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The hydraulic characteristics and geochemistry of hyporheic and parafluvial zones in Arctic tundra streams, north slope, Alaska

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Abstract

Sodium bromide and Rhodamine WT were used as conservative tracers to examine the hydrologic characteristics of seven tundra streams in Arctic Alaska, during the summers of 1994–1996. Continuous tracer additions were conducted in seven rivers ranging from 1st to 5th order with samples collected from instream, hyporheic, and parafluvial locations. Tracer data was used as input for a computer model to estimate hydrologic characteristics of each study reach. While solute concentrations during the tracer additions indicated that steady-state or "plateau" conditions had been reached, interstitial samples indicated that there were additional hyporheic and parafluvial zones that had not been fully labeled at the time of apparent steady state in the stream channel (plateau). Exchange between channel and hyporheic water was a function of location within a pool–riffle sequence, with rapid downwelling at the head of riffles and delayed upwelling in riffle tails. The extent of exchange between channel and hyporheic water was positively correlated with apparent streambed hydraulic conductivity. Tracer additions indicated interstitial velocities ranging from 0.030 to 0.075 $cm\,s^{-1}$ and hydraulic conductivities from 2.4 to 12.2 $cm\,s^{-1}$. Hyporheic and in-channel samples were collected for N, P, DO, and CO_2 analyses in conjunction with conservative tracer additions in four of the stream reaches for which the interstitial velocities were also determined. Transformation rates based on these data indicated that there was rapid nitrification of mineralized organic N and production of ammonium, phosphate, and carbon dioxide in the interstitial zones of all four reaches. Dissolved oxygen did not appear to be limiting in the reaches studied. The hyporheic zone of all four reaches was a source of nitrate, carbon dioxide, and ammonium to the channel water based on the average concentration of upwelling waters. Increased contact time with hyporheic and parafluvial zones was related to decreased temperature and increased conductivity. Net nitrogen flux from the hyporheic zone was equivalent to 14–162% of benthic N uptake requirements for the Kuparuk River. These observations are important because we expected that the presence of continuous permafrost in this Arctic environment would limit the importance of hyporheic processes, either physically (i.e., through the presence of a restricting thaw bulb in the permafrost) or biogeochemically (i.e., through low temperatures). Instead, we found that biogeochemical processes in the hyporheic zone of these Arctic streams are at least as important as it is in similar temperate stream ecosystems.

Keywords: Transient storage zone; OTIS; Hyporheic zone; Arctic streams

1. Introduction

Transient storage zones are areas within or adjacent to the streams where a parcel of water leaves the main body of flowing water and becomes entrained by some stream feature. These features may include hyporheic zones below the open channel flow [53] and parafluvial zones adjacent to the open channel flow [23]. In addition to these interstitial volumes, storage may occur in eddies formed by boulders, debris dams, and plant biomass [34].

Water flow through hyporheic and parafluvial zones is of particular importance because as water moves

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through interstitial spaces in the sediments it comes in intimate contact with sediment surfaces. There is thus a high opportunity for biogeochemical processing of dissolved materials [14,43]. Vaux [49] identified three key factors that control movement of water through these interstitial areas: changes in bed thickness, changes in streambed permeability, and changes in longitudinal shape of the streambed (either convex or concave). Munn and Meyer [35] found that the rate of infiltration into the hyporheic zone was faster in cobble substrates than in fine sand substrates. Morrice et al. [33] correlated an increase in the relative size of the modeled storage zone with an increase in hydraulic conductivity.

Findlay [14] stated that the importance of hyporheic nutrient processing is a function of these physical factors rather than biological processing rates. For example reduction of permeability in the hyporheic zone results in reduced dissolved oxygen [45,47,48], decreased NO_3 [16], increased NH_4 [8], and increased PO_4 [20]. The concentration of hyporheic dissolved oxygen (DO) is an indicator of the degree of water exchange with the open channel or distance along an interstitial flowpath [20]. Increased depth typically is related to decreased DO [54]. Zones of downwelling may inject particulate and dissolved organic carbon into the hyporheic zone and increase respiration at downwelling sites compared with upwelling sites [25]. Jones and Holmes [26] also found that these streams can be sources of nitrate, through nitrification, if hyporheic DO remains high. Furthermore, high concentrations of mineralized nitrogen and phosphorus in upwelling water may support local benthic production [52], and significantly increases the rate of post-spate recovery of algae [46]. Meyer and Likens [31] found that subsurface zones were a source of P in Bear Brook, New Hampshire and contributed 11% of P inputs to this stream.

Stream solute transport models that include transient storage [5,11,17,42] have been used to estimate the relative sizes of transient storage in a variety of streams. Harvey et al. [19] evaluated the widely used OTIS model [42] and found that under base flow conditions the model reliably estimated stream to streambed exchanges while at high flows the modeled storage was controlled by surface storage zones such as eddies. Thus, modeled transient storage should not be assumed to equal hyporheic storage. However, it is difficult to ascertain what portion of the transient storage is due to entrainment in interstitial sediment zones (hyporheos and parafluvial zones) and what portion is due to hydraulic retention (e.g. in eddies).

While there is a growing literature on hyporheic and parafluvial processes in temperate streams, there is essentially no information regarding the hydrologic and chemical dynamics of these zones in Arctic tundra streams [22,50]. The presence of permafrost suggests that hyporheic dynamics in these streams might be restricted when compared with similar temperate streams, thereby influencing modeled storage zone properties. To address this question, we conducted 17 conservative tracer additions to Arctic tundra streams between 1994 and 1996. The stream reaches studied varied in discharge by three orders of magnitude, stream order (first through fifth), morphology (sinuous, braided, beaded), and substrate type (peat, cobble, and gravel). We used tracer responses in hyporheic samplers and OTIS-P simulations of tracer transport in surface water to determine the in-stream hydrologic parameters for velocity (v), lateral inputs (Q_{lat}), storage-zone exchange rates (α), stream cross-sectional area (A), and storage zone cross-sectional area (A_s). We compared the relative magnitude of transient storage (A_s/A) in the different stream reaches and examined the exchange between channel and interstitial waters at local, whole-reach, and regional scales. We also quantified transport rates of water and materials through the hyporheic zone of selected Arctic tundra streams, gathered evidence of biogeochemical processing within hyporheic parafluvial zones, and estimated the potential importance of hyporheic and parafluvial nutrient processing on nutrient dynamics in these streams. Collectively, this information provides what we believe is the first comprehensive description of hyporheic and parafluvial processing in Arctic tundra streams.

2. Study sites

2.1. Site description(s)

The tundra streams examined in this study lie in the northern foothills of Alaska's Brooks Range. Clearwater tundra streams that drain the foothills and coastal plains do not originate from glaciers or springs, and generally have intermediate levels of productivity [9]. Stream side vegetation in these areas was typically comprised of moist tundra communities, predominantly sedges (*Carex aquatilis* and *Eriophorum vaginatum*) and patches of dwarf willows and birches (*Betula nana*) [21,24,29]. We selected seven stream reaches for study and conducted one to four conservative tracer additions on each reach. Six of the seven reaches were within 20 km of the Toolik Lake field station (68°38′N, 149°38′W). The 7th study reach was at the mouth of the Kuparuk River, 20 km inland from the Arctic Ocean (70°15′N, 149°00′W) (Fig. 1, Table 1). Hyporheic sampler networks were established in four reaches of two typical Arctic tundra streams, the Kuparuk River and Oksrukuyik Creek. Three networks were installed in close proximity to the Toolik Lake field station (68°38′N, 149°38′W) and the fourth was installed in a reach 15 km inland from the Arctic Ocean on mouth of the Kuparuk River (70°15′N, 149°00′W) (Fig. 1).

