Transient Storage, Discharge, and Nutrient Uptake in Small Streams of the Kolyma River Basin, Siberia

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Senior Integrative Exercise
March 10th 2010

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ABSTRACT

Discharge is increasing in arctic rivers and is predicted to continue to increase under future climate change scenarios. At the same time, permafrost thaw is predicted to increase with arctic warming, potentially increasing nutrient and organic matter inputs to headwater streams. Understanding how increased discharge will alter the ability of streams to process these material inputs is critical to assessing the potential impact of these changes on downstream ecosystems. Hydrologic factors, particularly transient storage of water as it moves downhill, are likely to change with discharge and to influence nutrient exports to larger streams. NH_4 and PO_4 enrichment experiments and conservative tracer additions were used to simultaneously assess nutrient uptake and the size of the transient storage zone in several small streams in the Kolyma River basin in Eastern Siberia. Results indicate a clear negative relationship between transient storage and discharge. Moreover, phosphorus uptake was negatively related to transient storage, while nitrogen uptake showed no relationship with transient storage. Results suggest the transient storage zone is relatively inactive in terms of nutrient uptake. Implications of this result are an increase in P uptake and a decrease in the N:P of uptake as discharge increases. Given the possibility that both discharge and nutrient inputs will increase as permafrost thaws, longer-term nutrient enrichment experiments are needed to develop predictions of change in these ecosystems with changes in climate.

Keywords: Transient storage, nutrient spiraling, arctic streams, discharge, nutrient uptake, active processing, Kolyma River

1. INTRODUCTION

In the coming century, warming is likely to be greater in arctic ecosystems than any other ecosystems on Earth (ACIA, 2005). One consequence of Arctic warming is the thawing of permafrost soils that underlay many Arctic ecosystems (Prowse et al., 2006). In Northeastern Siberia, permafrost is comprised of frozen organic-rich loess deposits, which represent important reservoirs of carbon (C) and other nutrients (Dutta et al., 2006). Permafrost thaw releases these reservoirs of organic matter (OM) and nutrients into the surrounding ecosystems. Thus, thawing presents a significant source of carbon, nutrients, and energy for organisms living in recipient ecosystems (Frey and Smith, 2005). To date, most studies have been concerned with processing of these materials in terrestrial soils, since elevated temperatures are likely to speed up bacterial decomposition and thus increase the rate of CO_2 respired to the atmosphere (Dutta et al., 2006). But in addition to being decomposed on land, liberated OM and nutrients can also leach into aquatic ecosystems as water moves through soils and into stream networks.

Much of this material originally enters surface water in small headwater stream channels, which occupy a key position in the Arctic landscape. Because these streams link terrestrial uplands to larger rivers and coastal oceans, they have the potential to regulate the export of dissolved organic carbon (DOC) and other nutrients (i.e. DON, DOP) to downstream ecosystems. In spite of the extensive area they occupy and the key position they hold in the cycle of nutrients, arctic headwater streams have received very little attention. The overarching goal of this study is to examine the role of these streams in the processing of organic matter and nutrient inputs from thawing permafrost, and how this impact may change as the Arctic warms.

Over the past three decades, following the publication of the "river continuum concept" (Vannote et al., 1980), there has been much research on the delivery and processing of terrestrial-derived organic matter in stream ecosystems. Terrestrial sources of organic matter generally dominate energy flow or organic matter flux through stream, riverine, and estuarine ecosystems (Mulholland et al., 1997; Frey and Smith, 2005; Holmes et al., 2008), but the fate of this material remains poorly understood (Webster and Meyer, 1997; Raymond and Bauer, 2000; Wetzel, 2001; Sobczak et al., 2005). Biological processes within streams alter the transport of organic matter to downstream ecosystems (Webster and Meyer, 1997), but the impact of these processes on carbon or nutrient cycling at larger scales is less clear. Cole et al. (2007) argue forcefully for the significance of inland aquatic ecosystems for global carbon cycling, suggesting that a large proportion of terrestrial-derived organic carbon is processed during hydrologic transport from terrestrial to marine ecosystems. They also point out the lack of quantitative information on the role of small streams, which they suggest could be substantial at the landscape scale and may further increase estimates of the impact of freshwater ecosystems. To help clarify the factors influencing the role of lotic ecosystems, they developed a conceptual model in which streams are classified as either 'active processors' or 'passive transporters' of carbon as a way to think about the impact of streams and rivers on biogeochemical cycling. This conceptual model can be expanded to include N and P cycles, and is the basic framework for this study (Fig. 1). Interestingly, a single stream can be classified as 'passive transporter' for some elements (i.e. conservative elements or elements that are not limiting to biological processes) and 'active processor' for others, depending on physical features and relative availability of

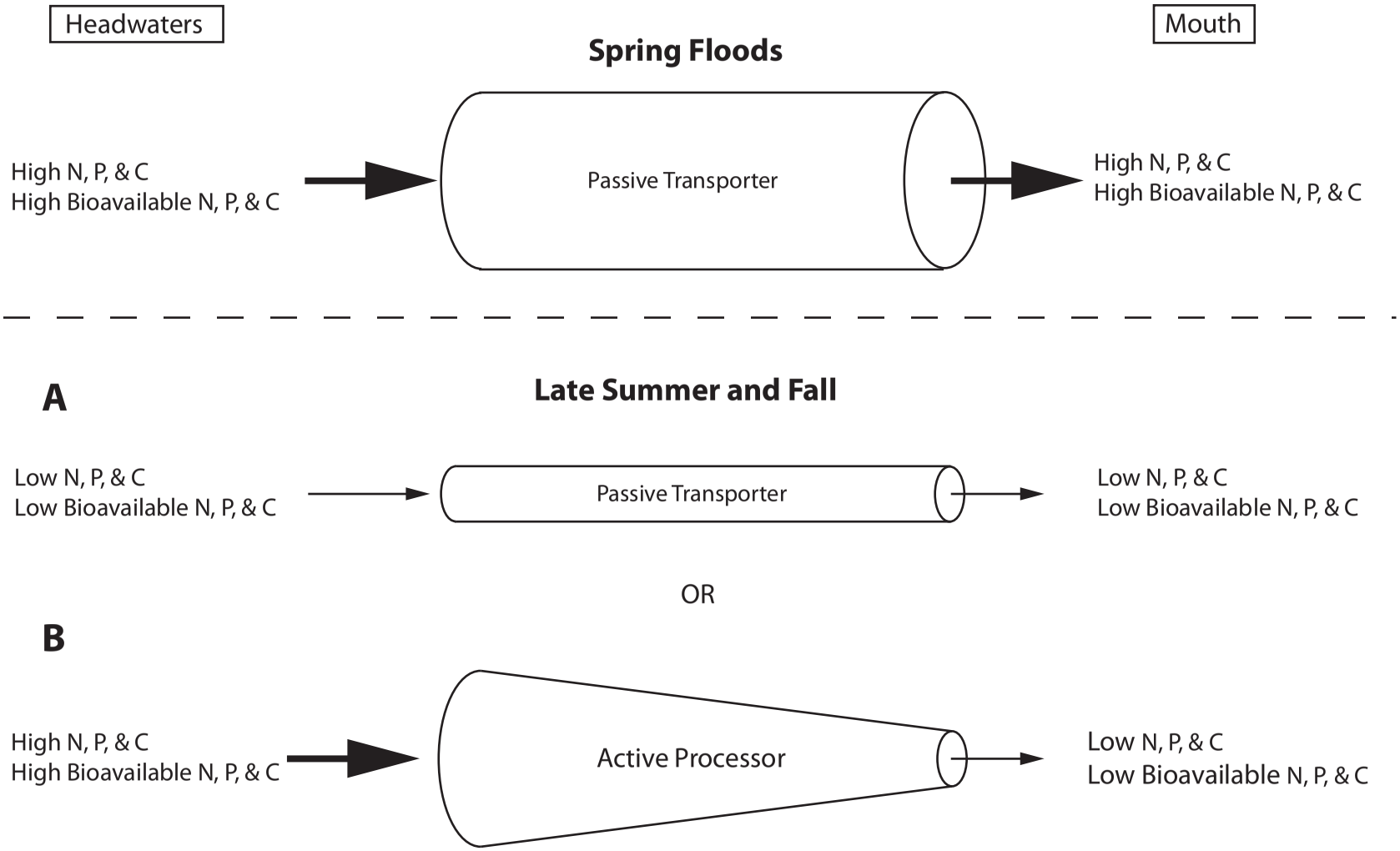

Figure 1. Conceptual model representing hypotheses about temporal variation in amount and bioavailability of Nitrogen (N), Phosphorus (P), and Carbon (C) and the role of headwater streams in processing each. During the spring floods, headwater streams are likely to be passive transporters. In late summer and fall, low concentration and bioavailability at the mouth suggests either A) universal low input to streams or B) or processing of bioavailable inputs from thawing permafrost in headwater streams. (Inspired by Cole et al. 2007)

elements. Furthermore, the classification of a particular stream may change over time as physical conditions change, for instance in the spring when discharge is high and/or biological activity is low, streams are more likely to be passive transporters (Holmes et al., 2008).

The main objectives of this study are to assess whether small arctic headwater streams are active processors or passive transporters of carbon or nutrients and whether hydrologic properties affect the rate of processing. I hypothesized that the small arctic streams of the Kolyma River basin are active processors. Previous work provides good evidence to suggest that small headwater streams play a disproportionate role in the uptake (removal from the water column) of carbon and nutrients. Alexander et al. (2000) found that nitrogen-loss rates declined rapidly with increasing channel size throughout the Mississippi watershed. Small streams have greater potential to develop into active processors than larger rivers because there is more contact between water and the streambed where microbes will decompose organic forms of nutrients (Sobczak and Findlay, 2002) and take up inorganic forms of nutrients (Alexander et al., 2000). Furthermore, carbon concentration and bioavailability within the Kolyma River basin showed significant declines with increasing channel size (Bill Sobczak, College of the Holy Cross, Personal Communication; Fig. 2).

