e.g., 30-fold for N and 3-fold for P) relative to those for uptake velocities (10-fold for N, 0.6-fold for P), suggesting that reduced water velocity in the restored channel was the primary mechanism enhancing nutrient uptake. Differences in uptake velocities between the channelized and restored segments were not statistically significant owing to high variability among subreaches of the constructed channel. However, higher values in the restored segment suggest that abiotic or biotic nutrient demand may have been greater relative to the channelized segment. Excavation of the new channel exposed clay and limestone materials and, as these have a high sorption capacity, may have contributed to higher abiotic P demand. Large (10-fold) increases in N uptake velocities suggest that biotic mechanisms were important as well (since nitrate has a low sorption potential). Greater incident radiation following relocation of the stream channel to the open (afforested) floodplain may have contributed to biotic demand by stimulating autotrophic production. High P uptake rates with increases in solar radiation and benthic algal production were attributed to the loss of canopy shading along a Mediterranean stream (*32*). Increases in incident solar radiation were also reflected in warmer water temperatures in the restored segment, and these may have stimulated both autotrophic and heterotrophic metabolism.

A specific design feature that played an important role in water and nutrient retention was the routing of the new channel through a segment of the old channel (merged subreach). Experiments conducted in this subreach yielded estimates of transient storage and nutrient uptake that were consistently higher than those observed elsewhere in the restored channel and included the highest values measured in this study. Because the new channel was higher in elevation relative to the former (incised) channel, the section of the old channel that had been incorporated into the restored segment became a deep pool. Lower water velocities through this deeper section of the channel likely contributed to higher nutrient uptake. In this subreach, a recirculation zone exchanged water between the active channel and a backwater area that formed in a remnant of the old channel. Prior work on New Hampshire streams has demonstrated that side pools along the channel margin have a longer hydraulic retention than those in the active channel (*33*) and may exert a disproportionate influence on water and solute dynamics relative to their area. Organic materials (predominantly leaf litter) were observed to accumulate within the backwater and likely resulted in elevated rates of bacterial metabolism relative to the active channel. Bacterial nutrient demand, coupled with the gradual exchange of water between the storage zone and active channel, could account for the high uptake velocities observed in this reach. Occasional samples revealed low nitrate and dissolved oxygen concentrations relative to the active channel, suggesting high rates of denitrification (see Supporting Information). These data further support the hypothesis that the backwater area was a biogeochemically active zone.

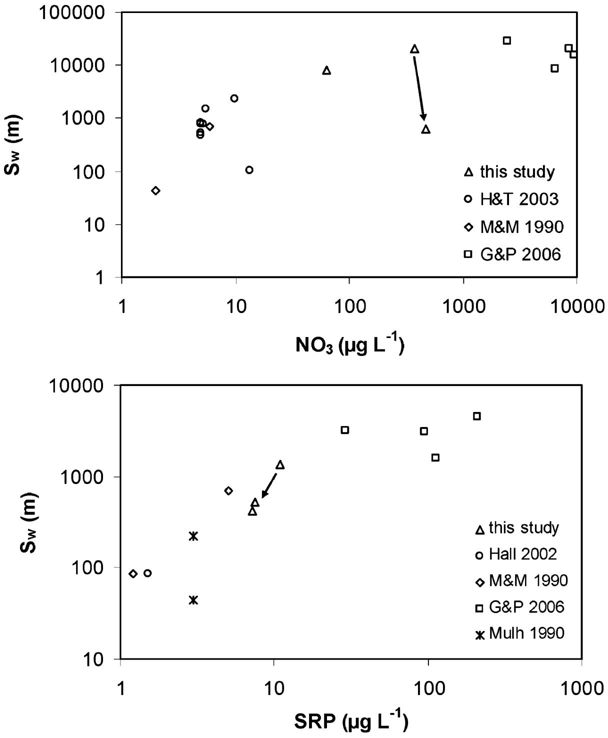

FIGURE 3. A comparison of N and P uptake lengths reported in this study with previously published values from NO_3 and SRP addition experiments (*11, 31, 32, 33, 35*). Arrows denote the change from channelized to restored conditions based on an average value for each site.