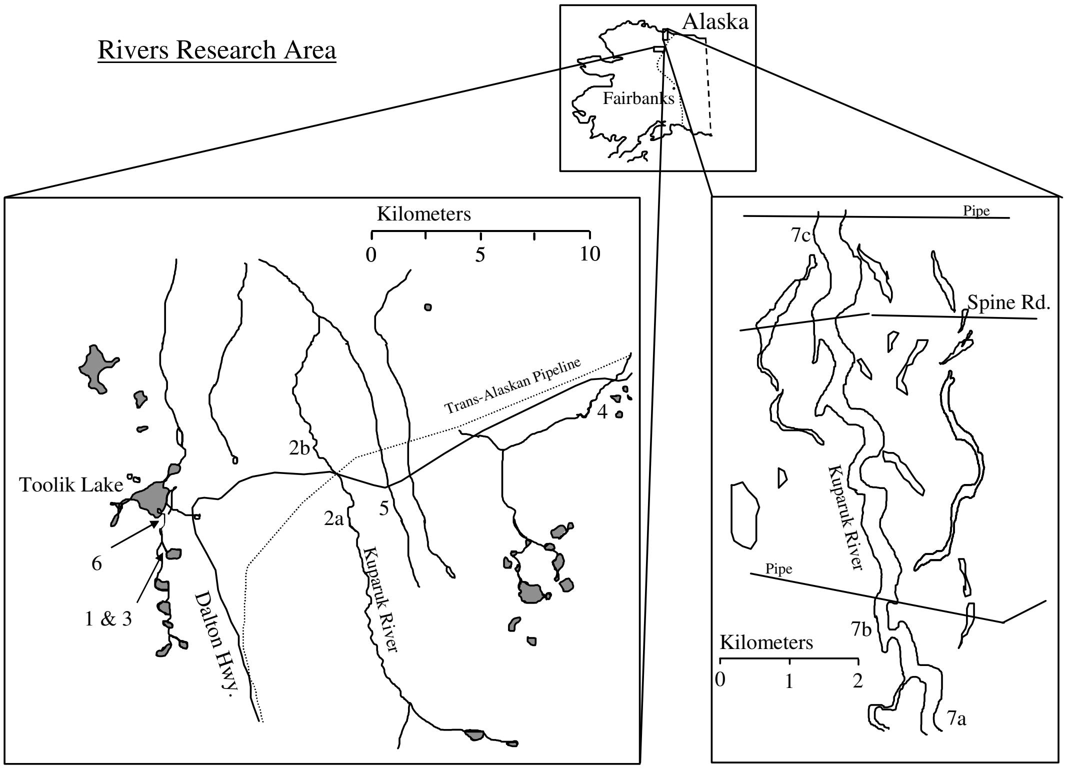

Fig. 1. Location of rivers and solute addition sites used in this study. (1) Blueberry Creek, (2) Kuparuk River (a: reference, b: fertilized), (3) tributary to Blueberry Creek, (4) Oksrukuyik Creek, (5) Imnavait Creek, (6) Toolik Inlet, and the (7) mouth of the Kuparuk River; (7a) Rhodamine WT addition, (7b) interstitial and continuous sampling, and (7c) continuous sampling.

Table 1
Information about solute releases and stream reaches used in this study

River	Date	Tracer	Number of sites	Reach lengths (m from dripper)	Substrate	Morphology	Order	% Gradient
Tributary to Blueberry Cr.	July 21, 1994	NaBr	1	30	Cobble	Water-track	1	7.00
Imnavait Cr.	July 3, 1995	NaBr	2	79/137	Peaty	Beaded	2	0.24
Imnavait Cr.	July 6, 1995	NaBr	2	32/61	Peaty	Beaded	2	0.24
Blueberry Cr.	June 25, 1994	RWT	2	60/760	Cobble	Sinuous	2	0.11
Blueberry Cr.	July 2, 1994	RWT	2	299/785	Cobble	Sinuous	2	0.11
Blueberry Cr.	July 12, 1994	RWT	2	182/600	Cobble	Sinuous	2	0.11
Blueberry Cr.	August 6, 1994	NaBr	2	182/600	Cobble	Sinuous	2	0.11
Toolik Inlet Stream	July 21, 1995	NaBr	1	543	Cobble	Sinuous	3	0.14
Toolik Inlet Stream	July 5, 1996	NaBr	2	229/574	Cobble	Sinuous	3	0.14
Oksrukuyik Cr.	July 11, 1995	NaBr	1	331	Gravel	Sinuous	3	0.05
Oksrukuyik Cr.	June 26, 1996	NaBr	2	550/1056	Gravel	Sinuous	3	0.05
Kuparuk R. (ref. & fert.)	July 5, 1994	NaBr	2	848/1618	Cobble	Sinuous	4	0.55
Kuparuk R. (ref.)	July 15, 1995	NaBr	2	720/1370	Cobble	Sinuous	4	0.55
Kuparuk R. (fert.)	July 25, 1995	NaBr	2	740/3840	Cobble	Sinuous	4	0.55
Kuparuk R. (ref. & fert.)	June 21, 1996	NaBr	2	775/3100	Cobble	Sinuous	4	0.55
Kuparuk R. (ref. & fert.)	July 26, 1996	NaBr	2	775/3100	Cobble	Sinuous	4	0.55
Kuparuk R. Mouth	July 12–17, 1996	RWT	2	1800/10,400	Gravel	Braided	5	0.05

The small tributary to Blueberry Creek was studied in 1994 during high flow (reach 3, Fig. 1). At low flow, there was no observable surface discharge from the tributary. The tributary was the steepest in the study with a gradient of 7% over the studied reach (Table 1).

Imnavait Creek, is a peat bottom, ‘‘beaded’’ stream (reach 5, Fig. 1) characterized by short runs of 5–10 m that link deep pools (beads) having an average volume of 51 m^3 each. This beaded geomorphology is common for streams that drain the Alaskan North Slope foothills and coastal plain. A submerged eelgrass species (probably *Vallisneria*) covered 0–80% of the substrate and may have offered some degree of physical structure in the beads. Two whole-stream tracer additions were

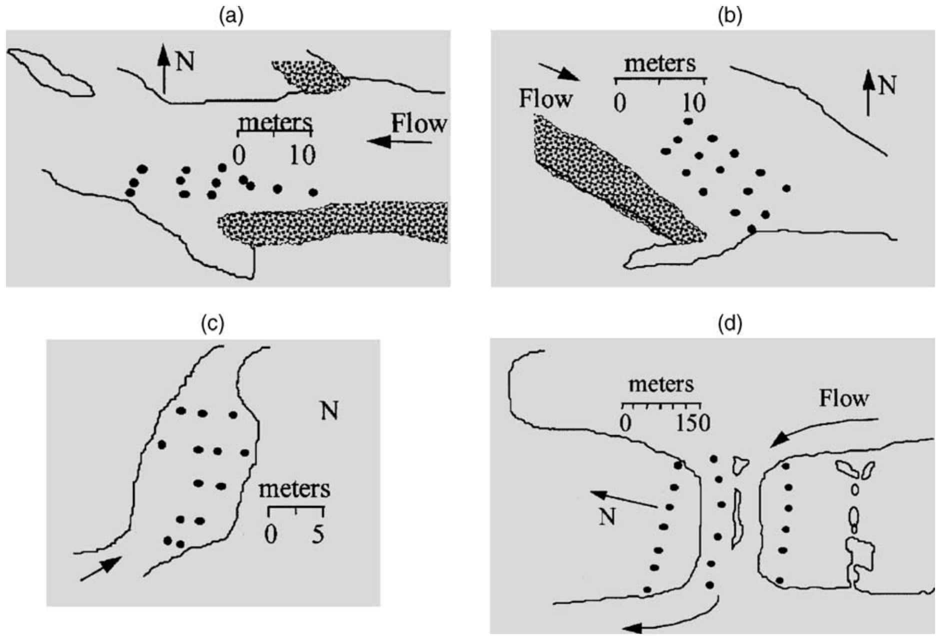

Fig. 2. Hyporheic and parafluvial sampler layout in specific reaches studied: (a) Reference reach of the Kuparuk River, (b) fertilized reach of the Kuparuk River, (c) Oksrukuyik Creek, and (d) mouth of the Kuparuk River.

conducted on this reach in 1995. Samples were taken in one of the beads at a depth of 2 m and stainless steel canulas were used to draw water out of the streambank 15 cm inland from the channel.

The main stem of Blueberry Creek (reach 1, Fig. 1) is a cobble-bottomed, lake-outlet stream with a gradient such that the study reach consisted nearly exclusively of riffles. The upper portion of the reach was dominated by epilithic algae mats of the diatom *Didymosphenia geminata*; the lower portion of the reach was dominated by a mixed community of diatoms. Four conservative tracer addition experiments were done on this reach in 1994. Blueberry Creek was instrumented with 11 hyporheic samplers at regular intervals along the 1000 m reach.