Missing from Cole et al. (2007) is discussion of how in-stream hydrologic properties can dramatically affect the processing of water-borne carbon or nutrients. These hydrologic properties include discharge, morphology, and transient storage. Transient storage refers to the temporary detainment of water-borne solutes by stream features in “storage zones” such as eddies or porous sediments (Runkel, 1998). Carbon or

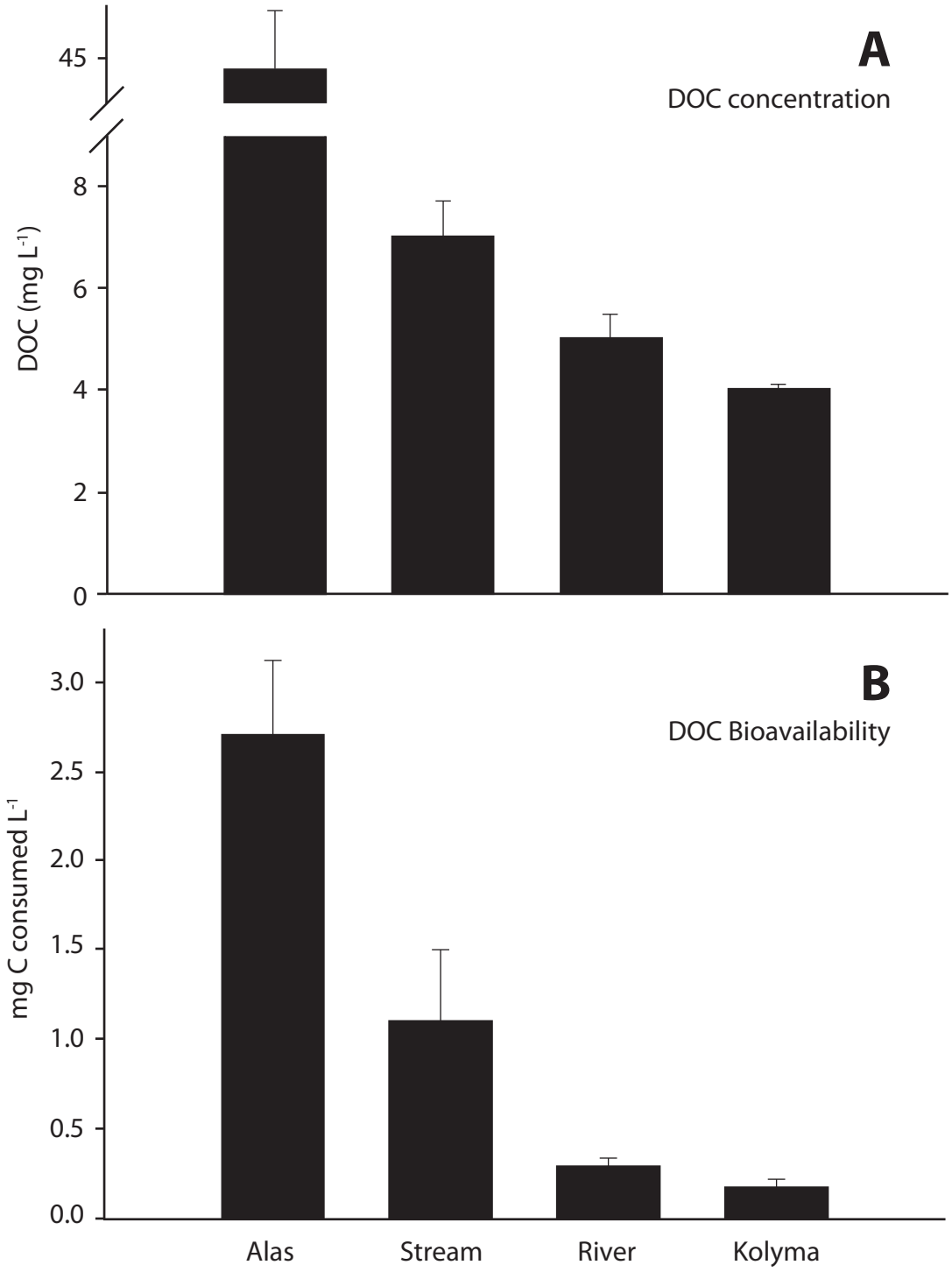

Figure 2. Measured dissolved organic carbon (DOC) concentrations (A) and bioavailability (B) in different sized waterbodies in the Kolyma River Basin during July, 2009.

nutrients can be retained in these storage zones and experience different rates of processing. I hypothesized that transient storage would be correlated to nutrient processing, although I could not predict whether transient storage would facilitate active or passive transport. Some studies relating transient storage and nutrient processing have found positive correlations, suggesting that biological activity or physical sorption can be facilitated by the detainment of solutes in storage zones (Hall et al., 2002). Other studies have found a negative relationship between transient storage and nutrient processing, which suggests that some transient storage zones may be biologically less active (Marti et al., 1997; Valett et al., 2002).

This study has two main objectives: to examine whether small arctic streams within the Kolyma Basin are active processors of N and P and to explore the affect of hydrologic properties on processing rates. Nutrient limitation likely plays a vital role in carbon processing, and thus an initial focus on N and P processing provides an important first look at the potential for active processing of carbon in small headwater streams.

2. STUDY SITE

The study area was located in the Kolyma River Basin, near the town of Cherskiy in Northeastern Siberia (Fig. 3). The Kolyma River Basin is unique in that it is the only watershed in the world underlain by continuous permafrost (Walter et al., 2006). This study focused on 5 streams, selected based on proximity to and accessibility from the Northeast Science Station. Two streams were located in the low-lying floodplain and three were located in the topographically higher Yedoma soils. Floodplain soils are primarily comprised of Holocene sediments whereas the Yedoma complex is a largely

Figure 3. Location of study site within the Kolyma River Basin. Stream locations were all within 5km of Cherskiy, Russia.

frozen and distinct deposit of Pleistocene loess-sediments that extends over much of Northeastern Siberia (Walter et al., 2007).

The surrounding Boreal Forest ecosystem is a densely vegetated and peat dominated landscape. All study streams tended to be small (discharge of .5-3 L/s) and beaded, with heavily vegetated banks and silty substrates. The floodplain stream channels were more silty, wide, and tortuous than those in the Yedoma soils.

3. METHODS

3.1 Experimental Solute Injections

Simultaneous injections of a conservative tracer (non-biologically active solute, i.e. Cl) and two biologically active solutes (PO_4 and NH_4) were conducted in 5 arctic streams during summer base flow in July, 2009. Of the 5 streams, 3 were located in Yedoma deposits and 2 were located in the topographically lower flood plain.

The solutes were added to 30 liters of stream water and dissolved in a separate reservoir. Solute concentrations varied based on the specific discharge of each stream. Streams with higher estimated discharge were injected with more a concentrated mixture. The concentrated mixture was added at a constant rate to the top of each reach (T1, Fig. 4) using a metering pump (Fluid Metering Inc.). Pump sites were chosen based on their degree of constriction and mixing potential. Constricted sites that were followed immediately by a riffle provided thorough mixing thereby ensuring an equal distribution of solutes downstream. Reach lengths varied from 40 to 60 meters and were divided into 5 equally spaced transects. Background water samples were taken at every transect prior to the injection.

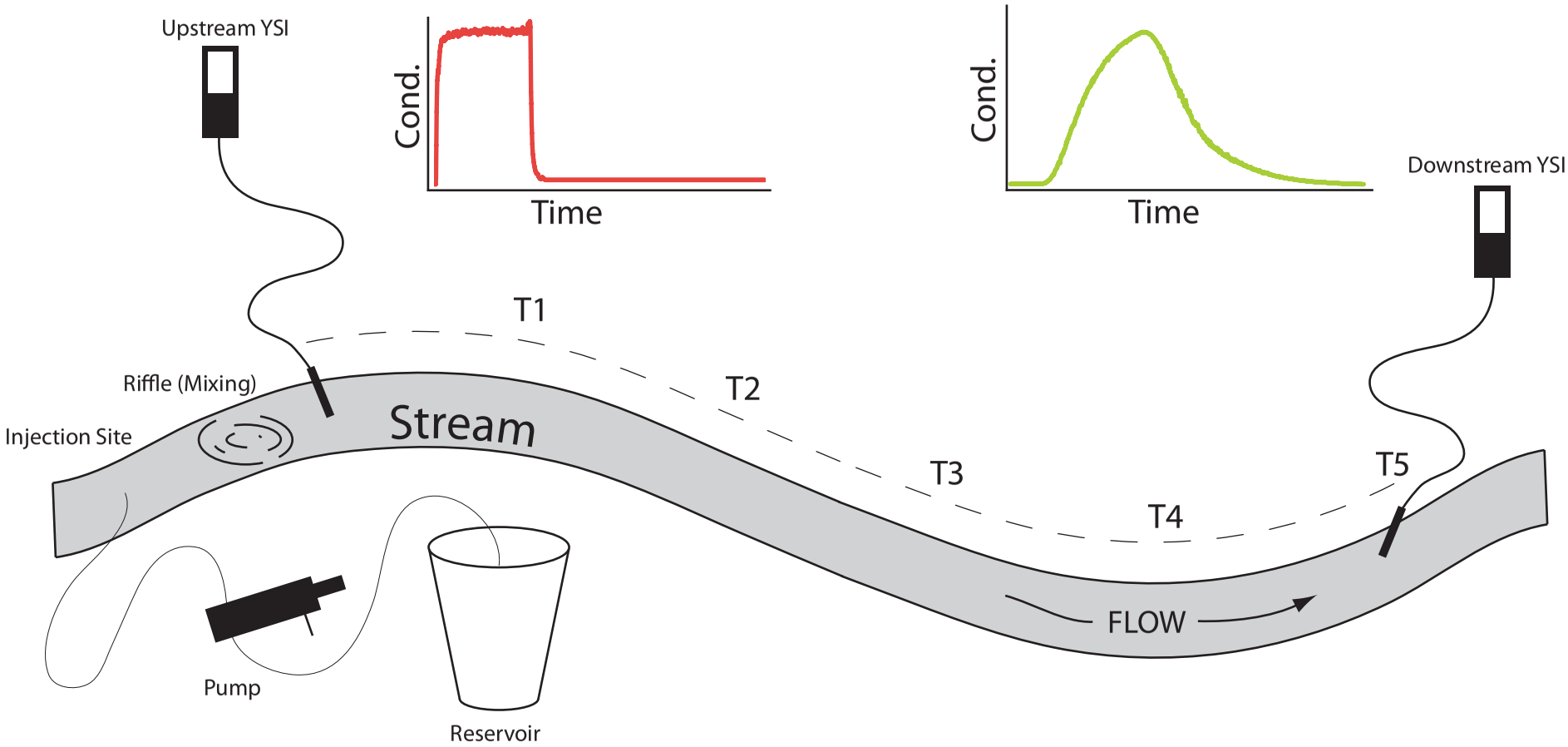

Figure 4. Example setup for solute addition experiment. T1 - T5 represent the different transects for nutrient sampling. The two plots illustrate times series of conductivity at T1 (red) and T5 (green).

Two YSI 560 multiprobe meters were used to monitor conductivity (a proxy for Cl concentration), temperature, dissolved oxygen, and pH. One YSI was placed just below the pump and mixing zone at the top of the reach while the second was placed at the last transect downstream (T5, Fig. 4). After the pumping commenced, the downstream YSI was monitored until it reached plateau. At this point, the entire stream was saturated with the mixture, and water samples were taken at each transect. Experimental setup is summarized in Figure 4.