To assess restoration effects in the context of interstream variation in nutrient uptake, data from this study were compared to previously published values derived by similar methodology (nonisotope nutrient additions). Uptake lengths were plotted as a function of ambient nutrient concentrations (Figure 3). The former are widely reported, and therefore a useful comparative metric while the latter represent a gradient of anthropogenic nutrient enrichment. A complicating factor is that uptake lengths vary as a function of discharge and are sensitive to levels of nutrient addition. In the compiled dataset, P uptake lengths were correlated with discharge ($R^2 = 0.42$, $p = 0.02$) whereas N uptake lengths were not. Both were correlated with ambient concentrations (for P: $R^2 = 0.70$, $p = 0.001$; for N: $R^2 = 0.35$, $p = 0.01$). Prior studies have largely focused on streams with low ambient nutrient concentrations and uptake lengths less than 1000 m (*11, 33, 34*). Data presented in this paper and a recently published study (*35*) serve to extend the range of observed variation to streams with higher ambient nutrient concentrations and correspondingly longer uptake lengths. Since candidate sites for restoration typically occur in human-dominated landscapes, characterization of uptake processes at high ambient nutrient concentrations is central to assessing potential benefits arising from restoration. A comparison of the magnitude of change in uptake lengths following restoration against the range of interstream variation suggests that moderate (for P) to large (for N) gains in nutrient retention may be possible in streams with high ambient concentrations by ameliorating channelized conditions.

Response parameters derived from conservative tracer and nutrient addition experiments were useful for distinguishing functional attributes of the reference, channelized, and restored sites. Reach-scale estimates integrate longitudinal variation in flow conditions, an attribute that is likely important for attaining other restoration objectives (e.g., maintenance of biodiversity). Dispersion values for the naturalized segment were intermediate of those observed in the channelized segment and reference stream, suggesting greater complexity of flow conditions within the restored channel. Both velocity and dispersion varied as a function of discharge, and therefore their utility for characterizing restoration effects depends upon capturing a similar range of discharge conditions before and after channel modification. Transient storage was not sensitive to discharge, suggesting that diverse storage zones become active in water exchange during different phases of the stream hydrograph. Transient storage was quite uniform over a range of discharge conditions (excluding merged subreach) such that only three to four experiments were required to yield an average value within 10% of that attained from all experiments (10+) at a given site. The reliability of the method and its potential utility as an indicator of hydrologic processes relevant to stream functioning (e.g., in-stream structure, hyporheic exchange) suggest that transient storage may be a useful metric for assessing restoration success. An unresolved issue is the relationship between transient storage and nutrient uptake as some prior reports have suggested a positive association whereas others have not (*13*, *33*). Data from this study does not resolve this issue. Transient storage and nutrient uptake were lower in the channelized stream relative to the reference site, but naturalization of the channel resulted in higher nutrient uptake even when transient storage was unaffected.

Despite uncertainty about the importance of transient storage for nutrient retention, findings from the Wilson Creek study suggest that naturalization of channel form results in greater retention of both N and P. Prior studies have demonstrated the benefits of adding in-stream structure to increase water travel time and nutrient uptake (*16*, *17*), but the present study is the first to document these effects in a constructed channel designed to mimic morphological features of natural streams. Two factors should be considered in interpreting the broader significance of these findings. First, uptake coefficients measured in this study reflect in-stream processes for periods when discharge was below bank-full capacity. Although restoration of floodplain connectivity was a central feature of the restored channel, nutrient uptake within the floodplain was not measured due to logistical factors that limit the utility of injection experiments during flood conditions (e.g., need for large quantities of nutrients as well as stable flow and uniform lateral mixing). The restored channel enters its floodplain more frequently (vs incised prerestoration channel) and floodplain areas are biogeochemically active particularly for denitrification (*36*). Therefore, my findings represent a conservative estimate of likely gains in nutrient retention arising from restoration. Second, data collected in this study represent the short-term (2 year) effects of restoration which may or may not be indicative of long-term response. Development of in-stream structures through the accumulation of woody debris and secondary sorting of bed materials may lead to greater in-stream and hyporheic storage and further enhance nutrient retention. Continued monitoring will be required to assess the long-term effect of these and other processes (e.g., reestablishment of the riparian canopy) on nutrient retention in the restored reach. Despite these limitations, the findings of this study suggest that stream restoration is a useful management strategy in the context of basin-wide efforts to mitigate downstream nutrient transport.

Acknowledgments

I am indebted to Jeff Jack for providing data on the backwater area, Randall Kelly for his assistance in the field, and Rich Schultz for sample analyses (University of Louisville, Department of Biology). Thanks go to my co-investigators on the Wilson Creek Restoration Project: M. Shea (Bernheim Forest), A. Parola and W. Vesely (University of Louisville), and A. Datillo and C. Rhoades (University of Kentucky). R. Hall, P. Mulholland, and B. Gücker gave useful advice on methodology and data analyses. Funding for this project was provided by the Environmental Protection Agency.

Supporting Information Available

Channel restoration methodology including site map (Figure S1), results from a typical injection experiment (Figures S2, S3), Damköhler values (*DaI*), water chemistry for an adjoining backwater area (Figure S4). This material is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) Palmer, M.; Bernhardt, E.; Chornesky, E.; Collins, S.; Dobson, A.; Duke, C.; Gold, B.; Jacobson, R.; Kingsland, S.; Kranz,. R.; Mappin, M.; Martinez, M. L.; Micheli, F.; Morse, J.; Pace, M.; Pascual, M.; Palumbi, S.; Reichman, O. J.; Simons, A.; Townsend, A.; Turner, M. Ecology for a crowded planet. *Science* **2004**, *304*, 1251−1252.