The Toolik Lake Inlet stream (reach 6, Fig. 1) is a 3rd order, cobble-bottomed stream, in which a mixed epilithic diatom community dominates the substrate. Tracer addition experiments were done during a spate in 1995 and at base flow during 1996.

Oksrukuyik Creek, is a 3rd order stream (reach 4, Fig. 1) composed of course gravel and stones in the reach studied. Addition experiments at Oksrukuyik Creek were conducted within the same reach as a long-term, P- and N-fertilization experiment in progress at that time [18]. Benthic cover in the fertilized reach was dominated by filamentous green algae (15%) and diatoms (75%); bryophytes made up less than 5% of benthic cover [18]. One conservative tracer addition was done in the fertilized reach of Oksrukuyik Creek in both 1995 and 1996. Oksrukuyik Creek was instrumented with two sets of four samplers in two transects of 10 m total length on point bars (+0.9 and +1.2 km). An additional five hyporheic samplers were installed in a transect of 10 m total length in a riffle in the reference zone (−0.80 km). In 1996, 13 hyporheic samplers were installed in a pool–riffle–pool sequence at +0.57 km in the fertilized zone (Fig. 2c). All river locations are referenced to the position of the fertilizer dripper (0 km) used in the study reported by Harvey et al. [18].

The upper Kuparuk River study area (reaches 2a and 2b, Fig. 1) is the site of the long-term, P-fertilization experiment described by Peterson et al. [38]. The reference reach (upstream, 2a) is a cobble-bottom stream with roughly equal portions of riffle and pool habitat and low primary productivity [7]. An epilithic diatom community covers 80% of the substrate [32]. The remaining benthic community is comprised of *Schistidium agassizii* (a bryophyte) and several other seasonal macroalgae [6]. In contrast, the P-fertilized reach (downstream, 2b) is dominated by two bryophytes *Hygrohypnum ochraceum* and *Hygrohypnum alpestre* which cover almost 50% of the riffle substrate [6,15]. Several other bryophytes are present to a lesser extent, but collectively the bryophyte community covers up to 70% of the riffle area in the fertilized reach [3]. The remaining substrate is colonized by epilithic diatoms and various macroalgae assemblages. One tracer experiment covering both reaches was conducted in 1994, separate tracer addition experiments were done in the reference and fertilized reaches in 1995, and two tracer additions were conducted in 1996 encompassing both reaches together. In the upper Kuparuk River, 10 samplers were installed along a 20 m transect of the fertilized reach (+2.75 km) and 12 samplers were installed in a 25 m transect of the reference reach (+0.075 km) (Fig. 2a) of the Kuparuk River during the 1995 ice-free season. In 1996, a grid of 13 samplers were installed in the reference reach of the Kuparuk River along 25 m of a riffle (+0.075 km). In the fertilized reach in 1996, a grid of 15 samplers were installed in a riffle, along a transect of 20 m total length at +2.4 km (Fig. 2b). All river locations are in reference to the position of the original Kuparuk fertilizer dripper location (0.0 km) in 1983.

A three-day addition was conducted during July 1996 at the mouth of Kuparuk River (reach 7, Fig. 1), a 5th order, moderately braided, course-gravel stream with relatively low productivity about 18 km upstream from the Arctic Ocean. The Lower Kuparuk River was instrumented with 6 hyporheic samplers over a transect of 90 m in a pool–riffle–pool sequence. An additional 14 samplers were installed within the adjacent left and right point bars, along transects parallel to the hyporheic samplers and main stream flow, 100 and 115 m in length, respectively (Fig. 2d).

3. Methods

3.1. Hyporheic samplers

The hyporheic samplers consisted of a 1/8 in. O.D. stainless steel (SS) tube housed in a 3/4 in. O.D. PVC pipe. The lower end of the SS tube extended into a 15 cm length of screened (0.01 in. slot width) PVC tube, isolated both above (by a rubber stopper) and below (by a solid PVC tip). The upper end of the SS tube extended above the PVC tube and was outfitted with a Pharmaseal, 3-way stop-cock to facilitate sampling with a 60 cc, BD plastic syringe. The isolated segment minimized the volume that had to be cleared prior to sampling and also minimized contact between the atmosphere and samples that were to be used for gas analysis.

Samplers were inserted into the streambed by forcing a pry bar into the streambed to the depth of refusal, typically 35–55 cm. The sampler was then worked down into the hole and the pry bar removed, allowing the hole to cave in around the sampler. Fine sediments among the cobbles effectively sealed the samplers in place. Parafluvial samplers were inserted so that the screened area was 35–55 cm below streambed depth.

A second sampler type was designed to be portable and was used to sample shallow (15 cm) hyporheic waters at the mouth of the Kuparuk River. Like the standard samplers, it was screened over 10 cm, however this sampling region was centered at a depth of 15 cm. The key difference was that the shallow sampler casing was made of steel pipe with a stainless steel well screen and had a foot peg to aid with insertion into the streambed.

3.2. Tracer additions

Estimates of lateral inputs and discharge were obtained from continuous injections of conservative tracers (sodium bromide or Rhodamine WT [RWT]) using standard methods and computations suggested by Kilpatrick and Cobb [27] and the Stream Solute Workshop [44]. Either a Cole Palmer peristaltic pump or a Fluid Metering Inc. valveless piston pump was used to ensure a constant rate of injection. For all tracer experiments, except the 1994 Blueberry Creek tributary and 1995 addition to Toolik Inlet, two downstream channel sampling sites were established. All downstream sites were located on the basis that they be far enough apart to detect the effects of lateral inputs and close enough to the dripper to allow for tracer plateau within a reasonable time period (typically several hours). The instream sampling regime was designed to provide more frequent samples during the rising and falling limbs of the solute curve.

3.3. Conservative tracer analysis

Sodium bromide was used for the majority of the tracer additions (1994–1996). Channel concentrations of bromide were monitored continuously throughout each addition using an Orion 290A multimeter with a bromide ion-selective electrode (ISE) and a reference electrode (AgCl, KNO_3) at each site. The bromide electrodes were used primarily to monitor the progress of the experiment and not for precise estimates of concentration. As a consequence, an ionic-strength-adjustment solution was not used. At intervals during the addition experiment, grab samples were taken and the associated mV value on the meter was recorded. Bromide concentrations in the grab samples were quantified by high pressure liquid chromatography (HPLC) on a Dionex AS4A anion column. A regression between the in-stream mV readings from the bromide ISE and the associated bromide concentrations obtained by HPLC was used to associate bromide concentrations with the remaining instream bromide ISE measurements. Due to changing sensitivity of the ISE probes, separate regressions were typically developed for the rising and receding limbs of the conservative tracer curves. The r^2 values for these regressions were typically >0.98. Hyporheic samples were analyzed on the same anion column as channel samples.

Rhodamine WT (RWT) was used in the early part of the 1994 field season during additions to Blueberry Creek. Samples were collected in borosilicate vials and Rhodamine WT concentrations were determined on a Turner Designs, Model 111 fluorometer. Rhodamine WT was again used during the July 1996 addition to the mouth of the Kuparuk River. Samples were collected in 13 mm diameter borosilicate glass vials with Teflon liners that fit into a Turner Designs 10-AU field fluorometer so that no transfer of liquid was necessary.

3.4. Solute modeling

Stream solute concentrations were initially modeled using the one-dimensional transport with inflow and storage (OTIS) model [41] via an iterative "visual best fit" approach. Stream cross-sectional area was determined in the field at 50 m intervals, based on average depth and channel width and used as a starting point in fitting the advective front of the model. The "visual best fits" were used as input to OTIS-P [42], a newer version of the transport model that uses nonlinear least squares analysis to adjust the parameters for a best statistical fit. The model's governing equations are described fully in [5,42]. The Damkohler I number (DaI) was calculated to evaluate the reliability of the OTIS-P parameter estimates for each parameter set [51]. The Damkohler number, (DaI):

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

where α is the stream-storage zone exchange coefficient, L is the experimental reach length, and v is the velocity in that reach [4].

Output from OTIS simulations include both channel and storage-zone solute concentrations. Determination of the ratio of storage zone cross-sectional area to stream channel area (A_s/A) was used to compare the relative sizes of storage zones in differing streams types and under different discharge conditions within a stream. Potential storage zones in streams were sampled for comparison to the OTIS-P predictions. Storage zone area (A_s) and exchange rate (α) were later used to estimate the potential contribution of the hyporheic zone to benthic metabolism requirements.