3.2 Solute Transport Modeling

One-dimensional modeling of transport with transient storage was used to characterize some of the hydrologic properties of the sample streams. The model, One-Dimensional Transport with Inflow and Storage (OTIS), was developed by the USGS to characterize the fate of solutes in rivers and streams (Runkel, 1998), and has been used in many studies since (Edwardson et al., 2003; Salehin et al., 2003; Ensign and Doyle, 2005; Zarnetske et al., 2007). The OTIS model is an extension of the advection-dispersion equation, which accurately describes the movement of solutes in the main channel of a river or stream. The OTIS model is comprised of a set of mass balance equations for two conceptual parts of the stream 1) the main channel in which solute transport is governed by the advection-dispersion equation and 2) the storage zone, where advection and dispersion are disregarded because downstream transport from these zones is negligible (Runkel, 1998). Transient storage refers to the temporary retention of solutes in the storage zone, which may exist as small eddies, stagnant pools, or within the porous banks outside the main channel (Fig. 5). Because the fate of solutes, including organic

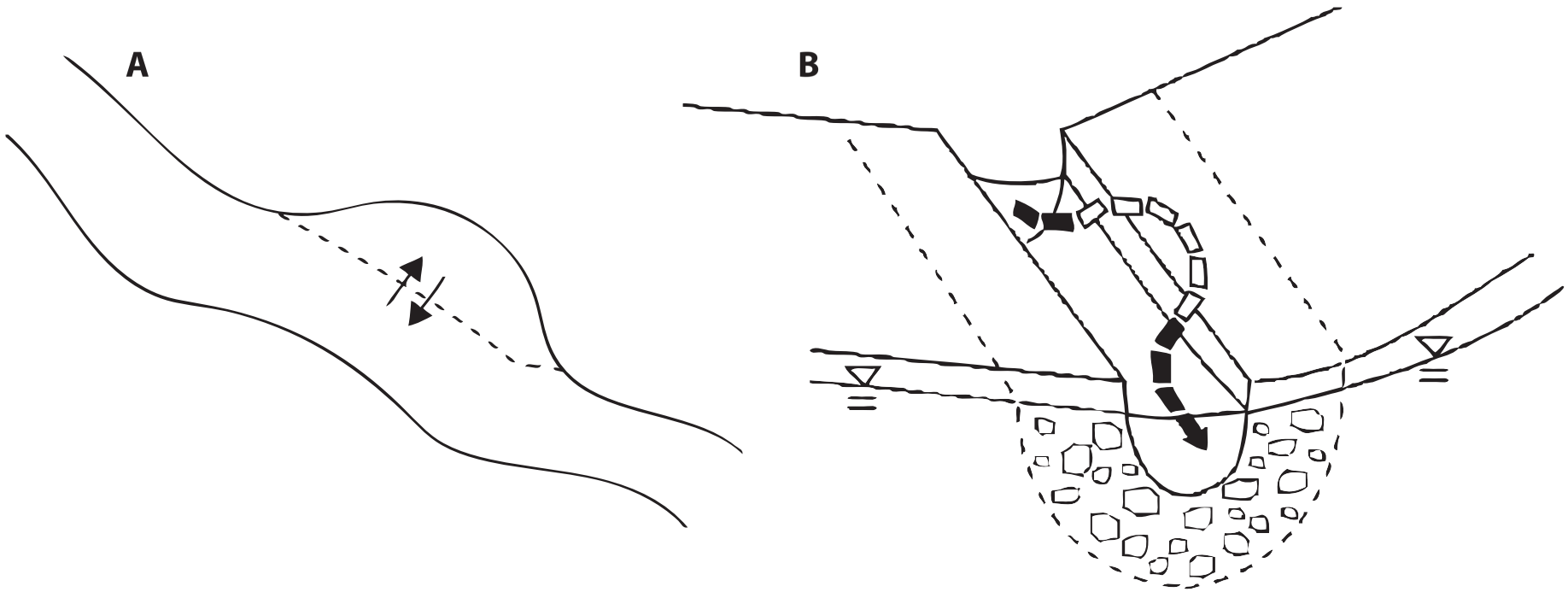

Figure 5. Schematic mechanisms of transient storage. Transient storage occurs when A) solutes enter a side pool or eddy and B) when solutes enter the porous sediments that comprise the bed and banks of the channel. Arrows indicate solute movement between the main channel and the storage zone. (Adapted from Runkel 1995)

matter and nutrients, can depend on the residence time and biological activity of different stream zones, it is important to experimentally model the physical size and exchange between the main channel and the transient storage zone.

The primary assumption of the model is that solute concentrations vary only longitudinally (hence the 'one-dimensional' model). In other words, it is assumed that solute concentrations do not vary with width or depth (Runkel, 2000). Lateral inflow and outflow, or the volume of water moving in and out of the stream for a given reach, were deemed to be a negligible component of channel flow due to the small reach lengths (max. 60 m). Over this short distance, the potential for lateral inflow or outflow to affect solute addition experiments is minimal (Ensign and Doyle, 2005). For this reason, OTIS was run assuming no lateral inflow or outflow. The mass balance equations used by the OTIS model to couple the concentration of solutes in (1) the main channel and (2) the storage zone are:

$$\frac{\partial C}{\partial t} = -\frac{Q}{A}\frac{\partial C}{\partial x} + \frac{1}{A}(AD\frac{\partial C}{\partial x}) + \alpha(C_S - C) \qquad (1)$$

$$\frac{\partial C_S}{\partial t} = \alpha\frac{A}{A_S}(C - C_S) \qquad (2)$$

where A is the main channel cross-sectional area (m^2), A_S is the storage zone cross-sectional area (m^2), C is the main channel solute concentration (spc m^{-3}), C_S is the storage zone solute concentration (spc m^{-3}), D is the dispersion coefficient (m^2 s^{-1}), Q is the volumetric flow rate or discharge (m^3 s^{-1}), t is time (s), x is distance (m), and α is the storage zone exchange coefficient (s^{-1}) (Modified from Runkel, 1998 to exclude lateral inflow/outflow).

These two equations describe only the physical processes that affect solutes in rivers or streams and thus can only be applied to conservative or non-reactive solutes (Runkel, 1998).

The OTIS model operates by taking the set of known parameters from the upstream YSI (the upstream boundary conditions) combined with the known discharge and projecting the downstream behavior based on a set of user specified conditions for A, A_S, D, and α. The projected behavior was then matched against the actual data recorded from the downstream YSI (Fig. 6). While the fitting is a trial and error process, the initial values for A, A_S, D, and α were constrained by known reasonable values (Steven Thomas, University of Nebraska, Personal Communication). Once a close fit for the downstream data was found manually, the user specified conditions were then input into an automated parameter estimation model (OTIS-P), which uses Nonlinear Least Squares (NLS) to optimize the original results. The optimized output from OTIS-P was then used for analysis.

3.3 Transient Storage Metrics

Three metrics were used to characterize transient storage in the five sample streams. First, the ratio of storage zone area to the main channel area (A_s/A) was used to provide a general comparison of the size of the two zones. This metric is limited in that it does not incorporate the rate of exchange between the two zones. For this reason, A_s/A does not reflect how long a given molecule spends in the storage zone. The second metric is the modeled storage zone exchange coefficient (α), which represents the rate at which molecules move between the main channel and the storage zone. The third metric, mean

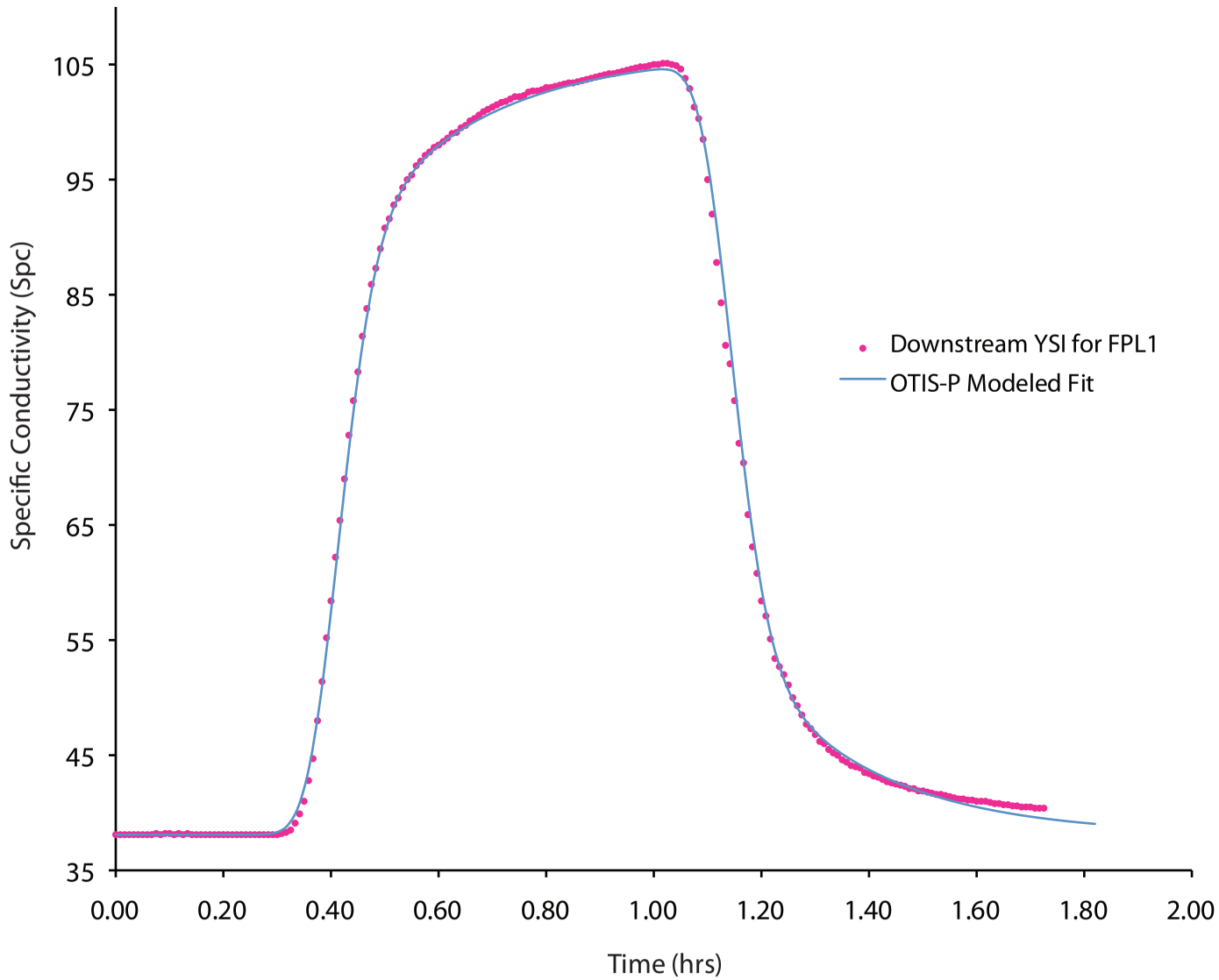

Figure 6. Specific conductivity measured in the channel (symbols) in FPL1 at 50 meters downstream of solute addition point. Solid line represents downstream pattern predicted by OTIS model.

storage residence time (t_{stor}), which represents the average time that a water particle spends in storage, is calculated as:

$$t_{stor} = \frac{1}{\alpha} \cdot \frac{A_S}{A} \quad (3)$$

where A_s/A is the ratio of the storage zone area to the main channel area and α is the storage zone exchange coefficient. Thus, t_{stor} is the most useful metric because it incorporates both the spatial ratio of the storage zone to the main channel and the exchange rate between the two zones.