(2) Bernhardt, E. S.; Palmer, M. A.; Allan, J. D.; Alexander, G.; Barnas, K.; Brooks, S.; Carr, J.; Clayton, S.; Dahm, C.; Follstad-Shah, J.; Galat, D.; Gloss, S.; Goodwin, P.; Hart, D.; Hassett, B.; Jenkinson, R.; Katz, S.; Kondolf, G. M.; Lake, P. S.; Lave, R.; Meyer, J. L.; O'Donnell, T. K.; Pagano, L.; Powell, B.; Sudduth, E. Synthesizing U. S. river restoration efforts. *Science* **2005**, *308*, 636−637.

(3) Muotka, T.; Laasonen, P. Ecosystem recovery in restored headwater streams: the role of enhanced leaf retention. *J. Appl. Ecol.* **2002**, *39*, 145−156.

(4) Nilsson, C.; Lepori, F.; Malmqvist, B.; Törnlund, E.; Hjerdt, N.; Helfield, J. M.; Palm, D.; Östergren, J.; Jansson, R.; Brännäs, E.; Lundqvist, H. Forecasting environmental responses to restoration of rivers used as log floatways: An interdisciplinary challenge. *Ecosystems* **2005**, *8*, 779−800.

(5) Scavia, D.; Rabalais, N. N.; Turner, R. E.; Dubravko, J.; Wiseman, W. J., Jr. Predicting the response of Gulf of Mexico hypoxia to variations in Mississippi River nitrogen load. *Limnol. Oceanogr.* **2003**, *48*, 951−956.

(6) Dodds, W. K. Nutrients and the "dead zone": the link between nutrient ratios and dissolved oxygen in the northern Gulf of Mexico. *Front. Ecol. Environ.* **2006**, *4*, 211−217.

(7) Fellows, C. S.; Valett, H. M.; Dahm, C. N. Whole-stream metabolism in two montane streams: Contribution of the hyporheic zone. *Limnol. Oceanogr.* **2001**, *46*, 523−531.

(8) Sabater, S.; Guasch, H.; Romani, A.; Munoz, I. The effect of biological factors on the efficiency of river biofilms in improving water quality. *Hydrobiologia* **2002**, *469*, 149−156.

(9) Bencala, K. E. Hyporheic exchange flows. In *Encyclopedia of Hydrological Sciences*; Anderson, M., Ed.; John Wiley & Sons Ltd.: New York, 2005; Vol. 3, Part 10, pp 1733−1740.

(10) Alexander, R. B.; Smith, R. A.; Schwarz, G. E. Effect of stream channel size on the delivery of nitrogen to the Gulf of Mexico. *Nature* **2000**, *403*, 758−761.

(11) Hall, R. O.; Tank, J. L. Ecosystem metabolism controls nitrogen uptake in streams in Grand Teton National Park, Wyoming. *Limnol. Oceanogr.* **2003**, *48*, 1120−1128.

(12) Mulholland, P.; Marzolf, E.; Webster, J.; Hart, D.; Hendricks, S. Evidence that hyporheic zones increase heterotrophic metabolism and phosphorus uptake in forest streams. *Limnol. Oceanogr.* **1997**, *42*, 443−451.

(13) Gücker, B.; Boëchat, I. G. Stream morphology controls ammonium retention in tropical headwaters. *Ecology* **2004**, *85*, 2818−2827.

(14) Packman, A. I.; MacKay, J. S. Interplay of stream-surface exchange, clay particle deposition, and streambed evolution. *Water Resour. Res.* **2003**, *39*, 1097.

(15) Rhoads, B. L.; Schwartz, J. S.; Porter, S. Stream geomorphology, bank vegetation and three-dimensional habitat hydraulics for fish in midwestern agricultural streams. *Water Resour. Res.* **2003**, *39*, 1218.

(16) Ensign, S. H.; Doyle, M. W. In-channel transient storage and associated nutrient retention: Evidence from experimental manipulations. *Limnol. Oceanogr.* **2005**, *50*, 1740−1751.

(17) Roberts, B. J.; Mulholland, P. J.; Houser, J. N. Effects of upland disturbance and in-stream restorations on hydrodynamics and ammonium uptake in headwater streams. *J. North Am. Benthol. Soc.* **2007**, in press.

(18) Riseng, C. M.; Wiley, M. J.; Stevenson, R. J. Hydrologic disturbance and nutrient effects on benthic community structure in midwestern US streams: a covariance structure analyses. *J. North Am. Benthol. Soc.* **2004**, *23*, 309−326.

