Hyporheic exchange and water chemistry of two arctic tundra streams of contrasting geomorphology

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[1] The North Slope of Alaska's Brooks Range is underlain by continuous permafrost, but an active layer of thawed sediments develops at the tundra surface and beneath streambeds during the summer, facilitating hyporheic exchange. Our goal was to understand how active layer extent and stream geomorphology influence hyporheic exchange and nutrient chemistry. We studied two arctic tundra streams of contrasting geomorphology: a high-gradient, alluvial stream with riffle-pool sequences and a low-gradient, peat-bottomed stream with large deep pools connected by deep runs. Hyporheic exchange occurred to ~50 cm beneath the alluvial streambed and to only ~15 cm beneath the peat streambed. The thaw bulb was deeper than the hyporheic exchange zone in both stream types. The hyporheic zone was a net source of ammonium and soluble reactive phosphorus in both stream types. The hyporheic zone was a net source of nitrate in the alluvial stream, but a net nitrate sink in the peat stream. The mass flux of nutrients regenerated from the hyporheic zones in these two streams was a small portion of the surface water mass flux. Although small, hyporheic sources of regenerated nutrients help maintain the in-stream nutrient balance. If future warming in the arctic increases the depth of the thaw bulb, it may not increase the vertical extent of hyporheic exchange. The greater impacts on annual contributions of hyporheic regeneration are likely to be due to longer thawed seasons, increased sediment temperatures or changes in geomorphology.

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1. Introduction

[2] Surface water in the open channel of streams exchanges with water in the interstitial spaces of porous sediments within the streambed in an area called the hyporheic zone [e.g., *Triska et al.*, 1989; *Harvey and Bencala*, 1993]. The distribution of sediments in a streambed is typically heterogeneous so hyporheic flow occurs through many different subsurface flow paths that exhibit a range of residence times, all of which are longer than the surface flow path through the thalweg of the stream [*Haggerty et al.*, 2000; *Gooseff et al.*, 2003a]. Because of the increased residence time of water in the hyporheic zone and its close contact with sediment biofilms, many important biogeochemical transformations occur in the hyporheic zone. These transformations include organic matter mineralization, nutrient uptake and cycling, and the regeneration of inorganic nutrients from the hyporheic zone to the surface water (i.e., nutrient regeneration) [*Grimm and Fisher*, 1984; *Valett et al.*, 1990, 1994; *Naegeli and Uehlinger*, 1997; *Dent et al.*, 2001; *Fellows et al.*, 2001; *Pepin and Hauer*, 2002].

[3] Hyporheic exchange is strongly influenced by a variety of stream physical characteristics, including stream size [*D'Angelo et al.*, 1993], parent material of the stream catchment, sediment size, hydraulic conductivity [*Morrice et al.*, 1997; *Storey et al.*, 2003], stream channel friction, channel vegetative cover [*Harvey et al.*, 2003] and seasonal changes in stream discharge, head gradients and local groundwater recharge [*Wroblicky et al.*, 1998; *Storey et al.*, 2003]. Important geomorphic factors include abrupt changes in channel gradient due to streambed topography [*Harvey and Bencala*, 1993], degree of channel constraint, presence of secondary channels or channel splits [*Kasahara and Wondzell*, 2003], channel sinuosity [*Wroblicky et al.*, 1998] and degree of channel complexity due to land use [*Gooseff et al.*, 2007].

[4] Most studies of hyporheic dynamics have been carried out in temperate streams; only a few studies have focused on hyporheic dynamics in Arctic [e.g., *Edwardson et al.*, 2003; *Zarnetske et al.*, 2007; *Zarnetske et al.*, 2008]

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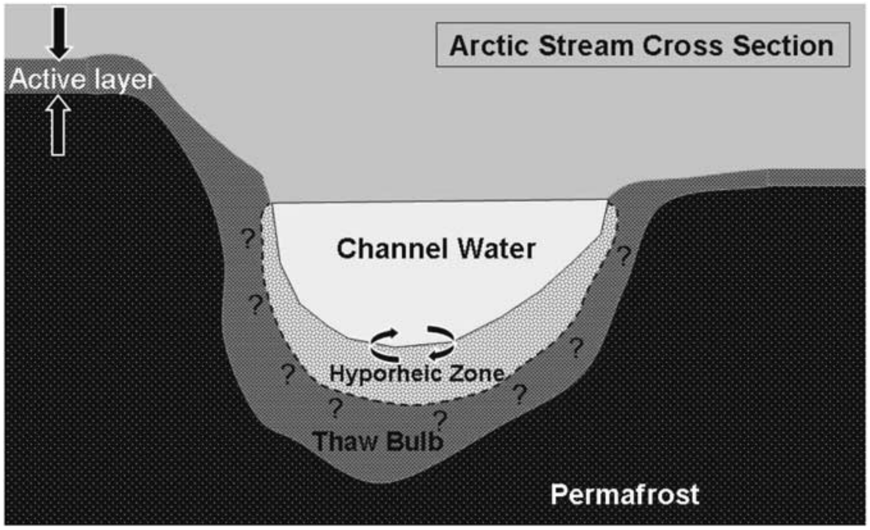

Figure 1. Cross section of an arctic tundra stream, showing the active layer and thaw bulb within the continuous permafrost. A goal of this study was to determine the proportion of the thaw bulb that participates in hyporheic exchange.

or Antarctic [e.g., *McKnight et al.*, 1999; *Gooseff et al.*, 2003b] environments. Continuous permafrost in the arctic environment might be expected to restrict hyporheic exchange in tundra streams. However, an active layer of thawed soil develops at the tundra surface to depths of about 25 to 40 cm deep in the summer (June through August) [*Hinzman et al.*, 1991]. This active layer extends beneath streambeds, where the energy of moving water creates a region of thawed sediments called the thaw bulb (Figure 1). *Brosten et al.* [2006] used ground penetrating radar (GPR) methods refined by *Bradford et al.* [2005] to compare the seasonal development of the thaw bulb in streams of contrasting geomorphology. They found that high-energy, cobble-lined streams responded more quickly to seasonal temperature changes than lower-energy, peat-lined streams, which were better insulated.

[5] *Edwardson et al.* [2003] found that this zone of thawed sediments creates the opportunity for significant hyporheic exchange and promotes nutrient regeneration in tundra streams on the North Slope of Alaska's Brooks Range. Upwelling from the hyporheic zone to the surface water supplied nitrate, ammonium, phosphate and carbon dioxide. The nutrients supplied by hyporheic regeneration are important to arctic tundra streams because primary production in these ecosystems is strongly limited by nutrients, primarily phosphorus [*Peterson et al.*, 1993; *Slavik et al.*, 2004].

[6] While the thaw bulb provides the opportunity for hyporheic exchange and nutrient regeneration, it is still unknown whether the entire depth of the thaw bulb is utilized in that hyporheic exchange. The objective of our study was to compare hyporheic exchange patterns and water chemistry in two arctic tundra streams with contrasting geomorphologies: (1) a high-gradient, cobble-bottom stream and (2) a low-gradient, peat-bottom stream. We had already established that thaw bulb characteristics differ in these two permafrost-controlled tundra stream types on the North Slope [*Bradford et al.*, 2005; *Brosten et al.*, 2006; *Zarnetske et al.*, 2007]. We hypothesized that the interaction between exchange depth within the thaw bulb and stream geomorphology would have important influences on the nutrient chemistry in these streams. Specifically, for the two contrasting stream types we asked:

[7] 1. What portion of the thaw bulb participates in hyporheic exchange in the two stream types?

[8] 2. Are there differences between the two stream types in subsurface water chemistry (DO, NO_3, NH_4, SRP, and DOC) with depth, stream feature or time?

[9] 3. Are there important differences in estimated net nutrient regeneration rates for NO_3, NH_4 and SRP between the two stream types?

2. Methods

2.1. Study Area

[10] The study area was located on the North Slope of the Brooks Range in Alaska, near the Toolik Field Station (68°38′N, 149°36′W) (Figure 2), about 180 km south of the Arctic Ocean [*Hobbie et al.*, 1999]. The North Slope has three main stream types: mountain, spring and tundra [*Craig and McCart*, 1975]. Tundra streams, which drain the tundra-covered foothills of the North Slope, freeze solid in the winter, flood in late May or early June and flow for about four months of the year. They typically exhibit lower turbidity than mountain streams and warmer temperatures, lower pH and lower conductivity than both mountain and spring streams. Depending on stream slope, two common stream geomorphologic types occur within the tundra stream classification: (1) high-gradient, alluvial streams with alternating riffle-pool sequences and (2) low-gradient, peat-bottomed streams with a "beaded" morphology in which large, deep pools are connected by narrow, deep runs. The two streams in our study represent these two contrasting tundra stream types. The two second-order, clear water streams run parallel to each other and are a part of a series of lakes and connecting streams that flow north into Toolik Lake and eventually into the Arctic Ocean (Figure 2). *Kling et al.* [2000] referred to these two stream reaches as the inlets to Lakes I-8 and I-Swamp in the I Series.