3.5. Vertical hydraulic gradient

The potential for upwelling or downwelling at a site was quantified by measuring the vertical hydraulic gradient (VHG) [55] or head difference between sub-surface and surface water. The VHG at each hyporheic sampler was determined 1–4 times during the 7-week field season. A hydraulic potentiomanometer was used [55] to make an accurate measurement of the difference in water depth inside and outside of the sampler. Negative VHG values indicate downwelling zones while positive values indicate upwelling zones. Average concentrations of constituents were calculated for groups of upwelling or downwelling samplers at each site.

3.6. Determination of hyporheic flow rates: conservative tracer injections

Hyporheic flow rates were examined using hyporheic sampler networks in each study reach. At the upper Kuparuk reference and fertilized reaches and the Oksrukuyik Creek reach, a concentrated solution of NaBr (490 g/l) was injected for 10 min (total volume 500 ml) into a hyporheic sampler, 35 cm deep, at the head of each sampler network, which served as a tracer source. Samples were taken from downstream samplers for 12 h and the specific conductance measured at the samplers was used to determine the velocity of the advective front.

During the 3d Rhodamine WT (RWT) injection to the reach at the mouth of the Kuparuk River, the upstream edge of the point bars was considered to be the upstream boundary and was used to calculate flow rates of the solute advective front.

Hydraulic conductivities were calculated using Darcy's law, the gradient between the samplers, a porosity of 0.4, and the nominal hyporheic water velocity determined from the NaBr and RWT injections. Interstitial flow was assumed to be laminar.

3.7. Nutrient chemistry

Samples of channel water were collected for nutrient analyses, directly from the stream via a 60 ml syringe and filtered in the field through a 25 mm diameter 0.45 μm cellulose acetate syringe filter (Nalgene). Hyporheic samplers were cleared to waste and then allowed to re-equilibrate prior to final sampling. All nutrient samples were stored cold (4 °C) and in the dark prior to analysis, which was done within 24 h. Analyses for PO_4, NO_3, and NH_4 were done on an Alpkem model 510 flow injection autoanalyzer. Ammonium was determined by the phenate method, PO_4 by the ascorbic acid method, and NO_3 by the cadmium reduction method [1].

Samples for analysis of dissolved oxygen were obtained from the hyporheic samplers using procedures to minimize contact with the atmosphere. The three-way stopcock on the hyporheic sampler was connected to a Tygon tube (1/4 in. O.D., 1/8 in. I.D.), which ran through a stopper into a large mouth jar and then into the bottom of a 30 ml glass vial within the jar. A hand-pump was used to create a low pressure vacuum in the jar, taking care to avoid degassing the sample. Water was allowed to overflow the vial several times. The stopper and tubing were then carefully removed from the jar leaving a "reverse meniscus" on the vial which was then capped taking care not to trap air bubbles. To maintain a stable temperature, samples were immediately placed in a cooler. Within 4 h dissolved oxygen samples were measured with a Solomat DO probe. In addition, temperature profiles of the interstitial waters were measured at the mouth of the Kuparuk River.

Carbon dioxide was measured directly by equilibration of a water sample in a closed syringe, with ambient air. The headspace air was then analyzed by thermal conductivity on a GC for CO_2 as per [28]. Concentrations were corrected for ambient concentrations, temperature, and pH.

3.8. Hyporheic contribution to stream nutrient processing

The nutrient contribution of the hyporheic zone to whole-stream nutrient dynamics was determined with the assumption that half of the modeled storage zone for a given site was true hyporheic exchange, the remainder being in eddies that were biogeochemically relatively unimportant. For a given 100 m reach of stream the net hyporheic flux of CO_2-C, NO_3-N, NH_4-N, and PO_4-P was calculated as the difference between flux into and flux out of the hyporheic zone. Estimated flux rates were calculated as the OTIS-P modeled exchange rate (α) times the volume of the exchanging zone ($0.50 \times A_s \times 100$ m) and converted to a per meter square of stream bottom rate (mmol m^{-2} h^{-1}). Estimated flux rates were then compared with rates of assimilation by the epilithic community, the flux from lateral inputs, and channel through-flow. Epilithon assimilation was calculated based on net primary production mg O_2 m^{-2} h^{-1} and the Redfield ratio of 106:16:1 (molar C:N:P) [40]. Net primary productivity data for the Kuparuk River, Oksrukuyik Creek, and the Mouth of the Kuparuk River came from previous studies [2,3]. Carbon dioxide concentrations in lateral-inflows were obtained from Kling (unpublished data). Percentage contribution by the flux of hyporheic, lateral inputs, and through-flow was calculated for a given nutrient and compared to the assimilative needs of the benthic community.

4. Results

4.1. Solute modeling

Results of OTIS model simulations of instream bromide or Rhodamine WT tracer experiments are presented

Table 2
Measured variables and modeled parameters for solute releases

River	Date	Site	Reach length (m)	Q ($l\,s^{-1}$)	Q_{lat} ($l\,m^{-1}\,s^{-1}$)	V ($m\,s^{-1}$)	α (s^{-1})	A (m^2)	A_s (m^2)	A_s/A	DaI
Tributary to Blueberry Cr.	July 21, 1994	1	30	28	NC	0.170	1.37E−03	0.19	0.082	0.44	0.8
Imnavait Cr.	July 3, 1995	1	45	132	NC	0.068	4.06E−03	1.58	1.33	0.84	5.9
		2	87	137	0.127	0.065	3.19E−03	1.66	0.98	0.59	11.5
Imnavait Cr.	July 6, 1995	1	32	30	NC	0.029	5.04E−03	0.42	1.06	2.54	7.7
		2	61	30	0.000	0.018	5.88E−04	1.27	1.01	0.79	4.5
Blueberry Cr.	June 25, 1994	1	60	266	NC	0.279	3.43E−04	0.94	0.23	0.24	0.4
		2	760	290	0.050	0.253	1.66E−04	1.09	0.24	0.22	2.8
Blueberry Cr.	July 2, 1994	1	299	177	NC	0.180	2.12E−04	0.79	0.58	0.73	0.8
		2	785	186	0.020	0.242	1.15E−04	0.70	0.20	0.29	1.7
Blueberry Cr.	July 12, 1994	1	182	203	NC	0.225	2.23E−04	0.93	0.14	0.16	1.3
		2	600	213	0.096	0.200	1.79E−04	1.07	0.70	0.65	1.4
Blueberry Cr.	August 6, 1994	1	182	147	NC	0.132	3.40E−05	1.15	1.28	1.12	0.1
		2	600	147	0.000	0.141	1.77E−04	1.04	0.32	0.30	3.2
Toolik Inlet Stream	July 21, 1995	1	543	7576	NC	0.900	3.13E−03	5.38	3.48	0.65	4.8
Toolik Inlet Stream	July 5, 1996	1	229	178	NC	0.115	2.18E−04	1.40	0.55	0.39	1.6
		2	574	218	0.115	0.134	3.36E−05	1.17	0.32	0.27	0.7
Oksrukuyik Cr.	July 11, 1995	1	331	685	NC	0.230	5.08E−05	3.68	0.70	0.19	0.5
Oksrukuyik Cr.	June 26, 1996	1	550	1269	NC	0.306	4.26E−04	3.71	0.50	0.13	6.5
		2	1056	1270	0.072	0.352	7.75E−05	3.08	0.43	0.14	1.9
Kuparuk R. (ref. & fert.)	July 5, 1994	1	848	1684	NC	0.323	1.65E−04	5.28	0.94	0.18	2.9
		2	1618	1684	0.090	0.259	3.28E−05	7.09	1.59	0.22	1.1
Kuparuk R. (ref.)	July 15, 1995	1	720	1595	NC	0.140	2.11E−04	7.50	1.27	0.17	7.5
		2	1370	2118	1.924	0.222	5.69E−05	7.17	1.06	0.15	2.7
Kuparuk R. (fert.)	July 25, 1995	1	740	3084	NC	0.441	1.21E−04	6.88	0.99	0.14	1.6
		2	3840	3976	0.331	0.467	4.64E−04	7.01	0.96	0.14	31.7
Kuparuk R. (ref. & fert.)	June 21, 1996	1	775	1583	NC	0.182	4.51E−04	7.11	2.62	0.37	7.1
		2	3100	1668	0.036	0.252	2.86E−05	5.06	0.72	0.14	2.8
Kuparuk R. (ref. & fert.)	July 26, 1996	1	775	1379	NC	0.239	2.12E−04	5.58	1.10	0.20	4.2
		2	3100	1682	0.136	0.235	1.55E−05	6.46	0.52	0.08	2.8
Kuparuk R. Mouth	July 12–17, 1996	1	1800	14995	NC	0.125	2.09E−04	105.57	19.81	0.19	19.0
		2	10,400	16675	0.195	0.259	1.88E−04	28.36	19.87	0.70	18.3