(19) Stevenson, R. J.; Rier, S. T.; Riseng, C. M.; Schultz, R. E.; Wiley, M. J. Comparing effects of nutrients on algal biomass in streams

in two regions with different disturbance regimes and with applications for developing nutrient criteria. *Hydrobiologia* **2006**, *561*, 149−165.

(20) Rosgen, D. *Applied River Geomorphology*; Wildland Hydrology Books: Pagosa Springs, CO, 1996.

(21) Stream Solute Workshop. Concepts and methods for assessing solute dynamics in stream ecosystems. *J. North Am. Benthol. Soc.* **1990**, *9*, 95−119.

(22) Peterson, B. J.; Wollheim, W. M.; Mulholland, P. J.; Webster, J. R.; Meyer, J. L.; Tank, J. L.; Marti, E.; Bowden, W. B.; Valett, H. M.; Hershey, A. E.; McDowell, W. H.; Dodds, W. K.; Hamilton, S. K.; Gregory, S.; Morall, D. D. Control of nitrogen export from watersheds by headwater streams. *Science* **2001**, *292*, 86−90.

(23) Kemp, M. J.; Dodds, W. K. The influence of ammonium, nitrate and dissolved oxygen concentrations on uptake, nitrification and denitrification rates associated with prairie stream substrata. *Limnol. Oceanogr.* **2002**, *47*, 1380−1393.

(24) McIsaac, G. F.; David, M. B.; Gertner, G. Z.; Goolsby, D. A. Nitrate flux in the Mississippi River. *Nature* **2001**, *414*, 166−167.

(25) Bukaveckas, P. A.; Guelda, D. L.; Jack, J. D.; Koch, R.; Sellers, T.; Shostell, J. Effects of Point Source Loadings, Sub-basin Inputs and Longitudinal Variation in Material Retention on C, N and P Delivery from the Ohio River Basin. *Ecosystems* **2005**, *8*, 825−840.

(26) Mulholland, P. J.; Tank, J. L.; Webster, J. R.; Bowden, W. B.; Dodds, W. K.; Gregory, S. V.; Grimm, N. B.; Hamilton, S. K.; Johnson, S. L.; Marti, E.; McDowell, W. H.; Merriam, J. L.; Meyer, J. L.; Peterson, B. J.; Valett, H. M.; Wollheim, W. M. Can uptake length in streams be determined by nutrient addition experiments? Results from an interbiome comparison study. *J. North Am. Benthol. Soc.* **2002**, *21*, 544−560.

(27) *APHA Standard Methods for the Examination of Water and Wastewater*, 20th ed.; American Public Health Association: Washington, DC, 1998.

(28) Hart, D. R. Parameter estimation and stochastic interpretation of the transient storage model for solute transport in streams. *Water Resour. Res.* **1995**, *31*, 323−328.

(29) Runkel, R. L. A new metric for determining the importance of transient storage. *J. North Am. Benthol. Soc.* **2002**, *21*, 529−543.

(30) Harvey, J. W.; Wagner, B. J. Quantifying hydrologic interaction between streams and their subsurface hyporheic zones. In *Streams and Ground Waters*; Jones, J. B., and Mulholland, P. J., Eds.; Academic Press: New York, 2000; pp 3−44.

(31) Kasahara, T.; Hill, A. R. Hyporheic exchange flows induced by constructed riffles and steps in lowland streams in southern Ontario, Canada. *Hydrol. Processes* **2006**, *20*, 4287−4305.

(32) Sabater, F.; Butturini, A.; Martí, E.; Munoz, I.; Romani, A.; Wray, J.; Sabater, S. Effects of riparian vegetation removal on nutrient retention in a Mediterranean stream. *J. North Am. Benthol. Soc.* **2000**, *19*, 609−620.

(33) Hall, R. O.; Bernhardt, E. S.; Likens, G. E. Relating nutrient uptake with transient storage in forested mountain streams. *Limnol. Oceanogr.* **2002**, *47*, 255−265.

(34) Mulholland, P. J.; Steinman, A. D.; Elwood, J. W. Measurement of phosphorus uptake length in streams: comparison of radiotracer and stable PO4 releases. *Can. J. Fisheries Aquat. Sci.* **1990**, *47*, 2351−2357.

(35) Gücker, B.; Pusch, M. T. Regulation of nutrient uptake in eutrophic lowland streams. *Limnol. Oceanogr.* **2006**, *51*, 1443−1453.

(36) Baker, M. A.; Vervier, P. Hydrological variability, organic matter supply and denitrification in the Garonne River ecosystem. *Freshwater Biol.* **2004**, *49*, 181−190.

Received for review July 7, 2006. Revised manuscript received December 14, 2006. Accepted December 19, 2006.

ES061618X