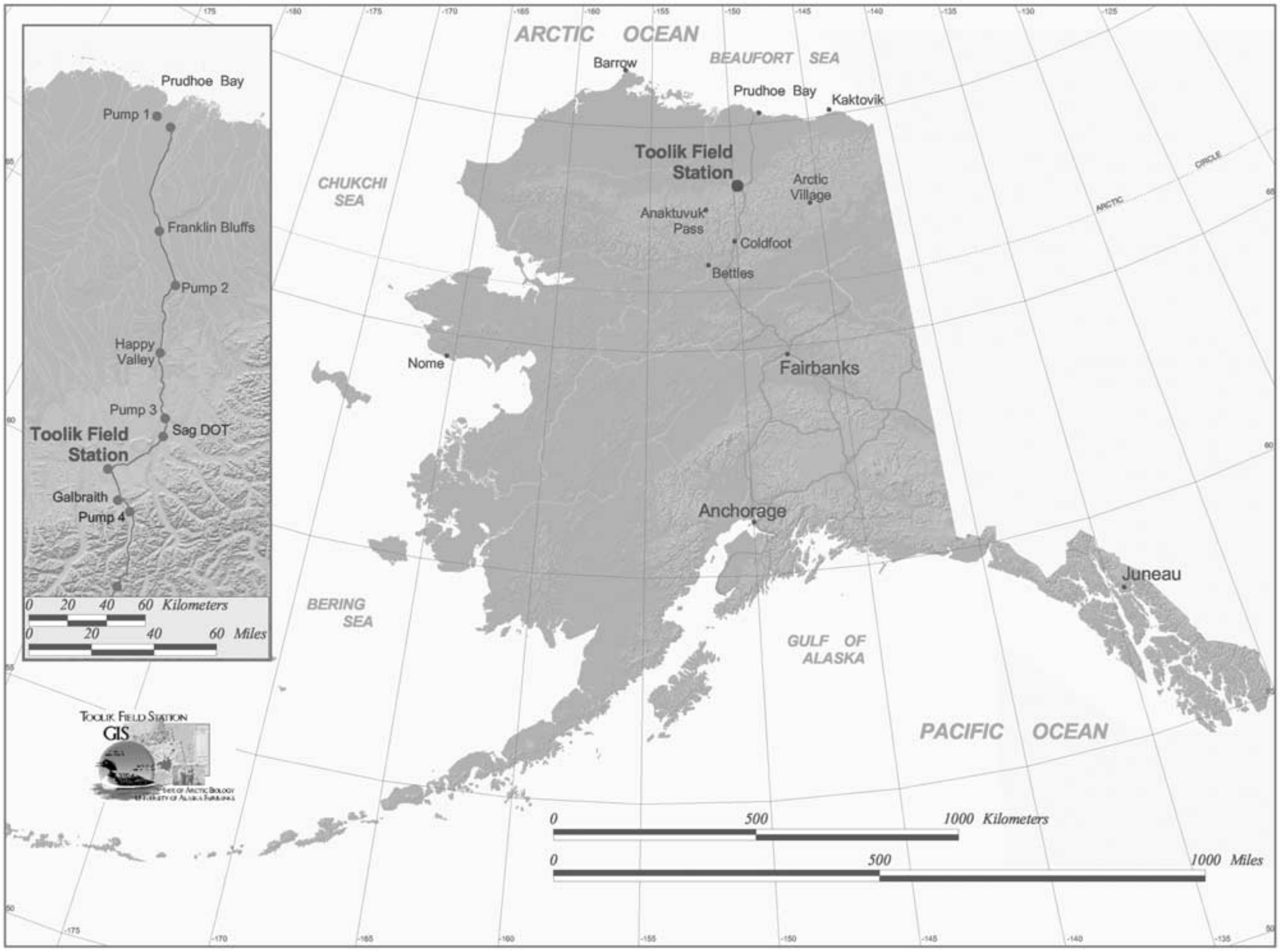

Figure 2a. Location of the Toolik Field Station (68°38′N, 149°36′W) on the North Slope of the Brooks Range in Alaska (credit A. Balser, http://www.uaf.edu/toolik/gis).

[11] Despite their close proximity to each other (less than 1 km), the two study streams have very different physical characteristics that represent two important, geomorphically distinct, headwater stream types on the North Slope of Alaska's Brooks Range (Table 1). The streams will be referred to as the alluvial stream and the peat stream, respectively. Both streams are underlain by permafrost. Ground penetrating radar (GPR) surveys showed that the average depths of subsurface thaw during the summer of 2005 were very different: 157 cm in the alluvial stream and 67 cm in the peat stream (T. Brosten, unpublished data, 2005). Other physical characteristics of the stream reaches and of the experiment periods are summarized in Table 1.

2.2. Hyporheic Sampling

[12] We sampled hyporheic water from sampling tubes inserted into the streambed to known depths (Table 2). Each sampling tube was constructed from a 1.5-m-long tube of rigid Delrin plastic with a 6.3-mm outer diameter and 3.2-mm inner diameter. Five holes were drilled into the walls of each sampling tube over the bottom 10 cm of its length and the bottom hole of each tube was left open (total open area of 68 mm^2). The drilled ends of the tubes were covered with a geotextile sleeve to prevent sediment clogging.

[13] We bundled the sampling tubes in sets of two (for the peat stream) or three (for the alluvial stream) so that the screened ends of the tubes were a known depth apart. Each bundle then provided 2 to 3 distinct sampling depths at one location in the streambed along the thalweg. We arranged the sampling tubes so that the deepest tube in each bundle was located at the deepest accessible point (i.e., depth of refusal), the shallowest tube was approximately 10–20 cm beneath the streambed and the middepth tube (in the alluvial sets only) was roughly one third of the way between the shallow and deep tubes. The average installed depths for the tubes were 15 cm, 50 cm and 110 cm in the alluvial stream and 12 cm and 33 cm in the peat stream (Table 2).

[14] We installed the nested bundles into the streambed using an insertion tool consisting of a hardened steel rod (19.0 mm diameter, 240 cm length) within a hardened steel sleeve (25.4 mm inner diameter, 235 cm length) similar to that described by *Baxter et al.* [2003]. We inserted the inner rod and sleeve into the streambed to the depth of refusal, using a fencepost driver where necessary. The inner rod was removed from the sleeve and the bundle of sampling tubes was inserted into the sleeve. The sleeve was then carefully removed, allowing the sediment to collapse around the bundle, securing its position within the thawed sediments.

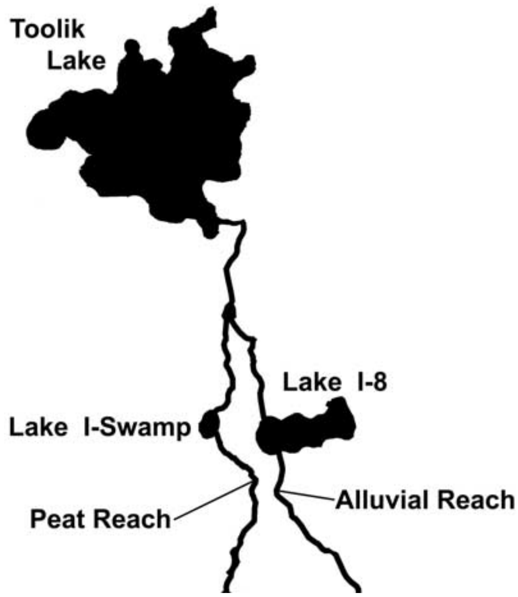

Figure 2b. Map showing the locations of the alluvial and peat reaches within the I series of lakes and streams that flow north into Toolik Lake and eventually into the Arctic Ocean.

[15] We installed nine bundles along a longitudinal transect in each of the two stream reaches to obtain three replicates of three different stream features. In the alluvial stream, the features were riffle heads, riffle tails and pools. In the peat stream, the analogous features were run heads, run tails and pools. Because the bundles consisted of three depths in the alluvial stream and two depths in the peat stream, the alluvial stream had a total of 27 sampling tubes and the peat stream had a total of 18 sampling tubes (Table 2).

[16] To take a hyporheic water sample, we attached a 60-mL disposable syringe to each sampling tube via a three-way disposable syringe stopcock. We drew a small volume of water (5–10 mL) into the syringe to clear the sampling tube and discarded it via the open port of the three-way stopcock without detaching the syringe from the tube.

[17] Approximately 50 mL of fresh sample water was then collected and processed for analysis as described in sections 2.3–2.6. Between sampling events we removed the syringes from the sampling tubes, but the three-way stopcocks were left in place in the off position.