in Table 2. Model fits to the solute curves were generally good with a median of the residual sum of squares equal to 0.12. With four exceptions, the Damkohler I (*DaI*) numbers for the 31 modeled stations ranged from 0.1 to 7.7, within the range expected for reliable transient storage parameter estimates [51]. On July 3, 1995, the velocity to site 2 of Imnavait Creek was 0.065 $m\,s^{-1}$. During the July 25, 1995 Kuparuk River solute addition and the Mouth of the Kuparuk River solute addition on July 12–17, 1996 the sampled reaches were 1800 and 10,400 m downstream from the injection point (Table 2).

While the general relationship of decreasing A_s/A with increasing discharge held true over the spectrum of the studied sites, the relationship was not significant. Similarly, no significant relationships between A_s/A and discharge were detected for a given reach.

The storage zone cross-sectional area of these Arctic streams was on average 43% of the stream cross-sectional area ($A_s/A = 0.43$, range = 0.08–2.54) or, without Imnavait Creek, 32% ($A_s/A = 0.32$, range = 0.08–1.12) of the stream cross-sectional area.

4.2. Characterization of the transient storage zone

On three dates we conducted time series sampling of likely zones of transient storage in selected streams. Within Oksrukuyik Creek the measured downwelling zone closely resembled the OTIS-P storage while upwelling zones only reached 75% of the channel concentration during the injection period (Fig. 3). Measured downwelling in the Kuparuk River on July 26, 1996 reached 80% of channel plateau while upwelling zones only reached 20% of the channel plateau concentration (Fig. 4). During the July 15, 1995 solute injection to the Kuparuk River, bromide concentrations were measured over time in parafluvial samplers ranging from 0.5 to 1.5 m from the channel to determine if there was any lateral exchange occurring. Concentrations in these samplers reached a maximum of 50% of the channel concentration. The water from the bottom of the bead (−1.7 m) in Imnavait Creek on July 6, 1995 was labeled rapidly but still lagged behind the modeled storage zone as predicted by OTIS-P (Fig. 5). No bromide was detected in samples of parafluvial water 30 cm from the channel after 4 h of solute injection.

4.3. Hyporheic hydraulic characteristics

In 1994, hyporheic exchange was examined qualitatively at a macro-scale during three different additions to Blueberry Creek. Once the tracer reached plateau in the channel (3–4 h after the tracer addition began), samples were taken from hyporheic samplers that were installed within the study reach. The degree of tracer penetration at each sampler was calculated as a percent of the channel concentration (Fig. 6). The degree of penetration was consistent over the season and varied by location along the reach from essentially 0% to 100% of channel concentration.

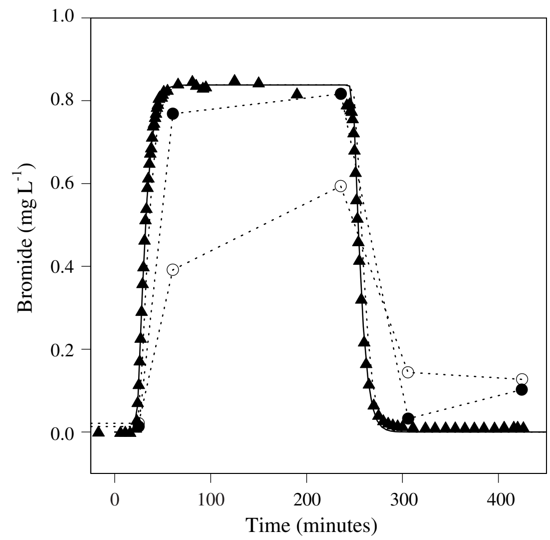

Fig. 3. Bromide concentrations measured in the channel (triangles) and those predicted by the OTIS model for the channel (solid line) and for the storage zone (dotted line), compared to values measured at downwelling hyporheic sites (filled circles) and upwelling sites (open circles) during the June 26, 1996 addition to the Oksrukuyik Creek.

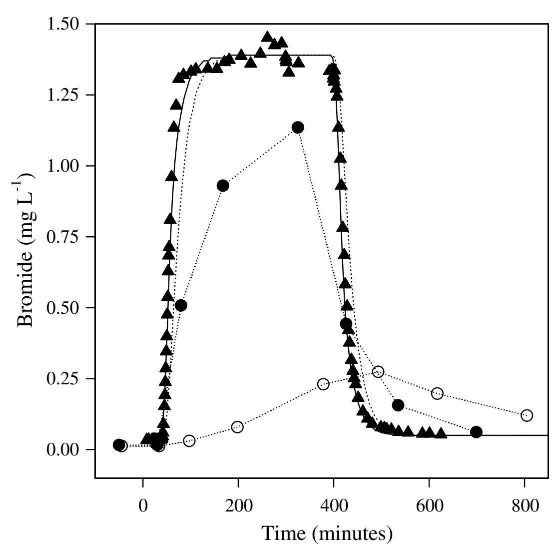

Fig. 4. Bromide concentrations measured in the channel (triangles) and those predicted by the OTIS model for the channel (solid line) and for the storage zone (dotted line), compared to values measured at downwelling hyporheic sites (filled circles) and upwelling sites (open circles) during the July 26, 1996 addition to the Kuparuk River.

During the large-scale tracer addition using Rhodamine WT at the mouth of the Kuparuk River from July 12–17, 1996 we examined the temporal dynamics of hyporheic exchange. Interstitial samples were taken at 13 times during the experiment. Samplers at the head of the riffle came to plateau within hours of the channel

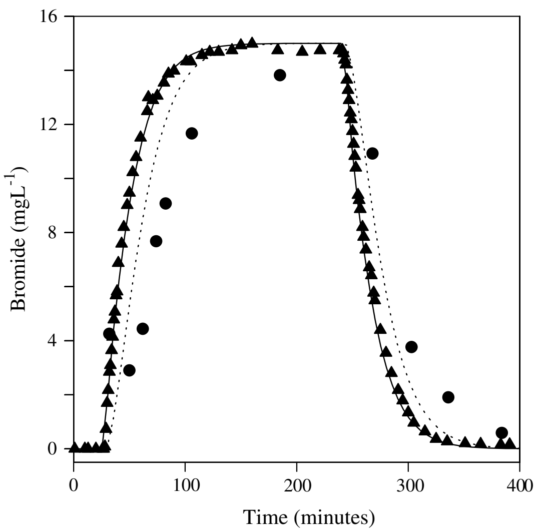

Fig. 5. Bromide concentrations measured in the channel (32 m reference point, triangles) and those predicted by the OTIS model (solid line), compared to Br concentrations predicted by the OTIS model (dotted line) in the storage zone at 37 m (dotted line) and measured in bead-bottom samples at 37 m (circles) during the July 6, 1995 addition to Imnavait Creek.