3.4 The Damkolher Index

The Damkohler Index number (DaI) was calculated to evaluate the reliability of OTIS-P parameter estimations for each reach (Edwardson et al., 2003). Wagner and Harvey (1997) explain that the uncertainties in OTIS-P estimation of exchange rates and storage-zone size are strongly dependent on the experimental Damkohler number. The DaI is a dimensionless combination of the rates of exchange between the main channel and storage zones, the velocity, and reach length of the experimental stream. DaI is calculated as:

$$DaI = \frac{\alpha(1 + A/A_S)L}{v} \quad (4)$$

where α is the storage zone exchange coefficient, A is the main channel cross-sectional area, A_S is the storage zone cross-sectional area, L is the experimental reach length, and v is the stream velocity.

3.5 Nutrient Spiraling

To measure processing rates of N and P for the sample streams, short-term nutrient addition experiments were performed. Specifically, nutrient addition experiments were conducted to estimate uptake length (S_W, Fig. 7) and uptake rate (U, Newbold et al. 1981). Pump speeds and injectate concentrations were determined for each stream separately based on discharge (Q) estimates. Solutes (NH_4, PO_4, NaCl) were pumped into the stream at a constant rate at the top of the reach using a metering pump (Fluid Metering Inc) for several hours until plateau concentrations were reached; conductivity was measured at the top and bottom of the 50m reach to indicate when plateau concentrations were reached. Chloride acted as a conservative tracer and was used to calculate stream discharge and groundwater inflow through the experimental reach.

Triplicate water samples were taken at 10-meter intervals down the reach once all transects had reached plateau concentrations. Water samples were filtered through GFF filters immediately upon return the laboratory, and analyzed for NH_4, NO_3, SRP and DOC at the Northeast Science Station within 24 hours, or were preserved and analyzed within 7 days. NH_4 concentrations were measured using the fluorimetric method developed by Holmes et al. (1999) and modified by Taylor et al. (2007) on a Turner Designs Aquafluor portable fluorimeter. Phosphate was measured the molybdate colorimetric method on a Biotek microplate spectrophotometer. Background nutrient concentrations were subtracted from all plateau concentrations for statistical analysis to calculate spiraling metrics.

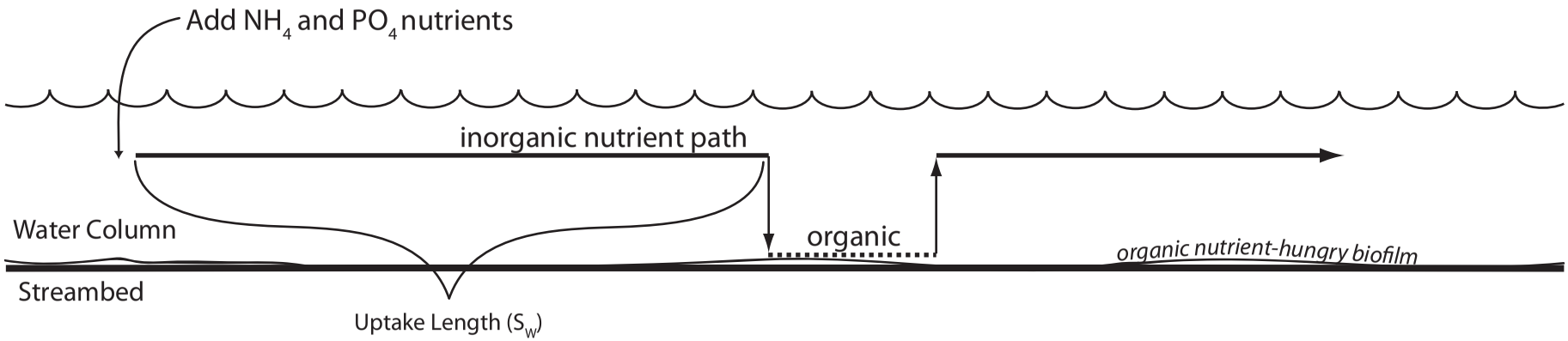

Figure 7. Diagram of nutrient uptake length (S_W) in a stream. Uptake Length is the distance a nutrient atom travels before it is taken up from the water column and converted to organic form.

3.6 Nutrient Uptake Calculations

Uptake lengths were estimated by regressing log-transformed, background-corrected nutrient concentrations at each plateau against distance downstream. The inverse of the regression slope is equivalent to the uptake length (S_W; Newbold et al., 1981) under specific enrichment conditions. Areal nutrient uptake rates were calculated as:

$$U = \frac{QC}{w \cdot S_W} \quad (5)$$

where U is the areal uptake rate (μg m^{-2} $s^{-}1$), Q is the discharge (L s^{-1}), C is the nutrient concentration (μg L^{-1}), and S_W is the uptake length (m).

4. RESULTS

4.1 Transient Storage Properties

The ratio of storage zone area to main channel area (A_s/A) displayed a strong inverse relationship with increasing discharge (Q) for four streams (R^2 = .95; Fig. 8A). It should be noted that A_S could not be accurately modeled for stream FPS2 due to incomplete upstream boundary conditions. For all streams, mean storage residence time (t_{stor}) decreased exponentially with increasing discharge, with a strong correlation (R^2 = .97; Fig. 8B). The relationships between discharge and A_S/A and t_{stor} are consistent, and they show a well-defined link between increasing discharge and decreasing transient storage in the sample streams.

The modeled storage zone exchange coefficient (α), which describes the rate of exchange between the main channel and storage zone, displayed a strong positive correlation with discharge among four streams (R^2 = .88, Fig. 9). As with A_S, α could not

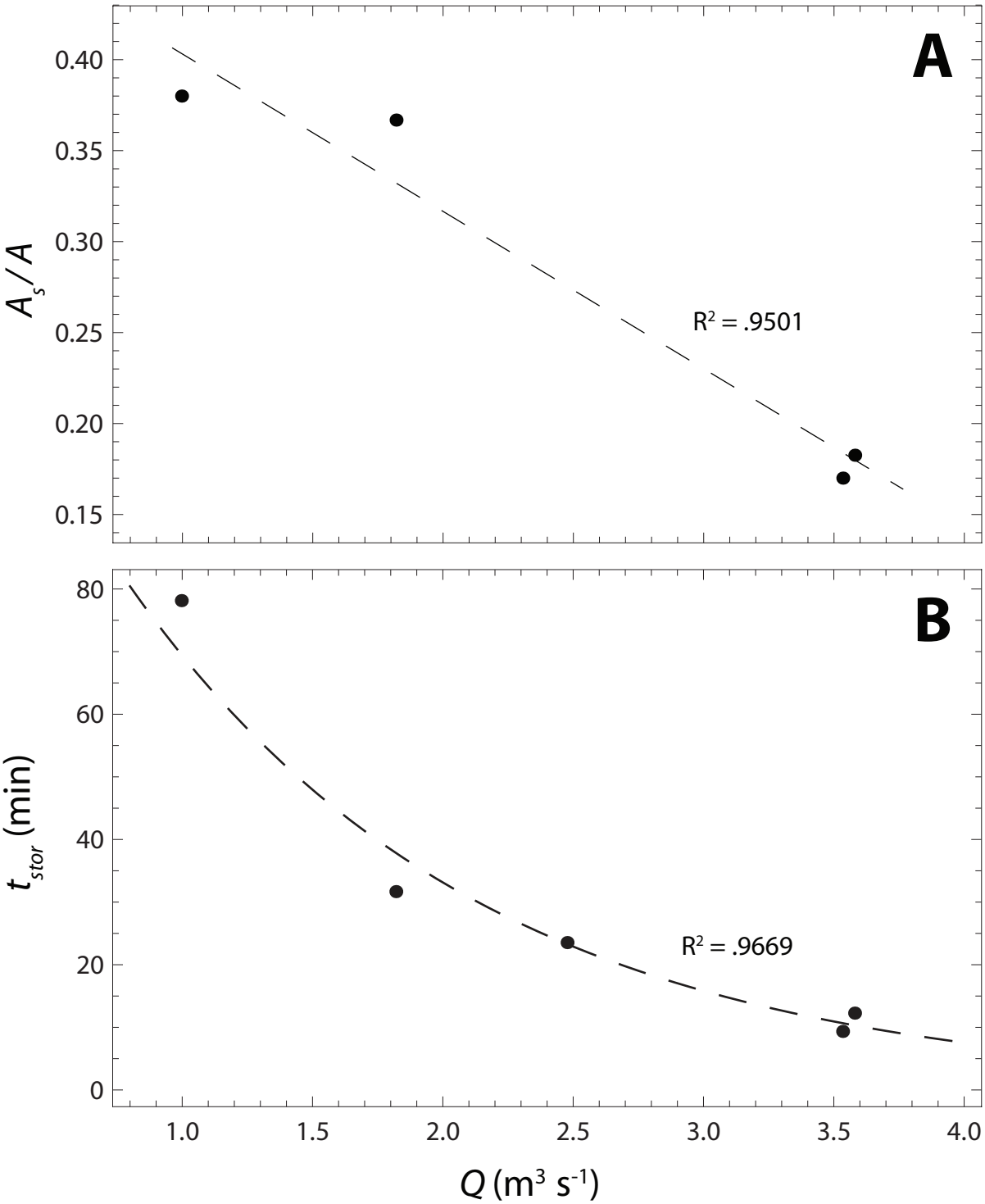

Figure 8. The relationship between discharge and (A) t_{stor} and (B) A_s/A for our study reaches. Note: A_s/A could not be accurately modeled for stream FPS2.