2.3. Extent of Hyporheic Exchange

[18] We performed solute injection experiments (SIEs) using Rhodamine WT (RWT) twice (June and August) during the summer season in each stream to determine the extent of hyporheic exchange within the thaw bulb. During each experiment, we dripped RWT into the stream water at a constant rate at the top of the reach until the surface water RWT concentration reached a plateau in the fully mixed zone of the streams. Throughout each SIE and for a period following the solute injection, we sampled surface and subsurface water at regular intervals. Sampling frequency was every 20 min for the first hour, every 30 min for the next hour and hourly for the rest of the experiment. One exception was the August peat SIE because it was much longer in duration than the June peat SIE. For the second peat SIE, we sampled every 30 min for the first hour, hourly for the next 5 h and every 2 h for the remainder of the SIE. In all SIEs, samples were taken more frequently at the beginning of the experiment so that we could adequately characterize the rise to plateau. Samples were returned immediately to the laboratory for analysis of RWT concentration using a Turner Designs 10-AU fluorometer. For each subsurface sampling location, a tracer breakthrough curve (RWT concentration versus time) was obtained for the surface water and each subsurface location sampled for each SIE.

[19] We calculated the percent connection to surface water (P_C) for each of the subsurface sampling locations using

$$P_c = \frac{\text{Subsurface}_{\text{MAX}}*100}{\text{Surface}_{\text{MAX}}} \quad (1)$$

where $\text{Subsurface}_{\text{MAX}}$ is the maximum subsurface water RWT concentration at each subsurface sampling location and $\text{Surface}_{\text{MAX}}$ is the maximum RWT concentration at the corresponding surface water location. These maximum concentrations were identified from surface and subsurface breakthrough curves at each location.

2.4. Water Chemistry Sampling and Analysis

[20] We sampled surface and subsurface water from both streams on four occasions during the summer of 2005 (alluvial: 29 June, 4 July, 1 Aug, 15 Aug; peat: 27 June, 1 July, 29 July, 10 Aug) We analyzed the samples for concentrations of nitrate (NO_3), ammonium (NH_4), soluble reactive phosphorus (SRP), dissolved oxygen (DO) and dissolved organic carbon (DOC). For each stream, we averaged the results from the first two sampling dates and reported them as June data and averaged the results from the last two sampling dates and reported them as August data. We paired early summer chemistry data with June SIE data and late summer chemistry data with August SIE data.

[21] We measured the concentration of DO in water samples in the field (directly in the sampling syringe after carefully removing the plunger) with a WTW Oxi 340i handheld dissolved oxygen meter. The reported accuracy for this dissolved oxygen meter is ±0.01 mg/L (WTW, Weilheim, Germany). However, under the conditions in which we used this equipment, we assumed a more conservative estimate of accuracy of ±0.1 mg/L. We filtered all other water samples through 0.45 μm, 25 mm diameter,

Table 1. Physical Characteristics of the Two Study Streams

	Alluvial	Peat
Reach length, m	188	175
Mean channel width, m	3.1	2.9
Channel gradient, %	0.7	0.03
Substrate	cobble and sand	peat
Average subsurface thaw depth, m	1.57	0.67
Mean surface water temperature, °C		
16 June to 15 July 2005	10.4	10.7
16 July to 14 August 2005	10.9	11.9
Discharge during June SIE, L s^{-1}	31	24
Discharge during August SIE, L s^{-1}	25	20

Table 2. Locations of Each of the Sampling Tubes Installed in the Alluvial and Peat Subsurface[a]

Sampling Tube ID	Stream Feature	Distance Downstream From SIE Dripper, m	Depth Beneath Streambed Surface, cm
		Alluvial	
aa1	Riffle Tail	30	29
aa2	Riffle Tail	30	57
aa3	Riffle Tail	30	136
a1	Pool	45	14
a2	Pool	45	44
a3	Pool	45	103
b1	Riffle Head	73	26
b2	Riffle Head	73	53
b3	Riffle Head	73	139
c1	Riffle Tail	81	15
c2	Riffle Tail	81	45
c3	Riffle Tail	81	94
d1	Pool	86	19
d2	Pool	86	49
d3	Pool	86	81
e1	Riffle Head	104	11
e2	Riffle Head	104	41
e3	Riffle Head	104	102
f1	Riffle Tail	122	11
f2	Riffle Tail	122	40
f3	Riffle Tail	122	101
g1	Pool	128	9
g2	Pool	128	39
g3	Pool	128	104
h1	Riffle Head	132	24
h2	Riffle Head	132	54
h3	Riffle Head	132	118
		Peat	
a1	Run Head	57	10
a2	Run Head	57	30
b1	Run Tail	60	10
b2	Run Tail	60	30
c1	Pool	67	10
c2	Pool	67	30
d1	Run Head	76	10
d2	Run Head	76	30
e1	Run Tail	80	10
e2	Run Tail	80	30
f1	Pool	85	20
f2	Pool	85	40
g1	Run Head	126	12
g2	Run Head	126	42
h1	Run Tail	133	10
h2	Run Tail	133	30
i1	Pool	142	15
i2	Pool	142	35

[a]Letter indicates the location of the nest along the thalweg of the stream, and the number indicates its depth layer beneath the streambed (i.e., 1, shallowest; 3, deepest).

cellulose acetate syringe filters. The water samples were kept on ice for transport to the laboratory.

[22] Ammonium and SRP analyses were performed within 48 h at the Toolik Field Station. We used the orthophthaldialdehyde (OPA) method for ammonium analysis [*Holmes et al.*, 1999] and the colorimetric molybdate blue method for SRP analysis (Hach Company, Method 8048: Orthophosphate by colorimetry, in The 1997 Edition of the Hach Water Analysis Handbook, retrieved 18 April 2007 from National Environmental Methods Index at http://www.nemi.gov). Nitrate samples were immediately frozen at the field station and then transported to the University of Vermont's Rubenstein Ecosystem Science Laboratory in Burlington, Vermont, where they were analyzed within 6 months by the cadmium reduction technique [*Askew and Smith*, 2005, p. 123]. DOC samples were preserved with 6 N hydrochloric acid to a pH of 2, transported to the Ecosystems Center in Woods Hole, MA and analyzed by the persulfate-ultraviolet method [*Baird*, 2005, p. 23] within 6 months.

2.5. Calculation of Net Nutrient Regeneration Rates

[23] We used the tracer and water chemistry data to estimate net nutrient regeneration rates (R_{NR}) for NO_3, NH_4 and SRP for the two stream reaches in both June and August. To calculate the regeneration rates, we needed an estimate of the mean nutrient concentration in the hyporheic zone, which we expected to differ by depth. Furthermore, we expected that exchange rate would differ (decrease) with depth as well, in proportion to the percent connectedness (P_C) from equation (1). Thus, we calculated a weighted mean hyporheic concentration ($\overline{[N]_{SUB}}$) for each nutrient as follows:

$$\overline{[N]_{SUB}} = \frac{\sum_{ij}\left([N]_{SUBij} * P_{Cij}\right)}{\sum_{ij}\left(P_{cij}\right)} \tag{2}$$

where i is depth in the substrate and j is stream feature.

[24] We calculated net nutrient regeneration rate, R_{NR}, as the difference between the flux of a given nutrient into the subsurface (F_{IN}) and the flux of that nutrient out of the subsurface (F_{OUT}), as follows:

$$R_{NR} = F_{OUT} - F_{IN} \tag{3}$$

Positive values of R_{NR} indicate that the subsurface is a net source of a given nutrient and negative values of R_{NR} indicate that the subsurface is a net sink for that nutrient. F_{IN} was calculated by multiplying the average surface water nutrient concentration ($\overline{[N]_{SURF}}$) by the reach-averaged rate of water exchange into the subsurface ($R_{EXCH(IN)}$):

$$F_{IN} = R_{EXCH(IN)} * \overline{[N]_{SURF}} \tag{4}$$

Similarly, F_{OUT} was calculated by multiplying the connectedness-weighted, reach-averaged subsurface nutrient concentration ($\overline{[N]_{SUB}}$, described above) by the reach-averaged rate of water exchange into the subsurface ($R_{EXCH(OUT)}$):

$$F_{OUT} = R_{EXCH(OUT)} * \overline{[N]_{SUB}} \tag{5}$$

For the purposes of this study we assumed that $R_{EXCH(IN)} = R_{EXCH(OUT)} = R_{EXCH}$.