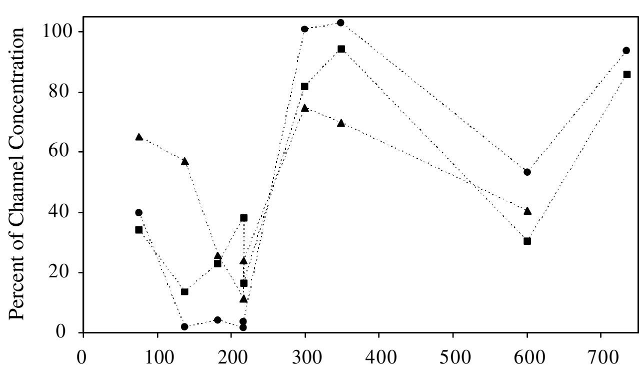

Fig. 6. Tracer concentrations within the hyporheic zone of Blueberry Creek as a percentage of channel plateau concentration. Samples were taken two to three hours after channel tracer concentration stabilized. All tracer additions were made during the 1994 field season; July 2 (circles), July 12 (squares), and August 6 (triangles).

plateau, while maximum Rhodamine WT in samplers at the tail of the riffle did not occur until two days after channel plateau (Fig. 7a). In addition, the concentration of Rhodamine WT at the head of the riffle reached 100% of the channel plateau, while concentration of Rhodamine WT at the tail of the riffle reached only 30% of the channel concentration (Fig. 7b). Time to maximum Rhodamine WT concentration in parafluvial samplers increased as the distance from the upstream boundary increased (5–120 m) (Fig. 7a). Maximum Rhodamine WT concentration as a percentage of channel concentration within parafluvial samplers decreased from 85%

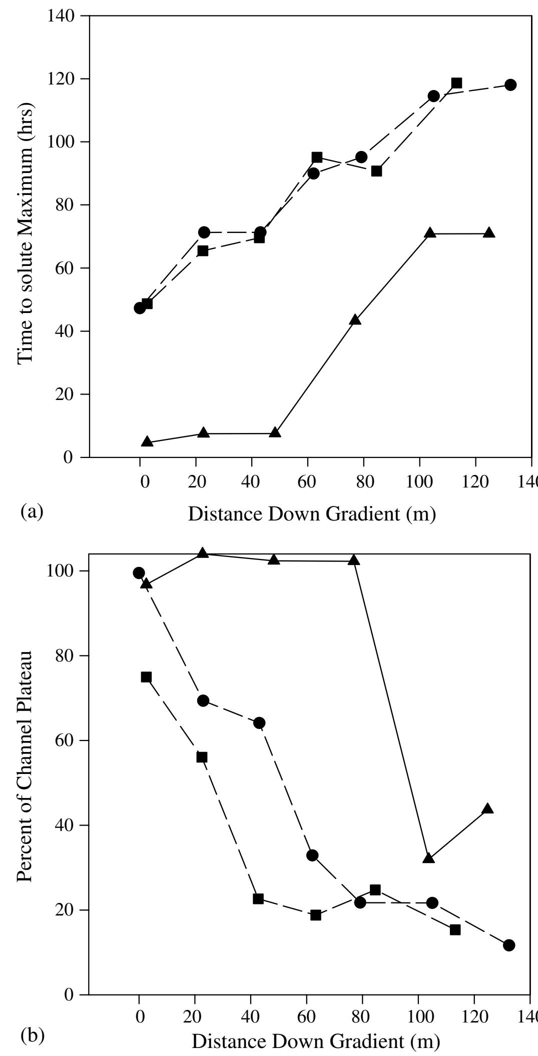

Fig. 7. Summary of tracer behavior in hyporheic (triangles) and parafluvial sampler (river right = circles, river left = squares) during the July 12–17, 1996 solute addition at the mouth of the Kuparuk River. (a) The elapsed time to tracer maximum in each sampler, (b) the concentration of RWT in each sampler as a percentage of the channel plateau concentration.

to 10% with increasing distance from the upstream boundary (Fig. 7b).

The velocity of interstitial water is indicative of the hydraulic conductivity of the sites. Interstitial velocities for the four reaches were similar and ranged from 0.030 to 0.075 cm s^{-1} (Table 3). Hydraulic conductivity ranged from 2.4 to 12.2 cm s^{-1}.

Table 3
Interstitial transformation rates within four Arctic tundra streams

Site	n	Velocity (m min^{-1})	K_{sat} (cm/s)
Oksrukuyik Cr.	3	0.039	5.05
Kuparuk R (ref.)	2	0.041	2.48
Kuparuk R (fert.)	2	0.045	2.35
Mouth of the Kuparuk River	6	0.018	12.21

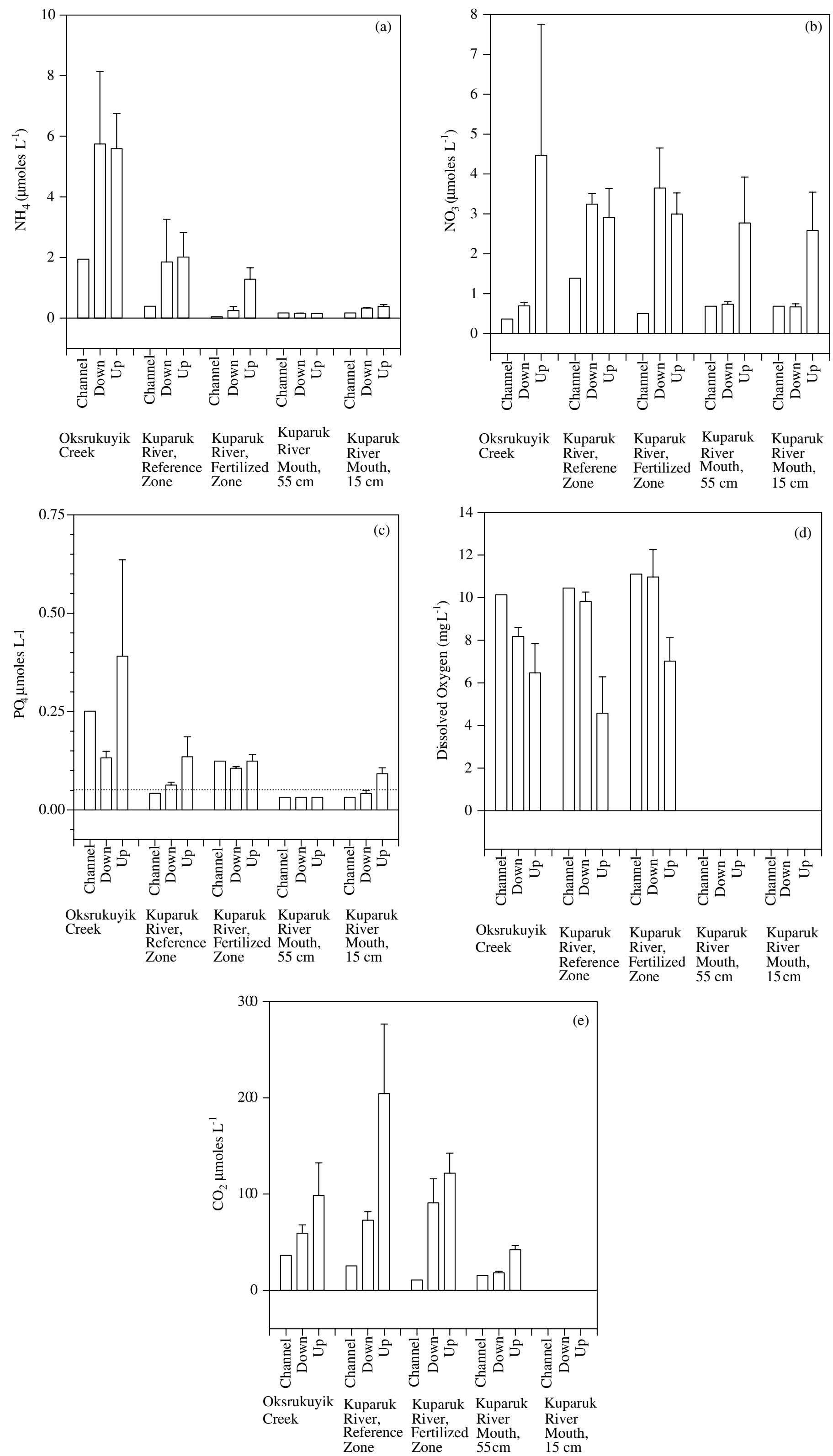

Fig. 8. (a) Average ammonium concentrations in channel water, downwelling hyporheic samplers and upwelling hyporheic samplers. Bars represent ±1 S.E. (b) Average nitrate concentrations in channel water, downwelling hyporheic samplers and upwelling hyporheic samplers. Bars represent ±1 S.E. (c) Average phosphate concentrations in channel water, downwelling hyporheic samplers and upwelling hyporheic samplers. Bars represent ±1 S.E. (d) Average dissolved oxygen concentrations in channel water, downwelling hyporheic samplers and upwelling hyporheic samplers. Bars represent ±1 S.E. (e) Average carbon dioxide concentrations in channel water, downwelling hyporheic samplers and upwelling hyporheic samplers. Bars represent ±1 S.E.