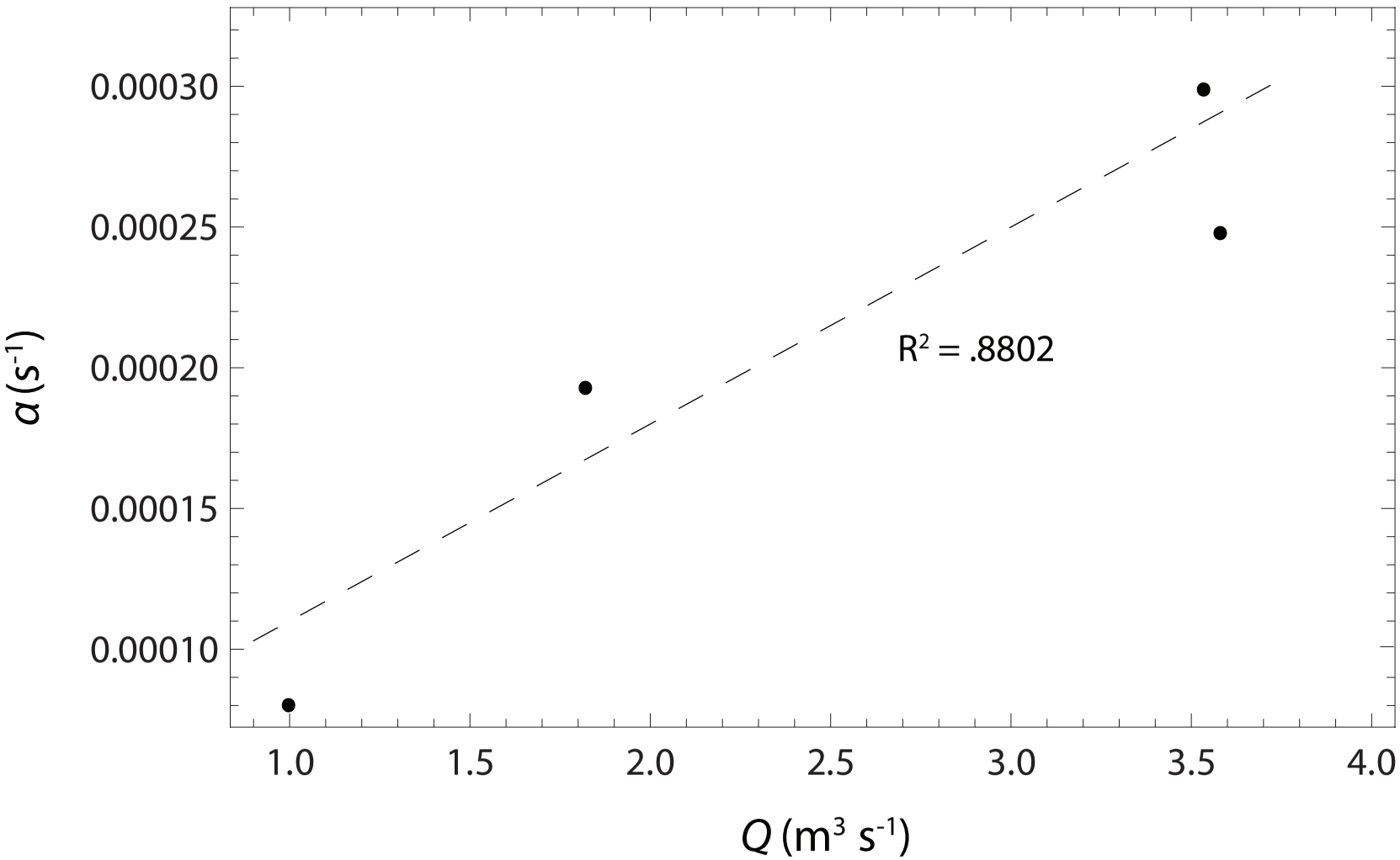

Figure 9. The relationship between storage zone exchange coefficient (α) and discharge (Q). Note: α could not be accurately modeled for stream FPS2.

be modeled for FPS2. The relationship between Q and α is also consistent with the above transient storage metrics; it shows how the storage zones become assimilated with the main channel as discharge increases, thereby reducing mean storage residence time and size of the storage zone. Transient storage stream metrics for all streams are summarized in Table 1.

4.2 Transient Storage Data Quality

Wagner and Harvey (1997) explain that parameter estimation uncertainties are lowest at DaI values on the order of 1.0. For DaI values much less than 1.0, parameter uncertainties are high due to high velocity, long exchange timescale, and/or short reach lengths. For DaI much greater than 1.0, solute exchange rates are fast relative to the stream velocity and thus all of the solute is exchanged with the storage zone. Wagner and Harvey (1997) experimentally manipulated the reach length to find the effect of the DaI on the coefficient of variation and found that the coefficient of variation for A_S and α estimates remains below ~0.5 from DaI values of 0.2-15. For this study, the DaI values for all streams ranged from good (~1) to acceptable (~5) (Edwardson et al., 2003). Interestingly, while all sample stream DaI values were in the acceptable range, they all exhibited values greater than 1.0. According to Wagner and Harvey (1997), the uncertainty of these slightly elevated DaI values tends to blend the effects of dispersion and storage zone exchange. This uncertainty is expected in streams where flow is extremely low and dispersion is high. DaI numbers for all streams are summarized in Table 1.

Stream	Date	Type	Q (m^3 s^{-1})	u (m/s)	A_S/A	α (s^{-1})	t_{stor} (min)	DiA
TDO	7/14/09	Yedima	1.820	7.37E-03	0.367	1.93E-04	31.7	4.88
DVY	7/17/09	Yedima	3.534	1.83E-02	0.170	2.99E-04	9.4	5.68
Y4_7	7/20/09	Yedima	0.997	1.04E-02	0.380	8.03E-05	78.1	1.41
FPS1	7/20/09	Flood Plain	3.580	1.66E-02	0.183	2.48E-04	12.3	4.84
FPS2	7/23/09	Flood Plain	2.477	8.05E-03	0.077	5.47E-05	23.5	4.74

Table 1. Discharge conditions, Optimized OTIS-P Solute Transport Model Parameters, and Transient Storage Metrics for all streams.

4.3 Nutrient Uptake

Mean uptake lengths of N (S_{WN}) were much longer in Floodplain streams than Yedoma streams (455 and 81 respectively; p = 0.006; Fig. 10A), while uptake lengths of P were similar (31 and 52 respectively; p = 0.43; Fig. 10A). As a result, S_{WN}:S_{WP} were much higher in Floodplain than Yedoma streams (15 and 1.6 respectively, p = .005; Fig. 10B). U_N and U_P showed a similar pattern to uptake lengths, although the differences were not statistically significant (Fig. 11A). The ratio of U_N:U_P was higher in Yedoma streams than Floodplain streams, although this difference was only marginally significant (p = .056; Fig. 11B).

Within Yedoma streams, S_{WN} and S_{WP} uptake lengths were not significantly different (~55-65m, p = .53), suggesting that these streams are co-limited by P and N (Fig. 10A). In the Floodplain streams however, P uptake lengths were significantly lower than N uptake lengths (~30 and ~450 respectively; p = .003; Fig. 10A), suggesting the possibility that the streams are P limited.

Uptake length for N and P also varied differently with discharge. In all streams, uptake length of P generally decreased with increasing discharge (Fig. 12A). Uptake lengths of N displayed a weak positive relationship with discharge and a clear difference between Yedoma and Floodplain streams (Fig. 12B). Floodplain streams exhibited much higher uptake lengths of N relative to the Yedoma streams, despite their similar discharge (Fig. 12B).

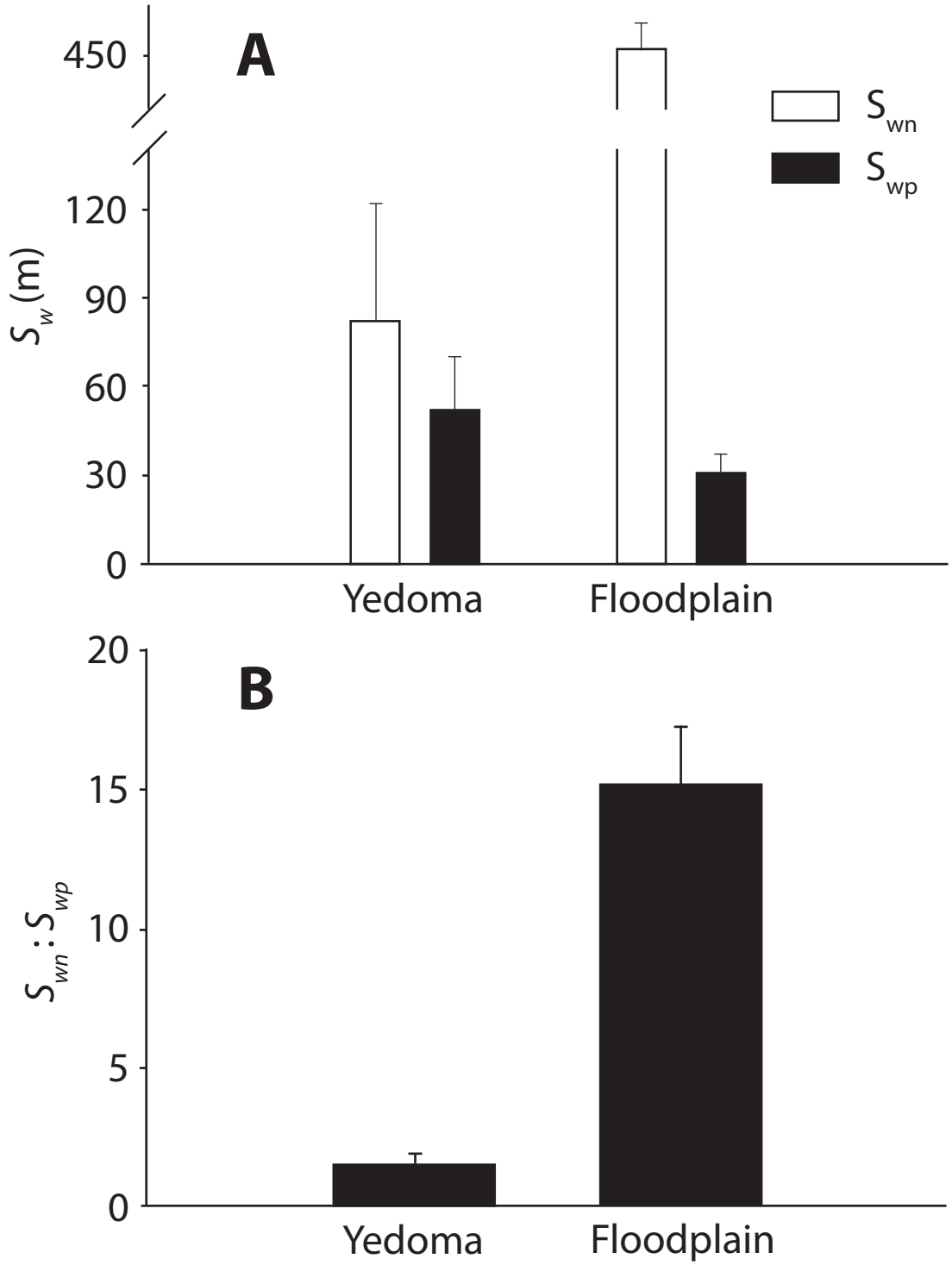

Figure 10. (A) Uptake lengths for N and P and (B) ratio of uptake lengths for Yedoma and Floodplain streams. Error bars indicate standard error.