2.6. Statistical Analysis

[25] We used nonparametric statistics to analyze these data because the total number of data points was relatively small and the majority of the tracer and water chemistry data was not normally distributed, could not be transformed to normality due to the large number of zero values, and may not have been independent within a stream type. First, Mann-Whitney tests were performed to determine if there were differences in water chemistry (median NO_3, NH_4, SRP, DO and DOC concentrations) between the two stream

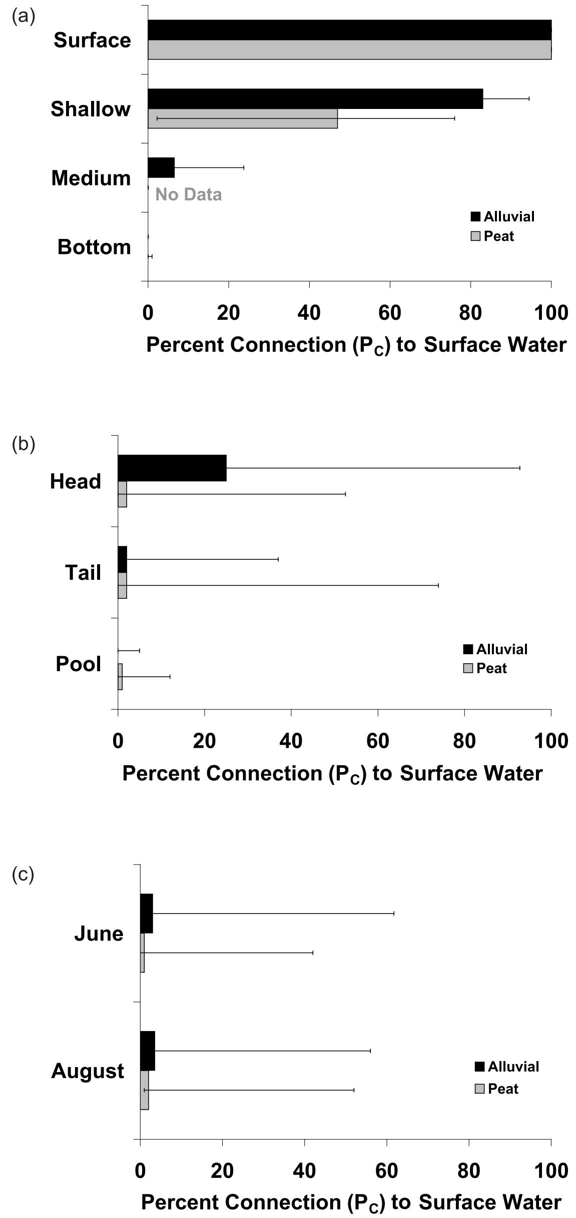

Figure 3. Median percent connection (P_C) values at (a) relative subsurface depths, (b) stream features, and (c) study periods in the alluvial and peat stream types (error bars indicate first and third quartile values).

types in both the surface water and subsurface water. Then, for each stream individually, separate Mann-Whitney tests were performed to determine if there were significant differences in median values of P_C, NO_3, NH_4, SRP, DO and DOC among subsurface depths, stream features (head, tail, pool) or study periods (June versus August). For depth comparisons, the median value for a given variable at a particular subsurface depth was compared to the median value for that variable in the surface water. The selected alpha value (α) for the Mann-Whitney comparison tests was 0.05, but because multiple comparisons were made in some cases, α was divided by the number of comparisons made for each response variable (n) to arrive at an adjusted alpha value (α') that was more conservative. P values from all Mann-Whitney comparisons are shown in the auxiliary material.[1]

3. Results

3.1. Extent of Hyporheic Exchange

[26] The alluvial SIEs were performed on 18 June 2005 (2.6-h duration) and 8 August 2005 (2.3-h duration). The peat SIEs were performed on 27 June 2005 (6.0-h duration) and on 11 August 2005 (9.8-h duration). Discharges were 31 and 25 L s^{-1} in the alluvial stream and 24 and 20 L s^{-1} in the peat stream during the June and August SIEs, respectively [*Zarnetske et al.*, 2008].

[27] The value for P_C decreased rapidly with depth in the subsurface in both streams to a point where the bottom subsurface locations in each had a median value of 0% connection to surface water (Figure 3a). P_C values in the shallow subsurface (median: 83%) and medium subsurface (median: 7%) depths of the alluvial stream were highly variable and not significantly different from 100%, the theoretical P_C value of the surface water [$\alpha' = 0.017$, p = 0.067 (shallow), p = 0.026 (medium)]. P_C values at the medium depth ranged from 0% to 94%, indicating that the flow paths there varied greatly in length, flow rate or both. The median P_C value at the bottom subsurface depth of the alluvial stream (0%), however, was significantly lower than the surface water value (p = 0.007). In the peat stream, the median P_C value in the shallow subsurface (47%) was not significantly different from the surface water P_C value of 100% ($\alpha' = 0.025$, p = 0.027), but the median P_C value at the bottom subsurface depth (0%) was significantly lower than the surface water P_C ($\alpha' = 0.025$, p = 0.013) (Figure 3a).

[28] In the alluvial stream, P_C was significantly higher in riffle head features (median of 25%) than in riffle tail (median of 2%) or pool features (median of 0%) (Figure 3b). There were no significant differences in P_C among features in the peat stream; all locations in the peat stream had median P_C values of $\leq$2%. There were no significant increases or decreases in P_C over time in either stream type (Figure 3c).

3.2. Water Chemistry Comparisons Between the Two Streams

[29] Surface water concentrations of DO, SRP, NH_4, NO_3, or DOC were not significantly different between the two study streams (Table 3). In contrast, subsurface concentrations of DO, SRP, NH_4, NO_3, or DOC were all significantly different between the two streams (Table 3). The alluvial subsurface water had significantly higher DO and NO_3 concentrations than the peat subsurface water, but had significantly lower SRP, NH_4, and DOC concentrations. Sections 3.2.1–3.2.5 describe how these variables differed as a function of subsurface depth, stream feature and study period.

3.2.1. Dissolved Oxygen

[30] In both streams, DO concentration decreased with depth in the subsurface (Figure 4a). DO was depleted much more steeply with depth in the peat subsurface than in the alluvial subsurface. In the alluvial stream, the median DO concentration in the shallow subsurface (8.3 mg/L)

[1]Auxiliary materials are available in the HTML. doi:10.1029/2007JG000549.

Table 3. Median Concentrations of DO, NO_3, NH_4, SRP, and DOC in the Surface and Subsurface Water of the Alluvial and Peat Streams

Parameter	Alluvial Median	Peat Median	Mann-Whitney p Value
	Surface Water		
DO, mg/L	9.7	9.2	0.312
NO_3, μM	5.75	7.49	0.885
NH_4, μM	0.20	0.52	0.194
SRP, μM	0.02	0.03	0.312
DOC, μM	310	339	0.384
	Subsurface Water		
DO, mg/L	6.7	1.3	<0.001[a]
NO_3, μM	7.15	0.00	<0.001[a]
NH_4, μM	0.36	43.8	<0.001[a]
SRP, μM	0.06	0.22	<0.001[a]
DOC, μM	291	538	<0.001[a]

[a]Statistically significant difference between stream types.

was not significantly different ($p = 0.131$) from the surface water (9.7 mg/L). Median DO concentrations at medium and bottom subsurface locations were moderate (4.7 mg/L and 4.1 mg/L, respectively) and were both significantly lower than the median alluvial surface water ($p = 0.008$ and $p = 0.003$, respectively). In the peat stream, median DO concentration in the shallow subsurface (4.2 mg/L) was significantly lower ($p = 0.002$) than the median surface water DO concentration (9.2 mg/L). Median DO concentration in the bottom subsurface of the peat stream (1.0 mg/L) was also significantly lower than that of the surface water ($p = 0.002$).

[31] In the alluvial stream, subsurface pool locations had a lower median DO concentration (2.5 mg/L) than riffle tail (median: 6.7 mg/L) or head (median: 8.1 mg/L) subsurface locations (Figure 4b). Median subsurface DO concentration was significantly higher in riffle head features than in pool features ($p = 0.001$). There were no significant differences in subsurface DO concentration among features within the peat stream (Figure 4b). Median subsurface DO concentrations were consistently significantly higher in the alluvial subsurface than in the peat subsurface. Median subsurface DO concentration increased significantly from June (4.2 mg/L) to August (7.3 mg/L) in the alluvial stream ($p = 0.026$). There was no significant difference in median subsurface DO concentration over time in the peat stream.

[32] In each stream, there was a positive correlation between subsurface DO concentration and P_C. The Spearman's correlation coefficient for these two variables was 0.74 ($p < 0.001$) in the alluvial stream and 0.78 ($p < 0.001$) in the peat stream (Figure 5).