4.4. Water quality characteristics

Concentrations of NH_4 were generally higher in upwelling water than in channel water (Fig. 8a). Concentrations in downwelling water tended to be intermediate between channel water and upwelling water, except in Oksrukuyik Creek. However, even in Oksrukuyik Creek, the hyporheic NH_4 concentrations in both downwelling and upwelling water were higher than the channel concentrations.

The concentration of NO_3 at downwelling sites was higher than that of channel water at all sites except the 15 cm samplers at the mouth of the Kuparuk River (Fig. 8b). The upwelling water at all sites was 0.9–2.5 $\mu mol\, NO_3\text{-}N\, l^{-1}$ higher than channel concentrations. Although the concentration of NO_3 tended to decrease between downwelling and upwelling sites in the reference and fertilized reaches of the Kuparuk River (Fig. 8b), this decrease was not significant.

Net estimated flux of nitrogen from the hyporheic zone of the upper Kuparuk and mouth of the Kuparuk River were potentially equivalent to 14–162% of the N-uptake by the epilithon (Table 4). In the N and P fertilized reach of Oksrukuyik Creek, the net hyporheic nitrogen appeared to be equivalent to 42% of the N-uptake by the epilithic community. Flux rates from the hyporheic zone and from lateral-inflow were similar and small compared to the flux attributed to channel through-flow (Table 4).

Phosphate in channel water for the four reaches studied ranged from below detection (0.05 $\mu mol\, P\, l^{-1}$) in the mouth and reference reaches of the Kuparuk River to 0.12 $\mu mol\, PO_4\text{-}P\, l^{-1}$ in the fertilized reach of the Kuparuk River and 0.25 $\mu mol\, PO_4\text{-}P\, l^{-1}$ in the fertilized Oksrukuyik Creek (Fig. 8c). Phosphate concentrations were higher at upwelling zones than downwelling zones for all rivers except at the deep (55 cm) sites at the mouth of the Kuparuk River (Fig. 8c). Interstitial upwelling concentrations of PO_4 suggested that all reaches except the P-fertilized reach of the Kuparuk River served as sources of PO_4 to surface waters. Hyporheic concentrations of PO_4 in the fertilized reach of the Kuparuk River were similar to channel concentrations.

Net estimated flux of phosphorus from the hyporheic zone of the Oksrukuyik Creek and the upper Kuparuk may be equivalent to 0–13% of the P-uptake by the epilithon and was small compared with lateral-inflow and through-flow fluxes (Table 4). In the mouth of the Kuparuk River, there was no net hyporheic phosphorus flux to the channel (Table 4).

Dissolved oxygen concentrations in channel water always exceeded that of hyporheic waters, and downwelling water always contained more dissolved oxygen than upwelling water (Fig. 8d). There was no dissolved oxygen data recorded for the mouth of the Kuparuk River due to probe failure.

Carbon dioxide concentrations were higher at upwelling sites than downwelling sites for all reaches during all sampling times (Fig. 8e). Hyporheic exchange appeared to be responsible for 50–299% of the C uptake by the epilithon, and like PO_4 was small compared with lateral-inflow and through-flow fluxes (Table 4).

The hyporheic temperature data (Fig. 9a) at the mouth of the Kuparuk River are consistent with the assumption that downwelling samplers would be warmer than upwelling samplers during warm periods. In the parafluvial samplers there was a more gradual temperature decline with longitudinal distance along a

Table 4
Benthic uptake as compared with flux rates by hyporheic upwelling, lateral inflow, and through-flow

		Benthic uptake ($mmol\, m^{-2}\, h^{-1}$)		Hyporheic flux ($mmol\, m^{-2}\, h^{-1}$)	Percentage of benthic uptake	Lateral inputs ($mmol\, m^{-2}\, h^{-1}$)	Percentage of benthic uptake	Through-flow ($mmol\, h^{-1}$)	Percentage of benthic uptake
Kuparuk River (ref. zone)	C	2.281	CO_2-C	3.355	*147*	415.584	*18217*	145909	*4264*
	N	0.344	NO_3-N	0.028	*8*	0.341	*99*	7466	*1446*
			NH_4-N	0.028	*8*	1.187	*345*	2872	*556*
	P	0.022	PO_4-P	0.002	*9*	0.264	*1227*	287	*890*
Kuparuk River (fert. zone)	C	6.313	CO_2-C	3.807	*60*	77.760	*1232*	115396	*1219*
	N	0.953	NO_3-N	0.082	*9*	0.064	*7*	5386	*377*
			NH_4-N	0.048	*5*	0.222	*23*	1077	*75*
	P	0.060	PO_4-P	0.000	*0*	0.049	*83*	1616	*1809*
Oksrukuyik Cr.	C	4.281	CO_2-C	2.127	*50*	37.626	*879*	165439	*6233*
	N	0.646	NO_3-N	0.140	*22*	0.031	*5*	1827	*456*
			NH_4-N	0.129	*20*	0.107	*17*	9136	*2280*
	P	0.040	PO_4-P	0.005	*13*	0.024	*59*	1142	*4561*
Mouth of the Kuparuk River	C	0.564	CO_2-C	1.687	*299*	5.591	*991*	825901	*12957*
	N	0.085	NO_3-N	0.138	*162*	0.005	*5*	32388	*3366*
			NH_4-N	0.000	*0*	0.016	*19*	10796	*1122*
	P	0.005	PO_4-P	0.000	*0*	0.004	*67*	2699	*4488*

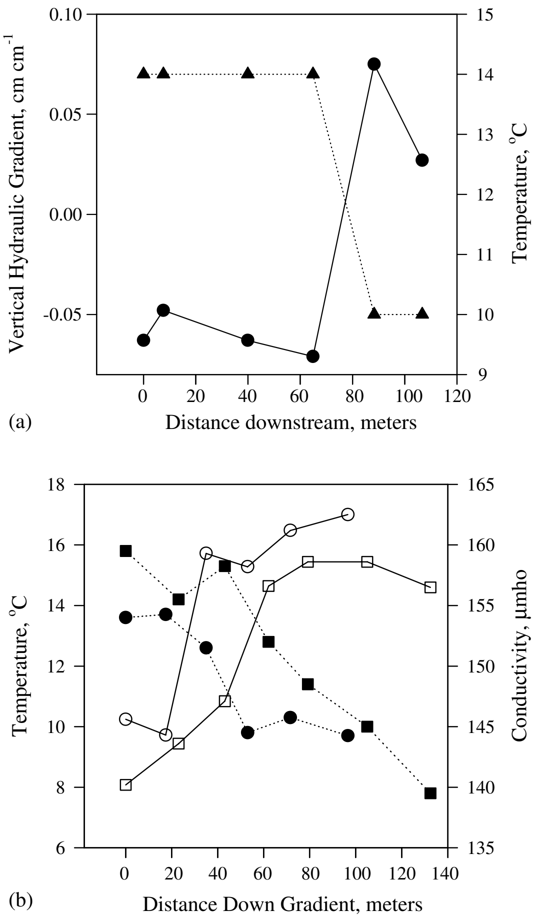

Fig. 9. (a) VHG (closed circles) and temperature (closed triangles) of hyporheic samplers with distance down a riffle in the mouth of the Kuparuk River. (b) Temperature (filled) and conductivity (unfilled) profiles of the left (circles) and right (squares) point bars with distance down gradient in the mouth of the Kuparuk River.

flowpath (Fig. 9b). In addition, there was a gradual increase in specific conductivity in parafluvial samplers consistent with the observed increase in soluble materials.

5. Discussion

5.1. Data quality

The Damkohler I (*DaI*) number has recently been applied to solute modeling to determine the quality of the model output [12,13,51]. Wagner and Harvey [51] found that the coefficient of variation for estimates of A_s and α were lowest (<0.1) at *DaI* values of about 0.7–2 in small high-gradient streams (slope > 1%). The coefficient of variation remains below about 0.5 from *DaI* values that range from ~0.2 up to ~15 and only approach values of 1 at *DaI* values <0.1 and $\gtrsim$ 30. In this study all but one of our streams had gradients that were less than 1%. Nevertheless, with only four exceptions (of 31 total) the *DaI* values for our experiments ranged from good (~1) to acceptable (0.2–15). All four exceptions yielded high *DaI* values. According to Wagner and Harvey [51] when the *DaI* value is high it is not possible to distinguish the storage zone exchange parameters from the dispersion parameter. The high *DaI* from the Kuparuk River (July 25, 1995) does not seem to be related to poor parameter estimates because the estimated parameters are similar to those derived from other runs in the same reach, where the *DaI* values were acceptable. A similar argument may be made for the high *DaI* for Imnavait Creek (July 3, 1995; #2). The high *DaI* values from the parameter sets for the experiments done at the mouth of the Kuparuk River in 1996 may relate to the fact that this was the lowest gradient reach among our experimental sites (0.05%). The substrate in this reach was a loose gravel in which we confirmed rapid penetration of the tracer. This is consistent with the non-identifiably condition described by Wagner and Harvey [51].