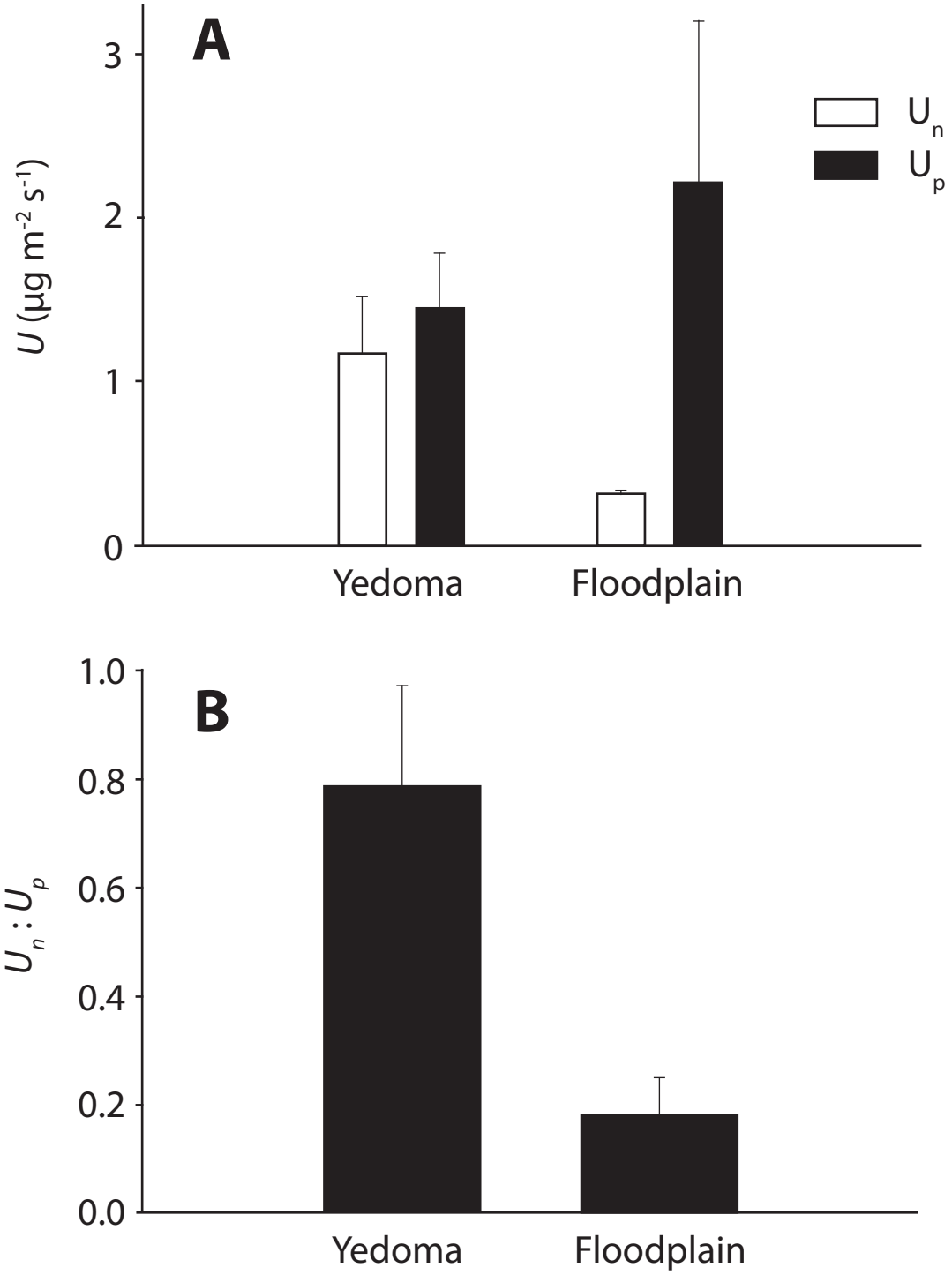

Figure 11. A) Uptake rates of N and P and (B) Ratio of uptake rates for Yedoma and Floodplain streams. Error bars indicate standard errror.

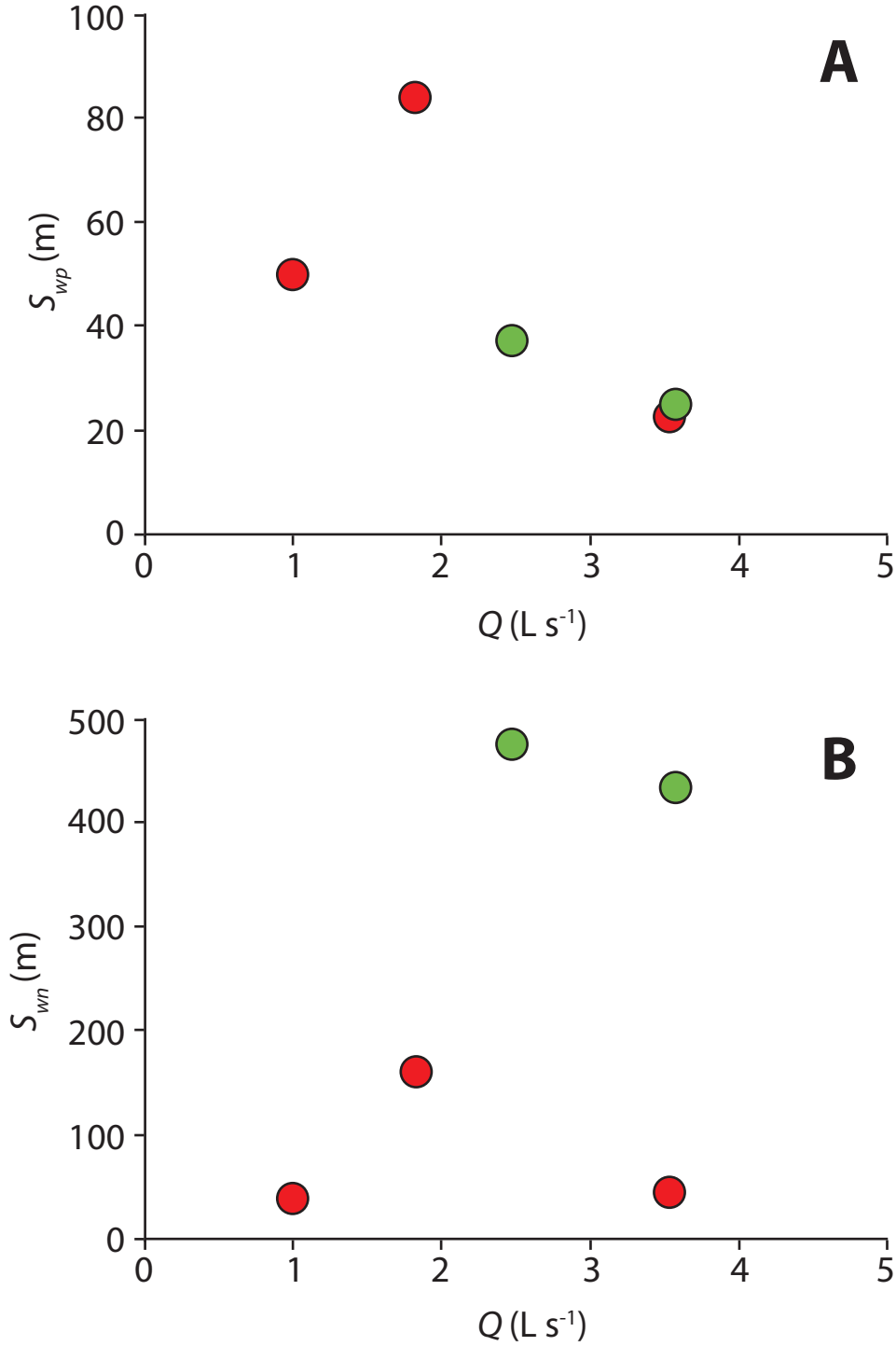

Figure 12. The relationship between uptake length (S_W) and discharge for (A) P and (B) N . Green points represent Floodplain streams and red points represent Yedoma streams.

4.4 Nutrient Uptake Relative to Transient Storage

For all streams, U_P decreased with transient storage (t_{stor}) (R^2 = ~.53; Fig. 13), while U_N showed no relationship with t_{stor}. Nutrient uptake length for P (S_{wp}) increased with transient storage, but this relationship was weaker (R^2 = ~.30). Again, N uptake length showed no relationship with transient storage.

5. DISCUSSION

5.1 Nutrient Uptake

Nutrient spiraling results indicate that Yedoma streams are active processors of N and P, while Floodplain streams are active processors of P and passive transporters of N. In Yedoma streams, both uptake lengths and rates were similar for N and P, which indicate an equal demand for both nutrients. In Floodplain streams, however, uptake lengths for P were significantly shorter than N. Correspondingly, uptake rates of P were more than 5 times those of N. Bacteria living in the stream require specific amounts of N and P to carry out their metabolic functions (Sterner and Elser 2002). Assuming that uptake is biological, this disproportionate demand for P in Floodplain streams may indicate a scarcity of P relative to N. Thus, P can be considered limiting in Floodplain streams, whereas both N and P are co-limiting in Yedoma streams.

The difference in nutrient demand between Yedoma and Floodplain may be biological or physical (Hall and Tank, 2003). In other words, the bacterial community living in Floodplain stream channels may be in metabolic need of P, which would increase the uptake rate. Alternatively, the elevated uptake rates of Phosphorus may be due to physical sorption, a process by which P is taken out of the water column through