3.2.2. Nitrate

[33] Nitrate concentrations increased with depth in the subsurface of the alluvial stream and decreased with depth in the subsurface of the peat stream (Figure 6a). Although the increase with depth was not statistically significant in the alluvial subsurface, median nitrate concentrations increased progressively from 5.75 μM in the surface water to 9.64 μM in the bottom subsurface water. Median nitrate concentration decreased significantly in the peat stream from 7.49 μM in the surface water to 2.25 μM ($p = 0.008$) in the shallow subsurface ($\sim$10 cm deep) and to below detection in the bottom subsurface ($\sim$30 cm deep) ($p < 0.001$). There were no significant differences in median subsurface nitrate concentration with feature or time in either stream (Figures 6b and 6c).

3.2.3. Ammonium

[34] There were no significant differences in median ammonium concentration with depth in the alluvial subsurface, but there were significant increases in ammonium concentration with depth in the peat subsurface (Figures 7a and 7d). Median ammonium concentration increased significantly from 0.52 μM in the surface water of the peat stream to 6.78 μM in the shallow subsurface ($p = 0.018$) and to 101.40 μM in the bottom subsurface ($p = 0.002$).

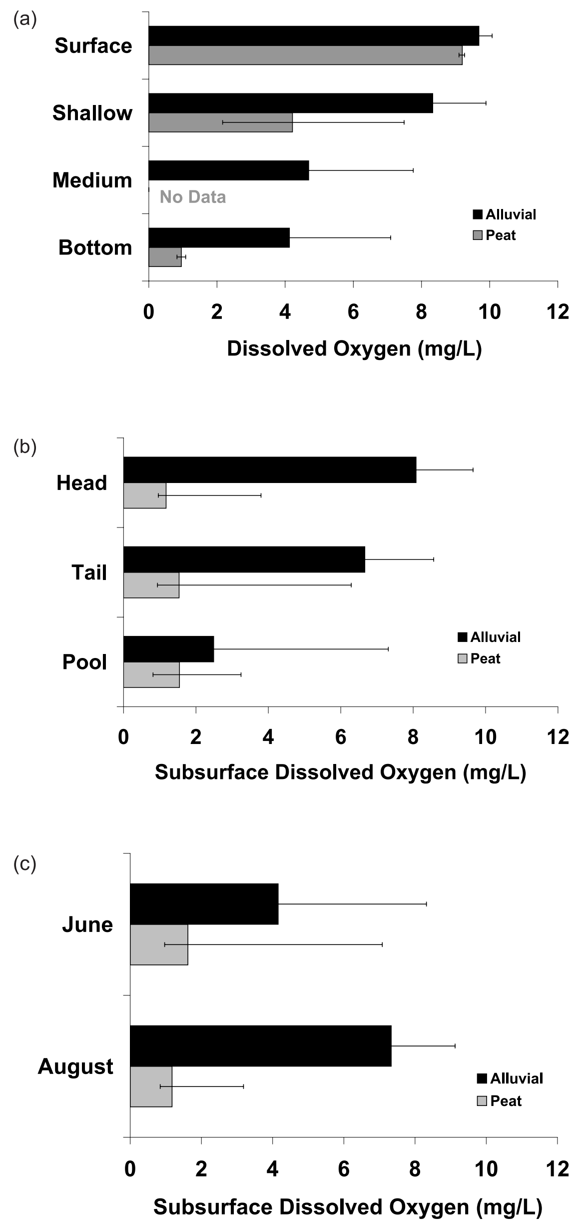

Figure 4. Median dissolved oxygen concentration at (a) relative subsurface depths, (b) stream features, and (c) study periods in the alluvial and peat stream types (error bars indicate first and third quartile values).

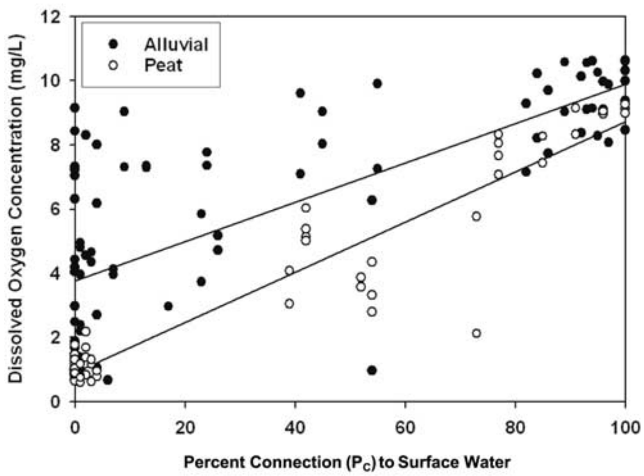

Figure 5. Subsurface dissolved oxygen concentration versus degree of surface-subsurface connection in the alluvial and peat streams. The Spearman's correlation coefficient between the two variables is 0.74 ($p < 0.001$) for the alluvial stream and 0.78 ($p < 0.001$) for the peat stream.

[35] There were no significant differences in subsurface ammonium concentration in the alluvial stream with respect to stream feature (Figure 7b). In the peat stream, however, the median subsurface ammonium concentration was significantly higher in pool locations (196 μM) than in run head (40.6 μM, p = 0.008) or tail (10.7 μM, p = 0.001) locations (Figure 7e). Subsurface ammonium concentrations decreased significantly (p < 0.001) from June (0.47 μM) to August (0.23 μM) in the alluvial stream (Figure 7c). No significant temporal pattern was evident with subsurface ammonium concentrations in the peat stream (Figure 7f).

3.2.4. Soluble Reactive Phosphorus

[36] Patterns of SRP concentration in the two stream types were similar to those seen for ammonium. Again, there were no significant differences in median SRP concentration with depth in the alluvial subsurface (Figure 8a). In the peat stream, however, median SRP concentration increased significantly with depth in the subsurface. It increased significantly from 0.03 μM in the surface water to 0.14 μM in the shallow subsurface (p = 0.003) and to 0.57 μM in the bottom subsurface (p = 0.002) (Figure 8a).

[37] In the alluvial stream, subsurface SRP concentration was not significantly different among stream features (Figure 8b). In the peat stream, however, median subsurface SRP concentration was significantly higher in pool locations (0.85 μM) than in run head (0.20 μM, p = 0.005) or tail (0.13 μM, p = 0.003) locations (Figure 8b). There were no significant changes in subsurface SRP concentration over time in either stream type (Figure 8c).

3.2.5. Dissolved Organic Carbon

[38] In the alluvial stream, there were no significant differences in median DOC concentration with depth in the subsurface (Figure 9a). However, in the peat stream, shallow subsurface (467 μM) and bottom subsurface (635 μM) median DOC concentrations were both significantly higher than the surface water median DOC concentration (339 μM) (p = 0.004 and p = 0.003, respectively) (Figure 9a).

[39] In the alluvial stream, there were no significant differences in median DOC concentration with respect to stream feature, but in the peat stream, pool locations had significantly higher median subsurface DOC concentrations (1057 μM) than run heads (535 μM) or tails (469 μM) (p < 0.001) (Figure 9b). There was a significant increase in median subsurface DOC concentration from June (285 μM) to August (301 μM) in the alluvial subsurface (p = 0.007), but no significant differences over time in the peat stream (Figure 9c).

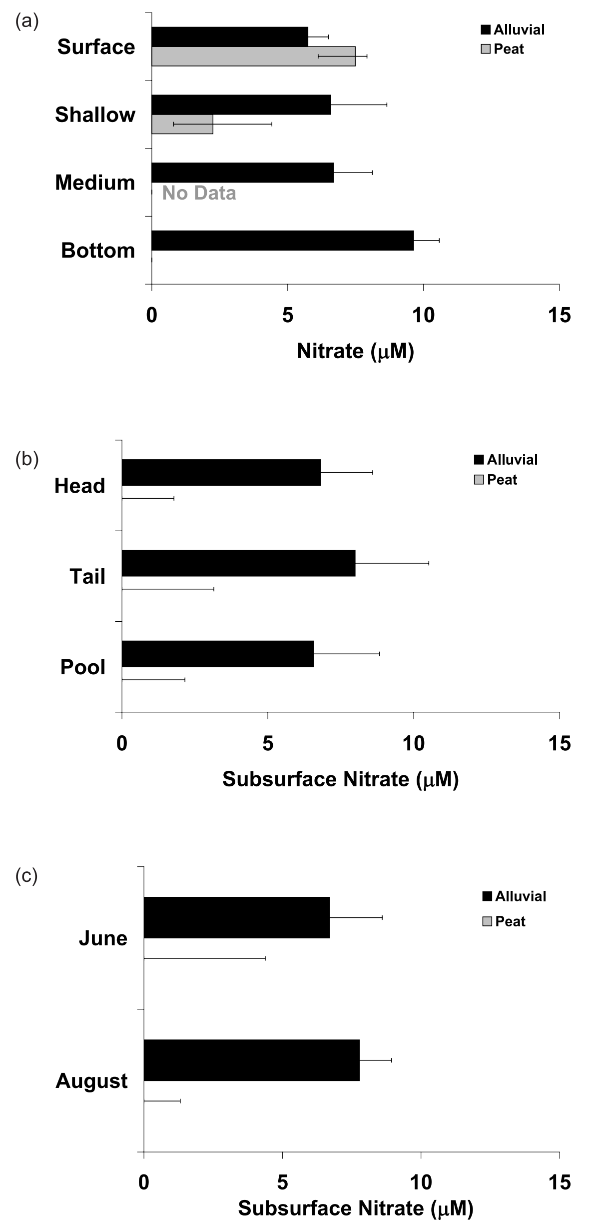

Figure 6. Median nitrate concentration at (a) relative subsurface depths, (b) stream features, and (c) study periods in the alluvial and peat stream types (error bars indicate first and third quartile values).

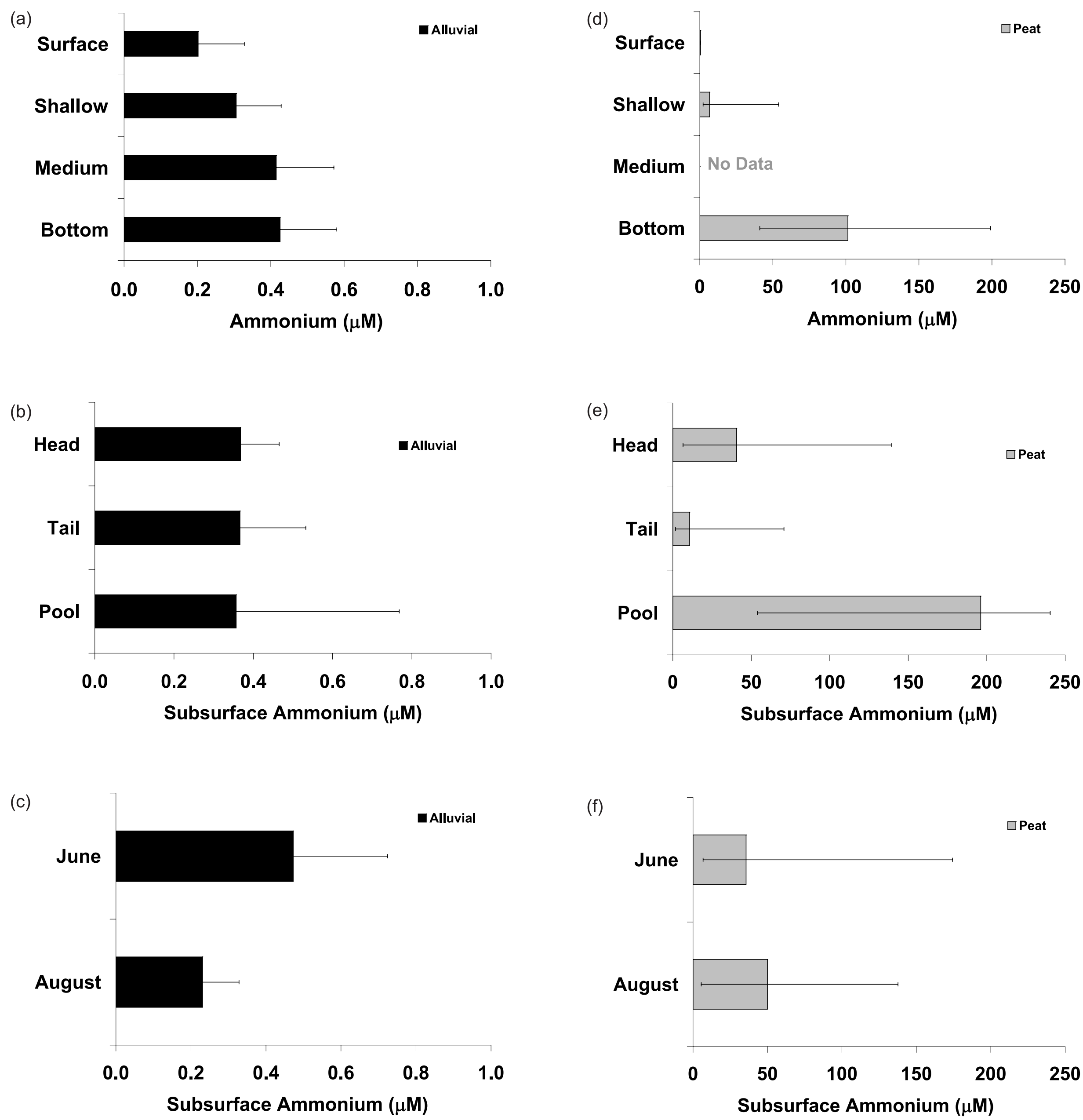

Figure 7. Median ammonium concentration at (a) relative subsurface depths, (b) stream features, and (c) study periods in the alluvial stream and at (d) relative subsurface depths, (e) stream features, and (f) study periods in the peat stream (error bars indicate first and third quartile values).

3.3. Estimates of Nutrient Regeneration Rates

[40] *Zarnetske et al.* [2008] used the SIE data reported here in conjunction with MODFLOW and MODPATH modeling to estimate the rate of surface-subsurface water exchange (R_{EXCH}) for each reach in June and August (Table 4). We assumed that in this permafrost-dominated environment it is likely that the influx of hyporheic water is completely recovered downstream; i.e., there is no loss of hyporheic influx to a larger aquifer (i.e., $R_{EXCH(IN)}$ = $R_{EXCH(OUT)}$ = R_{EXCH}). During our SIE experiments, the reaches were slightly gaining. The gains were 6% and 10% in the alluvial reach in June and August, respectively, and 4% and 3% in the peat reach, in June and August, respectively. The assumption that $R_{EXCH(IN)}$ = $R_{EXCH(OUT)}$ is not inconsistent with these observed gains. Gains in stream discharge could come from surface or subsurface lateral flow that may or may not interact with the hyporheic zone. We cannot distinguish among these alternative flow paths with our data. The potential effects on our estimates of regeneration rates are noted later.

[41] The values for R_{EXCH} were almost 2 orders of magnitude higher in the alluvial stream than in the peat stream (Table 4). On the basis of these values, the hyporheic zone in the alluvial reach was a source of ammonium (June, 1.50 μmol m^{-2} h^{-1}; August, 1.32 μmol m^{-2} h^{-1}) and SRP (June, 0.70 μmol m^{-2} h^{-1}; August, 0.39 μmol m^{-2} h^{-1}).

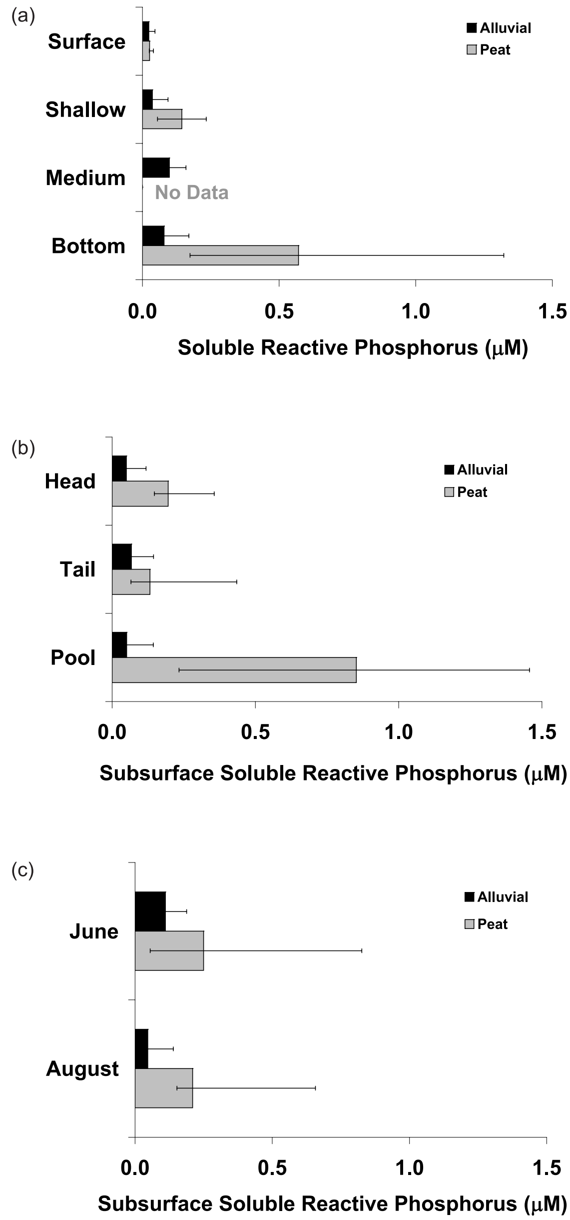

Figure 8. Median soluble reactive phosphorus concentration at (a) relative subsurface depths, (b) stream features, and (c) study periods in the alluvial and peat stream types (error bars indicate first and third quartile values).