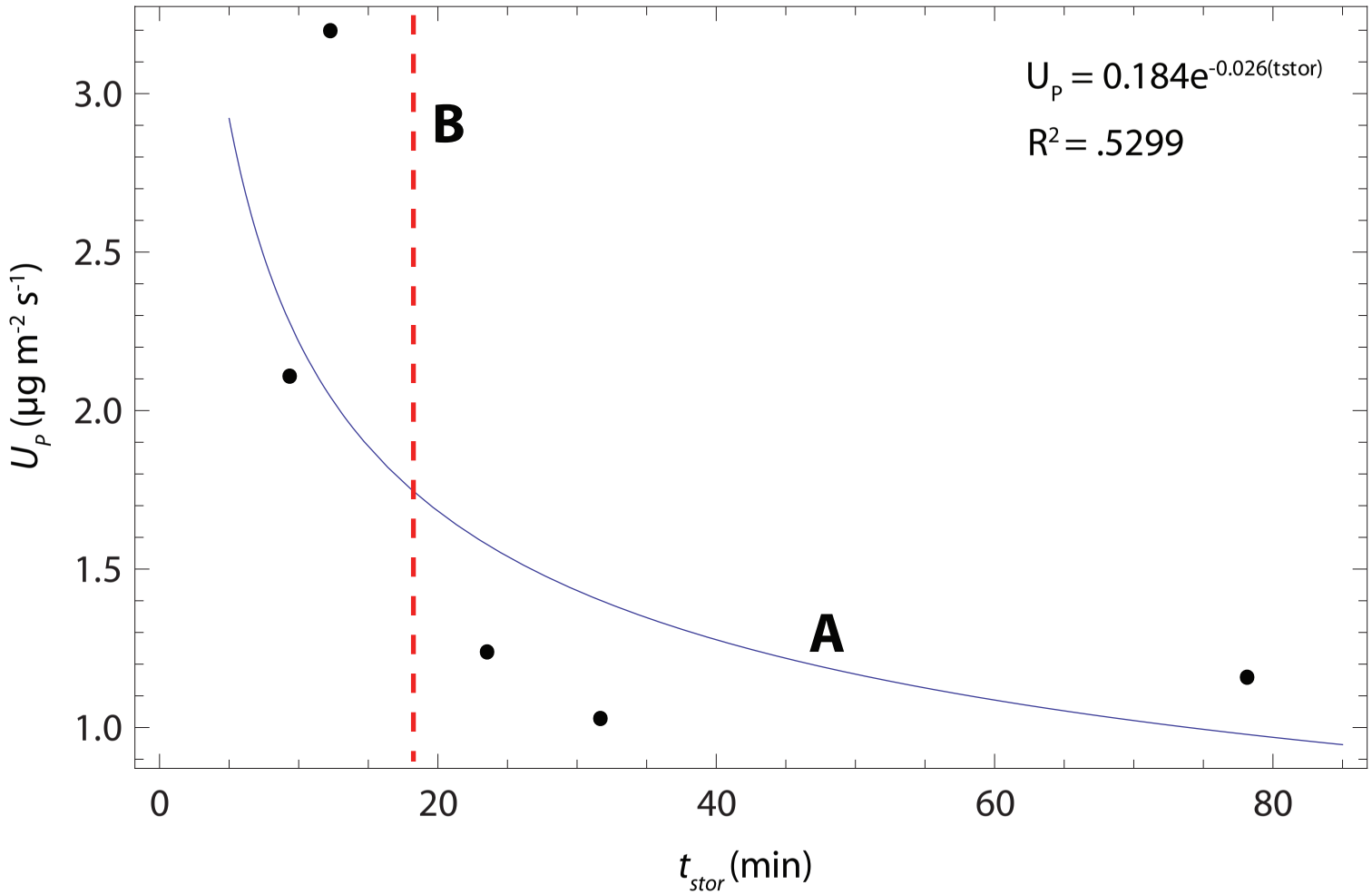

Figure 13. Relationship between U_P and transient stroage (t_{stor}). The relationship can be interpreted two ways: (A) the general decrease in U_P with increasing t_{stor} represented by the solid line or (B) as a t_{stor} threshold for uptake of P represented by the dashed line.

its chemical attraction to certain sediments (Lottig and Stanley, 2007). Thus, the P limitation in Floodplain streams could reflect a biologic demand or a physical condition unique from Yedoma streams.

Regardless of how P is taken up, nutrient uptake patterns indicate a difference in biogeochemical cycling between Yedoma and Floodplain streams, which may reflect differences in the surrounding soil. Yedoma soils are comprised of Pleistocene loess sediments and are rich in nutrients and carbon (Zimov et al., 2006). If both N and P are in abundance in Yedoma soils, this pattern may explain apparent co-limitation uptake processes by N and P in Yedoma streams. Floodplain streams, on the other hand, are surrounded by more recent Holocene sediments, which are relatively depleted in nutrients (Zimov et al., 2006). Thus, it is likely that the surrounding soils and their relative nutrient content are impacting the availability of nutrients to the sample streams. Indeed, the relationship between soil nutrients and their stream availability has been well documented in ecosystems around the world (Dillon et al., 1975; Mulholland, 1992; Sebestyen et al., 2008).

5.2 Transient Storage and Discharge

The results of this study are in agreement with previous studies that found an inverse relationship between transient storage (t_{stor}, A_s/A) and discharge (Q) (Zarnetske et al., 2007; Edwardson et al., 2003; D'Angelo et al., 1993). Transient storage seems to be driven by discharge, as evidenced by the strong correlations (>.95) between t_{stor} or A_s/A and Q.

The pattern of increasing exchange rate (α) with increasing discharge is consistent with hydrodynamic theory and the direct relationship between velocity and hyporheic exchange (Packman and Salehin, 2003). In essence, as discharge increases, the rate of exchange between storage zones and the main channel increases. Effectively, this greater exchange rate assimilates the storage zones and the main channel. Thus, the clear relationship between α and discharge provides insight into the mechanism by which discharge influences transient storage.

Zarnetske et al. (2007) found similarly strong correlations between discharge and transient storage in small arctic tundra streams. They suggested that the dominance of discharge might be due to the fact that their study streams were underlain by permafrost. Insofar as this permafrost was a barrier to deeper hyporheic exchange with groundwater aquifers and sediments, greater discharge may have resulted in increased advection and turbulent flow rates within the storage zones. Thus, the permafrost boundary in the sample streams may have increased the amount of 'flushing' in the storage zones, thereby amplifying the effect of discharge on the exchange rate (α).

5.3 Transient Storage Location

One of the limitations of the OTIS model is that it cannot differentiate between possible storage locations. Thus, the results of this study give no indication as to whether transient storage occurred in the hyporheic zone or in surficial pockets such as eddies. In their study of small arctic streams, Zarnetske (2007) did not find a significant relationship between transient storage and the depth of the thaw bulb underneath the stream. If storage were hyporheic, increasing the thaw bulb would presumably increase the size of the

transient storage zone, since the space between the sediments left from thawed ice could be filled by stream water. This suggests that the transient storage in their study streams may have been primarily due to surface features. In-channel storage is commonly produced by eddies, side pools, and slowed sections due to debris or vegetation (Runkel, 1998). This study's streams are characterized by dense stream vegetation and debris, suggesting the possibility that transient storage is caused by in-channel features. Furthermore, the stream banks of all 5 of the sample streams were comprised of silt to mud sized sediments, which likely reduced the porosity of the hyporheic zone and thereby lowered the potential for stream water to enter the hyporheic zone.

5.4 Transient Storage in Arctic and Temperate Streams

The results from this study indicate that the transient storage dynamics of arctic study streams are comparable to those in temperate ecosystems. The average A_S/A for the 5 study streams was ~.24 which is similar to the range of mean values of .2-.6 for temperate streams (Harvey et al., 2003; D'Angelo et al., 1993). Furthermore, the mean for this study is notably similar to the values reported by Zarnetske (2007) and Edwardson et al. (2003) who reported .31 and .32, respectively, for comparably small arctic streams.

5.5 Transient Storage and Nutrient Uptake

Results from this study also indicate that hydrologic properties, particularly transient storage, are likely affecting N and P processing rates. The results can be interpreted two ways. The first interpretation considers only the general decrease in U_P

with increasing t_{stor}. This inverse relationship is consistent with previous studies that found the transient storage zone to be less biologically active relative to the main channel (Marti et al., 1997; Valett, 2002). If uptake is biological, the location of transient storage can greatly affect whether nutrient uptake is positively or negatively correlated with size of the transient storage zone. When transient storage is primarily hyporheic, water flowing through sediments is more likely to reach biofilms, the site of most biological uptake (Mulholland et al., 1997; Harvey and Wagner, 2000; Hall et al., 2002). In this situation, higher transient storage reflects longer hyporheic residence times, which correspond to higher rates of biogeochemical processing, and a positive relationship between uptake and transient storage (Findlay, 1995). Alternatively, the storage zones may be located in in-channel features, such as side pools or eddies, which are less biologically active than the hyporheic zone. In these zones, the interaction between the water column and the sediments is lower, reducing the opportunity for microbes to take up nutrients (Hall et al., 2002). Thus, the negative relationship between transient storage and nutrient uptake found in this study would suggest that the storage zones modeled in the study streams were primarily surface zones. The qualitative observations of dense vegetation both in-stream and along the stream bank, the abundance of side pools, and the fine sediment size within the channel, also indicate surficial storage.

The second interpretation considers the dramatic drop in U_P above about 20 minutes of storage (t_{stor}) seen in Figure 13. While the sample size in this study is too small to say anything definitive, this sudden drop may indicate a transient storage threshold for P uptake, which would present an alternative relationship to the general inverse relationship discussed above. This would suggest that when the mean storage residence

time (t_{stor}) is above ~20 minutes, water spends disproportionately more time in the biological inactive storage zones and thereby reduces the rates of biogeochemical processing. Because t_{stor} is so closely related to discharge, this trend can also be seen in Figure 12A, where increasing discharge corresponds with an increase in U_P. In other words, for active processing of P, discharge must be high enough to overcome the residence times in biologically inactive storage zones. It has been widely acknowledged that nutrient uptake varies with discharge (Ensign and Doyle, 2006). All else being equal, nutrient uptake lengths are expected to increase with discharge. Thus, most studies report an upper threshold at which high discharges flush nutrients through the stream too quickly to be processed. If the drop in uptake rates with t_{stor} above 20 minutes is indeed a threshold, than this study suggests that small streams may be more affected by a lower threshold, at which low discharge contributes to higher storage in biological inactive zones.

If uptake is physical rather than biological, the location of transient storage is still likely to be surficial. If transient storage were primarily hyporheic, than as the time spent in storage zones increased, P molecules would have more time to interact with potentially sorptive sediments, thereby increasing uptake (Lottig and Stanley, 2007). Since this is not the pattern observed in this study, transient storage is likely to be surficial, regardless of whether or not uptake is due to physical sorption.

5.6 Implications with Climate Change

The patterns of nutrient uptake in the study streams, whether physical or biological, suggest that Yedoma streams are active processors of N and P, whereas Floodplain streams are active processors of P but passive transporters of N.

In the arctic, both permafrost thaw and discharge are projected to increase with continued warming (Peterson et al. 2002, Frey et al. 2007). In a study in West Siberia, Frey et al. (2007) found that with further permafrost thaw due to warming, export of DON, total dissolved nitrogen (TDN), and total dissolved phosphorus (TDP) are predicted to increase by ~30-50% by the year 2100. These changes are not likely to be isolated to West Siberia; warming in the Kolyma River basin is also likely to increase discharge and nutrient input. As this study has suggested, when discharge increases, transient storage decreases and nutrient uptake increases. If Yedoma streams are active for both N and P, that is, if Yedoma streams are not limited by a single nutrient, then their response to changes caused by warming are critical. The processing responses of Yedoma streams are of particular interest given their vast quantities of stored carbon (Zimov et al. 2006). In short, with continued warming, processing rates in Yedoma streams will likely first increase, due to an influx of C, N, and P, higher discharge, and lower transient storage. Yet this relationship will likely change if discharge increases substantially, given the extremely low discharge of Yedoma streams.

6. CONCLUSIONS

Nutrient spiraling results suggest that Yedoma streams are active processors of both N and P, while floodplain streams are active processors of P, but appear to be relatively passive transporters of N. Thus, N and P processing results of this study build

on the carbon-processing model provided by Cole et al. (1997) by suggesting that small streams may be active processors of other nutrients. Carbon processing may be strongly influenced by the availability of limiting nutrients (Holmes et al. 2008), emphasizing the importance of N and P cycling for understanding the carbon cycle within small streams. Thus, this study provides an initial framework on which the biogeochemical cycles of N, P, and C can be linked.