The alluvial hyporheic zone was a nitrate sink in June (-20.11 μmol m^{-2} h^{-1}) but was a nitrate source in August (35.84 μmol m^{-2} h^{-1}). The hyporheic zone of the peat stream was a source of ammonium (June: 3.68 μmol m^{-2} h^{-1}, August: 9.90 μmol m^{-2} h^{-1}) and SRP (June: 0.02 μmol m^{-2} h^{-1}, August: 0.07 μmol m^{-2} h^{-1}) and a sink for nitrate (June: -1.48 μmol m^{-2} h^{-1}, August: -1.58 μmol m^{-2} h^{-1}) (Table 4).

[42] If the detected water gains entered the stream via hyporheic flow paths (rather than lateral inputs), then mass flux of nutrients out of the hyporheic zone (F_{OUT}) must increase proportionately. The effect on R_{NR}, however, is disproportionate because R_{NR} is a function of both F_{OUT} and F_{IN}, which remains unchanged. To see the potential effect of these inputs on R_{NR}, we calculated R^*_{NR}, a term that used an updated R_{EXCH} value based on the assumption that all additional discharge inputs entered via the hyporheic zone. In this way, R_{NR} and R^*_{NR} serve as boundaries for our estimates of net nutrient regeneration. On average for the summer of 2005, R_{NR}* was higher than R_{NR} by 32%, 34%, and 18% for NO_3, NH_4 and SRP, respectively, in the alluvial reach and higher than R_{NR} by 4%, 4%, and 5% for NO_3, NH_4 and SRP, respectively, in the peat reach (Table 4). Note that in the case of negative net nutrient regeneration rates (e.g., NO_3 in the peat stream), the increase in net nutrient regeneration rate was actually due to a decrease in the net consumption rate.

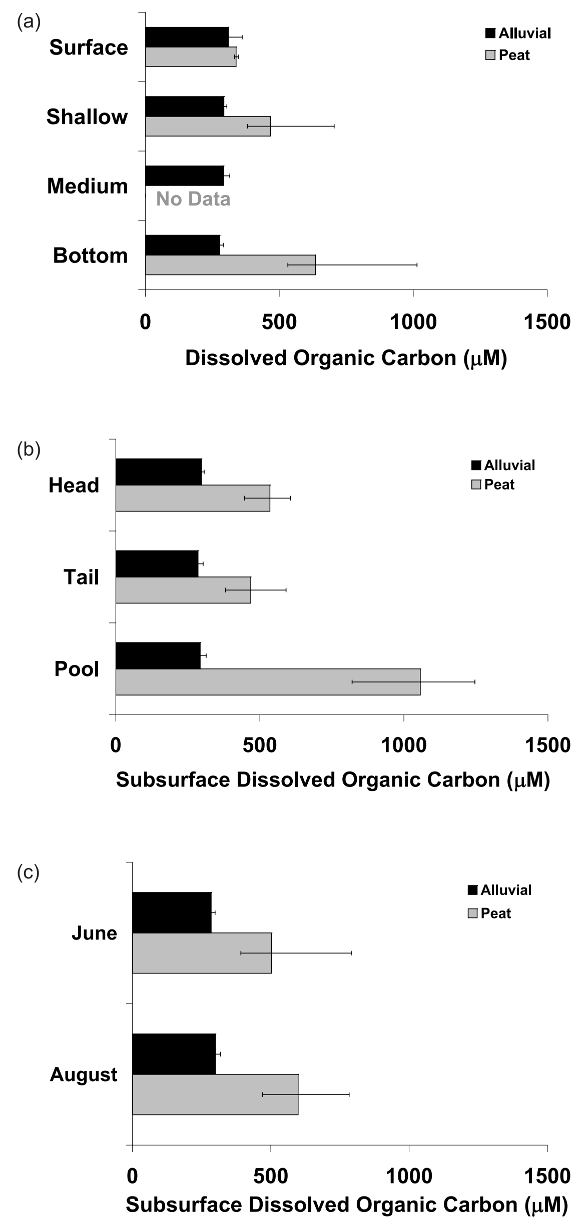

Figure 9. Median dissolved organic carbon concentration at (a) relative subsurface depths, (b) stream features, and (c) study periods in the alluvial and peat stream types (error bars indicate first and third quartile values).

Table 4. Estimates of Net Nutrient Regeneration Rate and Related Variables for the Alluvial and Peat Streams in June and August 2005

		Alluvial		Peat	
	Nutrient	June	August	June	August
$\overline{R_{EXCH}}$, L s^{-1}	-	2.78	2.93	0.0669	0.0732
$\overline{[N]}_{SURF}$, μM	NO_3	7.23	4.80	8.06	5.05
	NH_4	0.43	0.17	0.60	0.44
	SRP	0.06	0.02	0.03	0.05
TF_{SURF}, mmol h^{-1}	NO_3	807	432	696	364
	NH_4	48.0	15.3	51.8	31.7
	SRP	6.70	1.80	2.59	3.60
$\overline{[N]}_{SUB}$, μM	NO_3	5.98	6.65	4.86	2.00
	NH_4	0.53	0.24	8.54	19.50
	SRP	0.10	0.04	0.06	0.19
R_{NR}, μmol m^{-2} h^{-1}	NO_3	−20.11	35.84	−1.48	−1.58
	NH_4	1.50	1.32	3.68	9.90
	SRP	0.70	0.39	0.02	0.07
R^*_{NR}, μmol m^{-2} h^{-1}	NO_3	−14.33	48.70	−1.39	−1.55
	NH_4	2.01	1.78	3.84	10.20
	SRP	0.80	0.48	0.02	0.07
R_{NR}/TF_{SURF} (as percentage)	NO_3	−1%	5%	0%	0%
	NH_4	2%	5%	4%	16%
	SRP	6%	11%	0%	1%
R^*_{NR}/TF_{SURF} (as percentage)	NO_3	−1%	7%	0%	0%
	NH_4	2%	7%	4%	16%
	SRP	7%	13%	0%	1%

[43] To better understand the relative magnitude of hyporheic nutrient contribution in each stream reach, we needed to calculate the through flux of nutrients moving through the surface water of each reach ($\overline{TF_{SURF}}$). TF_{SURF} was calculated by simply multiplying $\overline{[N]}_{SURF}$ by stream discharge. We expressed both R_{NR} and R^*_{NR} as percentages of TF_{SURF} to compare the hyporheic nutrient flux to the surface water nutrient flux (Table 4).

4. Discussion

4.1. Extent of Hyporheic Exchange

[44] In both the alluvial and peat stream types, median values of P_C decreased steadily with depth (Figure 3a). The decrease P_C with depth was more marked in the peat stream than in the alluvial stream. As a result, the zone of hyporheic exchange was deeper in the alluvial reach (39 to 57 cm) than in the peat reach (10 to 15 cm). Ground penetrating radar data showed that the average thaw depths beneath the alluvial stream were 122 cm and 191 cm in June and August 2005, respectively. The average thaw depths beneath the peat stream were 54 cm and 79 cm in June and August 2005, respectively (T. Brosten, unpublished data, 2005). Thus, it is clear that the zone of active hyporheic exchange did not occupy the entire thaw bulb. Rather, the majority of the surface-subsurface water interaction was limited to the uppermost portions of the thaw bulb in both stream types. This is consistent with conclusions reported by *Zarnetske et al.* [2008], who used model simulations to show that transient storage of tracer solute did not increase with increasing thaw depths.

[45] Channel gradient is known to control key physical characteristics of streams, which may in turn dictate thaw depth and maximum depth of hyporheic exchange in these streams [see *Brosten et al.*, 2006; *Zarnetske et al.*, 2008]. In higher gradient reaches we expect to see coarse bed material (alluvial reaches). The combination of coarse bed material and high head gradients promotes deeper hyporheic exchange. In addition, the coarse bed materials (gravel, cobble, and boulders) have a relatively high thermal conductivity that facilitates deep thaw depths. By contrast, we expect to see fine bed materials in lower gradient reaches (peat reaches). The combination of fine bed materials and low head gradients restricts hyporheic exchange. In addition, fine bed materials, especially peat, have low thermal conductivity that will insulate permafrost below the streambed.

[46] The degree of surface-subsurface connection (i.e., P_C) seemed to vary more with depth than with stream feature (i.e., head, tail, pool). However, our data from the alluvial stream are consistent with earlier findings that hyporheic exchange tends to be greater at riffle heads and lower at riffle tails and in pools [e.g., *Harvey and Bencala*, 1993; *Morrice et al.*, 1997]. P_C was significantly higher in riffle head locations in the alluvial subsurface than in riffle tails or pools (Figure 3b). Because of the lower gradient of the peat stream, there were no prominent riffles, only runs. There were no significant differences in P_C between heads and tails of runs or in pools in the peat stream (Figure 3b).