This study expands on the Cole et al. (2007) model, by incorporating the role of hydrologic properties on nutrient cycling. Results from this investigation indicate that transient storage dynamics within small arctic streams in the Kolyma River basin are primarily governed by discharge. Furthermore, the results indicate that nutrient uptake may be inversely related to transient storage. This relationship, along with the qualitative observations of the sediment composition and dense vegetation in the 5 streams, points to surficial storage where there is either less biogeochemical processing or less physical sorption.

Future warming in the arctic is likely to result in permafrost thaw and increasing discharge within the Kolyma River basin, both of which have the potential to increase nutrient inputs to, and fluxes from, small streams in the Arctic. Results from this study suggest that increasing discharge may actually increase processing rates of materials in these streams, at least for P. Given the immense stores of carbon that remain frozen in the permafrost, this preliminary study illuminates the need for further research into the biogeochemical processing potential of small arctic streams, especially with respect to the biological influence on nutrient uptake. As suggested by Cole et al. (1997), these small streams may occupy key positions in the carbon cycle. If carbon is released by thawing

permafrost and actively processed in recipient streams, it can be converted to CO_2 and exported directly out of the stream to the atmosphere rather than exported to the ocean. By coupling the biogeochemical cycles of N, P, and C, future research can assess the extent to which small arctic streams will influence carbon fluxes, and the potential for future climate change. Thus, it is crucial that future studies examine the relationships between carbon and other nutrient cycles, as well as the general ecosystem functions of small arctic streams.

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8. REFERENCES

Alexander, R., Smith, R., and Schwarz, G., 2000, Effect of stream channel size on the delivery of nitrogen to the Gulf of Mexico: Nature, v. 403, p. 758-761.

Arctic Climate Impact Assessment, 2005, Arctic Climate Impact Assessment: Cambridge University Press, New York, 1042 pp. (Available at http:// www.acia.uaf.edu)

Cole, J. J., Prairie, Y. T., Caraco, N. F., McDowell, W. H., Tranvik, L. J., Striegl, R. G., Duarte, C. M., Kortelainen, P., Downing, J. A., Middelburg, J. J., and Melack, J., 2007, Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget: Ecosystems, v. 10, p. 171-184.

D'Angelo, D., Webster, J., Gregory, S., And Meyer, J., 1993, Transient storage in appalachian and cascade mountain streams as related to hydraulic characteristics: Journal of the North American Benthological Society, v. 12, p. 223-235.

Dillon, P., and Kirchner, W., 1975, Effects of geology and land-use on export of phosphorus from watersheds: Water Research, v. 9, p. 135-148.

Dutta, K., Schuur, E. A. G., Neff, J. C., and Zimov, S. A., 2006, Potential carbon release from permafrost soils of Northeastern Siberia: Global Change Biology, v. 12, p. 2336-2351.

Edwardson, K., Bowden, W., Dahm, C., and Morrice, J., 2003, The hydraulic characteristics and geochemistry of hyporheic and parafluvial zones in Arctic tundra streams, north slope, Alaska: Advances in Water Resources, v. 26, p. 907-923.

Ensign, S., and Doyle, M., 2005, In-channel transient storage and associated nutrient retention: Evidence from experimental manipulations: Limnology and Oceanography, v. 50, p. 1740-1751.

Ensign, S. H., and Doyle, M. W., 2006, Nutrient spiraling in streams and river networks: Journal of Geophysical Resources - Biogeosciences, v. 111, p. G04009.

Findlay, S., 1995, Importance of surface-subsurface exchange in stream ecosystems - the hyporheic zone: Limnology and Oceanography, v. 40, p. 159-164.

Frey, K., and Smith, L., 2005, Amplified carbon release from vast West Siberian peatlands by 2100: Geophysical Research Letters, v. 32, p. L09401.

Frey, K. E., Siegel, D. I., and Smith, L. C., 2007, Geochemistry of west Siberian streams and their potential response to permafrost degradation: Water Resources Research, v. 43, p. W03406.

Hall, R., Bernhardt, E., and Likens, G., 2002, Relating nutrient uptake with transient storage in forested mountain streams: Limnology and Oceanography, v. 47, p. 255-265.

Hall, R., and Tank, J., 2003, Ecosystem metabolism controls nitrogen uptake in streams in Grand Teton National Park, Wyoming: Limnology and Oceanography, v. 48, p. 1120-1128.

Harvey, J., Conklin, M., and Koelsch, R., 2003, Predicting changes in hydrologic retention in an evolving semi-arid alluvial stream: Advances in Water Resources, v. 26, p. 939-950.

Harvey, J. and Wagner, B., 2000, Streams and Ground Waters, Chapter 1: Quantifying hydrologic interactions between streams and their subsurface hyporheic zones, Academic Press, p. 4-41.

Holmes, R., Aminot, A., Kerouel, R., Hooker, B., and Peterson, B., 1999, A simple and precise method for measuring ammonium in marine and freshwater ecosystems: Canadian Journal of Fisheries and Aquatic Sciences, v. 56, p. 1801-1808.

Holmes, R. M., Mcclelland, J. W., Raymond, P. A., Frazer, B. B., Peterson, B. J., and Stieglitz, M., 2008, Lability of DOC transported by Alaskan rivers to the arctic ocean: Geophysical Research Letters, v. 35, p. L03402.

Lottig, N. R., and Stanley, E. H., 2007, Benthic sediment influence on dissolved phosphorus concentrations in a headwater stream: Biogeochemistry, v. 84, p. 297-309.

Marti, E., Grimm, N., and Fisher, S., 1997, Pre- and post-flood retention efficiency of nitrogen in a Sonoran Desert stream: Journal of the North American Benthological Society, v. 16, p. 805-819.

Mulholland, P., 1992, Regulation of nutrient concentrations in a temperate forest stream - roles of upland, riparian, and in-stream processes: Limnology and Oceanography, v. 37, p. 1512-1526.

Mulholland, P., Marzolf, E., Webster, J., Hart, D., and Hendricks, S., 1997, Evidence that hyporheic zones increase heterotrophic metabolism and phosphorus uptake in forest streams: Limnology and Oceanography, v. 42, p. 443-451.

Newbold, J., Elwood, J., Oneill, R., And Vanwinkle, W., 1981, Measuring nutrient spiraling in streams: Canadian Journal of Fisheries and Aquatic Sciences, v. 38, p. 860-863.

Packman, A., and Salehin, M., 2003, Relative roles of stream flow and sedimentary conditions in controlling hyporheic exchange: Hydrobiologia, v. 494, p. 291-297.

Peterson, B., Holmes, R., McClelland, J., Vorosmarty, C., Lammers, R., Shiklomanov, A., Shiklomanov, I., and Rahmstorf, S., 2002, Increasing river discharge to the Arctic Ocean: Science, v. 298, p. 2171-2173.

Prowse, T. D., Wrona, F. J., Reist, J. D., Gibson, J. J., Hobbie, J. E., Levesque, L. M. J., and Vincent, W. F., 2006, Climate change effects on hydroecology of Arctic freshwater ecosystems: Ambio, v. 35, p. 347-358.

Raymond, P., and Bauer, J., 2001, Riverine export of aged terrestrial organic matter to the North Atlantic Ocean: Nature, v. 409, p. 497-500.

Runkel, R. L., 1998, One-dimensional transport with inflow and storage (OTIS): a solute transport model for streams and rivers: USGS Water-Resources Investigations Report 98-4018, 73 pp.

Runkel, R. L., 2000, Using the OTIS to model solute transport in streams and rivers, USGS Fact Sheet FS-138-99, 4 pp.

Salehin, M., Packman, A., and Worman, A., 2003, Comparison of transient storage in vegetated and unvegetated reaches of a small agricultural stream in Sweden: seasonal variation and anthropogenic manipulation: Advances in Water Resources, v. 26, p. 951-964.

Sebestyen, S. D., Boyer, E. W., Shanley, J. B., Kendall, C., Doctor, D. H., Aiken, G. R., and Ohte, N., 2008, Sources, transformations, and hydrological processes that control stream nitrate and dissolved organic matter concentrations during snowmelt in an upland forest: Water Resources Research, v. 44, p. W12410.

Sobczak, W., Cloern, J., Jassby, A., Cole, B., Schraga, T., and Arnsberg, A., 2005, Detritus fuels ecosystem metabolism but not metazoan food webs in San Francisco estuary's freshwater Delta: Estuaries, v. 28, p. 124-137.

Sobczak, W., and Findlay, S., 2002, Variation in bioavailability of dissolved organic carbon among stream hyporheic flowpaths: Ecology, v. 83, p. 3194-3209.

Sterner, R. W., and Elser, J. J., 2002, Ecological stoichiometry: the biology of elements from molecules to the biosphere, Princeton University Press, 439 pp.

Taylor, B. W., Keep, C. F., Hall, R. O., Koch, B. J., Tronstad, L. M., Flecker, A. S., and Ulseth, A. J., 2007, Improving the fluorometric ammonium method: matrix effects, background fluorescence, and standard additions: Journal of the North American Benthological Society, v. 26, p. 167-177.

Valett, H., Crenshaw, C., and Wagner, P., 2002, Stream nutrient uptake, forest succession, and biogeochemical theory: Ecology, v. 83, p. 2888-2901.

Vannote, R., Minshall, G., Cummins, K., Sedell, J., And Cushing, C., 1980, River continuum concept: Canadian Journal of Fisheries and Aquatic Sciences, v. 37, p. 130-137.

Wagner, B., and Harvey, J., 1997, Experimental design for estimating parameters of rate-limited mass transfer: Analysis of stream tracer studies: Water Resources Research, v. 33, p. 1731-1741.

Walter, K., Edwards, M., Grosse, G., Zimov, S., and Chapin III, F., 2007, Thermokarst lakes as a source of atmospheric CH4 during the last deglaciation: Science, v. 318, p. 633.

Walter, K., Zimov, S., Chanton, J., Verbyla, D., and Chapin III, F., 2006, Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming: Nature, v. 443, p. 71-75.

Webster, J., and Meyer, J., 1997, Organic matter budgets for streams: A synthesis: Journal of the North American Benthological Society, v. 16, p. 141-161.

Wetzel, R. G., 2001, Limnology: Lake and River Ecosystems, 3rd edition: Academic Press, San Diego, California, 1006 pp.

Zarnetske, J. P., Gooseff, M. N., Brosten, T. R., Bradford, J. H., McNamara, J. P., and Bowden, W. B., 2007, Transient storage as a function of geomorphology, discharge, and permafrost active layer conditions in Arctic tundra streams: Water Resources Research, v. 43, p. W07410.

Zimov, S., Schuur, E., and Chapin, F., 2006, Permafrost and the global carbon budget: Science, v. 312, p. 1612-1613.