4.2. Water Chemistry Comparisons Between the Two Streams

[47] While there were no significant differences in the surface water chemistry between the two stream types, there were significant differences in the subsurface water chemistry. Concentrations of all five variables measured in the subsurface were significantly different between the two stream types. Thus, while the watershed characteristics that affect the surface water composition of the two streams were comparable, subsurface processes in the two streams were quite different.

[48] The hyporheic zone is a critical site for decomposition of organic matter, often accounting for a large proportion of whole stream respiration [*Grimm and Fisher*, 1984; *Naegeli and Uehlinger*, 1997; *Fellows et al.*, 2001]. Without regular renewal of respired DO, the subsurface environment would become anoxic, strongly influencing biogeochemical dynamics in stream sediments. As expected, we found a positive correlation in both the peat and alluvial streams between P_C and subsurface DO concentration (Figure 5). Thus, P_C strongly influences subsurface nutrient chemistry, directly through its effect on advective transport, and indirectly through its effect on DO. In turn, P_C directly influences R_{NR}.

4.3. Estimates of Net Nutrient Regeneration

[49] In the summer of 2005, the hyporheic zone was a net source of ammonium (alluvial average: 1.41 μmol m^{-2} h^{-1}; peat average: 6.79 μmol m^{-2} h^{-1}) and SRP (alluvial average: 0.54 μmol m^{-2} h^{-1}; peat average: 0.05 μmol m^{-2} h^{-1}) to the surface water in both stream types. The alluvial hyporheic zone was a much stronger source of SRP than the peat hyporheic zone, while the peat hyporheic zone was a much stronger source of ammonium. Average R_{NR} values for the summer of 2005 indicate that the hyporheic zone of the alluvial stream was a net source for nitrate (7.86 μmol m^{-2} h^{-1}) and that the hyporheic zone of the peat stream was a net sink for nitrate (−1.53 μmol m^{-2} h^{-1}). This

is likely due to the hypoxic to anoxic conditions in the peat subsurface that facilitate denitrification, dissimilatory nitrate reduction to ammonium, or other nitrate uptake processes. This is consistent with the conclusions of *McNamara et al.* [2008] that the spatial patterns of nitrate and ammonium in stream water are controlled by the presence of anoxic soils in catchments. There is clear evidence that differences in physical stream characteristics, which are driven by stream gradient, affect hyporheic exchange and ultimately result in important differences in net nutrient regeneration to the surface water.

[50] Two methodological factors in our study may have caused us to underestimate R_{NR}. They include potential RWT adsorption and downstream discharge gains. *Bencala et al.* [1983] and *Dierberg and DeBusk* [2005], among others, have noted that RWT may adsorb to stream sediments, particularly those with high organic content. We used RWT because it can be measured at much lower concentrations than commonly used halide tracers. We do not expect RWT to adsorb differentially with depth and so we think the general distribution of RWT with depth (decreasing) is correct. However, if a significant amount of RWT adsorbed to the sediment, we may have underestimated connectivity values, which would have led to conservative R_{NR} estimates.

[51] Our SIE data indicated that the stream reaches in this study were slightly gaining. The increased discharge could be attributed to surface inputs, subsurface inputs or both, but we cannot make that determination using our data. R_{NR} and R^{*}_{NR} represent the two outer boundaries of our net nutrient regeneration rate estimates. If none of the additional discharge inputs interact with the hyporheic zone, the estimated value would equal R_{NR}. If all of the additional discharge inputs enter via the hyporheic zone, the estimated value would equal R^{*}_{NR}. Because of the presence of permafrost, these streams lack a large-scale connection to an aquifer and it is likely that any additional inputs of water within the reach were the result of lateral inputs from melting permafrost.

[52] While R^{*}_{NR} values are higher than R_{NR} values, that difference is small in comparison with surface water through flux of nutrients (TF_{SURF}). For the two reaches that were the subject of this study, hyporheic regeneration was a small fraction of TF_{SURF}. This does not, however, mean that hyporheic regeneration is unimportant. Nutrient concentrations in these arctic streams are typically very low [*Kling et al.*, 2000; *Slavik et al.*, 2004; *McNamara et al.*, 2008]. In-stream nutrients can be taken up rapidly [*Peterson et al.*, 2001; *Wollheim et al.*, 2001] but must be rapidly replaced or nutrients would be completely consumed within a few hundred meters. It is likely that a high proportion of the nutrients taken up by autotrophs is returned to the water column relatively quickly (days to weeks) by direct remineralization. However, some portion (potentially large [e.g., *Wollheim et al.*, 2001]) of the nutrients that are immobilized in autotrophic biomass are transferred into organic forms that may be returned to the water column only slowly (e.g., particulate and dissolved organic matter) or not at all (e.g., insect emergence, denitrification). Therefore in-stream inorganic nutrients must be replenished by some combination of lateral inputs (surface or subsurface) and mineralization of allochthonous organic matter. Even if the loss rates are small, the system will eventually run down if the losses are not replenished. On average, the hyporheic zone of the alluvial reach regenerated a mass of SRP that was equivalent to ~9% of the in-stream mass through flux. Average ammonium and nitrate regeneration rates were 5% or less. On average, the hyporheic zone of the peat reach regenerated a mass of ammonium that was equivalent to ~10% of the in-stream mass through flux. Average nitrate and SRP regeneration rates were 1% or less. This regeneration of inorganic nutrients from the hyporheic zones of these two streams is likely to be supported by mineralization of allochthonous organic matter.

[53] Net nutrient regeneration rates estimated by *Edwardson et al.* [2003] for the reference reach of the Kuparuk River, Alaska and for Blueberry Creek, Alaska (K. Edwardson, personal communication, 2007) are similar to those estimated for the alluvial reach in this study. These streams are in relatively close proximity to the streams sampled in our study. The Kuparuk is a fourth-order, cobble-bottom, alluvial reach that is low in productivity and dominated by diatoms [*Slavik et al.*, 2004]. Blueberry Creek is a second-order alluvial reach that is the outlet stream from Lake I-8, whereas the alluvial stream in our study is the inlet to Lake I-8. *Edwardson et al.* [2003] found that the hyporheic zones of Blueberry Creek and the reference reach of the Kuparuk River were sources of nitrate, ammonium and SRP. Estimates of nitrate, ammonium, and SRP regeneration rates were 1.72, 4.82, and 0.02 μmol m^{-2} h^{-1}, respectively, in Blueberry Creek and 28, 28, and 2 μmol m^{-2} h^{-1}, respectively, in the Kuparuk River. These estimates are quite comparable to the rates we estimated for the alluvial stream in our study.

5. Conclusions and Implications

[54] The combination of tracer and water chemistry data from our study indicate that the majority of hyporheic exchange occurred in only the shallow layers of the thawed subsurface in both arctic tundra stream types we studied. However, patterns of surface-subsurface connection were different in higher-gradient, alluvial and lower-gradient, peat-bottomed streams. This, in turn, created very different patterns of nutrient chemistry in the subsurface water of the two stream types, which led to clear differences in net nutrient regeneration rates. While the hyporheic zone was a source of nutrients to the surface water in most cases in this study, the flux of nutrients coming from the hyporheic zone is a small fraction of the nutrient flux moving through the surface water of the stream channel. Although small, these inorganic nutrient inputs are very important to maintaining the in-stream nutrient balance. Furthermore, the alluvial R_{NR} estimates from our study are consistent with those presented for similar streams by *Edwardson et al.* [2003].

[55] Although climate warming is not predicted to affect the vertical extent of hyporheic exchange via increases to the thaw bulb extent, other possible effects of climate change could influence the magnitude of hyporheic nutrient processing and net nutrient regeneration. If net nutrient regeneration rates do not change, but the thaw season increases in length, the magnitude of net nutrient regeneration would be larger on an annual basis due to an increase in the number of days per year that conditions are favorable for hyporheic exchange (i.e., thawed subsurface sediments

and increased sediment temperatures). If increased sediment temperatures lead to increased rates of metabolism in the hyporheic zone, rates of nutrient regeneration could increase, but rates of nutrient consumption could also increase. Thus, it is not possible to accurately predict the net effect of increased metabolic rate on stream nutrient balance. Last, increased thaw may decrease the stability of the tundra, which may result in increased thermokarst failure. Thermokarst activity can result in substantial sediment and organic matter inputs to streams. These inputs could affect nutrient and organic matter budgets in streams as well as stream geomorphology, a factor that our research has shown can significantly affect hyporheic characteristics. We suggest that the overall impact of climate change on hyporheic processes in arctic tundra stream ecosystems will depend on the effects and interactions of increasing thaw season length, sediment temperature increases and geomorphic change in the arctic tundra environment.

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