5.2. Transient storage in these Arctic streams

Results from this research are in partial agreement with previous findings that A_s/A is inversely related to discharge [10,30,33]. Including the results from all of the tundra streams of this study, there was an inverse, but not significant, relationship between discharge and A_s/A. Streams of different morphologies may not be expected to correspond well with one another since the primary location of modeled storage is different. Even within a given stream, changes in flow have the potential to strongly alter the storage zones being modeled.

The tributary to Blueberry Creek had a relatively small storage zone when compared with the findings of other first order streams [10,33]. The morphology of this first-order tundra water-track resulted in complex, tortuous flow paths. The tracer addition to the Blueberry Creek tributary was conducted during a high flow event. Numerous eddies were observed along the reach's length forming transient storage zones. During base flow there was no observable direct discharge from the tributary to Blueberry Creek, yet small pools within the tributary's track did have flow. From this we may infer that even during high flow, it was likely that interstitial flow contributed to the modeled storage zone.

The ratio of storage area to channel area for Imnavait Creek was among the highest of the tundra streams studied. The high and variable A_s/A for Imnavait was a function of the stream morphology. It was expected that in this peat-bottomed, beaded stream a combination of the bead volume (12.7–160.2 m^3), low discharge (average 120 $l\,s^{-1}$ during the 1995 field season) and possible thermal stratification as seen in the beads upstream of our study [36], would produce large instream storage zones. The OTIS-P model is not sensitive to the slow exchange with the peat (due to low hydraulic conductivity). Rather, the model is more sensitive to rapid exchange, in this case with the in-channel dead-water zones within beads. The variability in the modeled storage was due to solute additions conducted on two different reaches. Although the bead volumes were similar, there were likely differences in the bead-water circulation patterns that impacted solute residence time and therefore transient storage.

Transient storage in the second-order Blueberry Creek was a combination of eddy and hyporheic storage. Three of the four discharge levels followed the trend of increasing transient storage with decreasing discharge. However, the last tracer experiment of the 1994 season (August 6) was the lowest discharge experiment of the season for Blueberry Creek and the downstream site had a low A_s/A. The apparent discrepancy may be explained by changes in the morphology of the stream. During the earlier (higher flow) tracer experiments there were two 50 m reaches of the stream that split from the main channel. However, during the August 8, 1994 addition, those two side channels did not contain surface flow, resulting in a physically different stream that apparently had very different A_s/A. While interstitial flow within the substrate of the side channels was likely during the August 6, 1994 addition, the time required for the labeled water to pass through the side channel to the open channel was longer than the tracer addition. Therefore, water that passed through the interstitial zone of the side channels appeared as lateral inputs.

The additions to the Toolik Inlet stream illustrate the importance of flood plain storage. During the high flow tracer addition the stream had spilled out into its primary flood plain, which likely acted as its primary source of transient storage. During the lower flow addition, the stream remained within its banks and solute was measured flowing from seeps at the downstream end of a point bar. The observed difference in A_s/A seen between low and high flow might be attributed to storage on the flood plain during high flow. Alternatively, the modeled storage during the high flow event might have been entirely controlled by surface storage, as suggested by Harvey et al. [19].

The value of A_s/A at the mouth of the Kuparuk River downstream site was much higher than that for the fourth-order portion of the river. The difference in the amount of transient storage was a function of stream morphology. Large streams such as the mouth of the Kuparuk River tend to be braided around extensive, loose gravel bars. In these systems, summer flow in open channels may only occupy 30% of the width between the natural levees. The open channel is present as either deep pools or broad, shallow runs. The depth to permafrost under the large gravel bars is below the surface elevation of open channel water, resulting in large interactive parafluvial areas. In contrast, small tundra streams tend to have distinct banks immediately adjacent to the open channel. In these smaller systems, permafrost is present above the river stage within several meters of the stream restricting lateral exchange.

These results illustrate that there are a wide variety of storage zones that collectively contribute to the single value of A_s that is estimated by OTIS-P. The fact that channel concentrations achieved an apparent plateau earlier than several of the hyporheic zone locations suggests that other transient storage zone locations (e.g. eddies) are more important determinants of A_s in these streams. Natural heterogeneity of hyporheic exchange accounts for the variation among hyporheic sampling locations. This does not mean that hyporheic storage is unimportant. Rather, it indicates that over a specific time interval, a relatively small fraction of the total flow through a stream cross section flows via the hyporheic path, compared to eddy storage or open channel flow. However, the biogeochemical importance of the hyporheic flow path may be disproportionately large compared to its hydrological magnitude.

The Arctic tundra streams studied here do not appear to behave very differently from similarly sized streams in temperate regions. Legrand-Marcq and Laudelout [30] reported a minimal immobile fraction (analogous to A_s/A) of approximately 0.2 for a forest stream near Chimay, France. In the tundra streams studied here there appears to be an asymptotic low end of about 0.1, for the relative size of the storage zone. It is may be reasonable to expect that the lower limit of A_s/A for a given tundra stream depends upon stream morphological characteristics and degree of permafrost thaw. The average A_s/A for the streams in this study was 0.32, excluding Imnavait Creek. In the range of discharges seen in this study, the data from D'Angelo et al. [10] is comparable. The average A_s/A modeled by D'Angelo et al. [10] for streams with discharges of 30 $l\,s^{-1}$ or greater, was 0.25.

Although these Arctic streams during the middle of the ice-free season did not seem to differ from temperate systems, it is important to note that conditions in the spring and fall are very different. In small Arctic tundra streams during the spring ice-out, anchor ice persists, protecting benthic regions from scour and preventing hyporheic exchange. One might anticipate that a tracer addition conducted during the spring ice-out period would likely have A_s/A values considerably lower than those seen during the summer due to high snow-melt discharge and reduced interstitial area during ice-out. As the ice-free season progresses, discharge decreases, and the increasing depth to thaw increases the potential for interstitial transient storage. During the fall, streamflow decreases further as the tundra freezes and more precipitation falls as snow [21]. Thus, we suggest that the relative importance of transient storage—specifically the hyporheic zone—probably increases during the season and is highest in late September or early October, just before the streams freeze solid and flow ceases until the spring ice-out.

5.3. Hyporheic velocities

Hyporheic water velocities averaged 0.065 $cm\,s^{-1}$ in Oksrukuyik Creek, 0.071 $cm\,s^{-1}$ in the upper portion of the Kuparuk River (reference and fertilized zones), and 0.030 $cm\,s^{-1}$ at the mouth of the Kuparuk River. These velocities are comparable to those published for streams in temperate regions. White [52] found an average porewater velocity of 0.010 $cm\,s^{-1}$ under hummocks in the East Branch of the Maple River, Michigan, and a higher value of 0.040 $cm\,s^{-1}$ for flow through sediments under a beaver dam. Valett et al. [47] reported a velocity of 0.062 $cm\,s^{-1}$ in the hyporheic zone of Sycamore Creek, Arizona. The relatively high velocities in the Arctic streams studies here may reflect the annual freeze-thaw cycle of streambeds in the region. Although freezing typically protects the streambed from scour during ice-out [21], repeated freezing and thawing has the potential to rearrange the substrate.

5.4. Water quality characteristics

Nitrification in the interstitial area of streams is dependent upon availability of sufficient dissolved oxygen and either sufficient organic matter to be mineralized or high channel NH_4 concentrations. Interstitial zones will only remain aerobic if the rate of downwelling water carrying dissolved oxygen is sufficient to meet heterotrophic demand for oxygen. Particulate organic nitrogen may be entrained in the hyporheic zone slowly over time or rapidly by a shifting bed during spates. Differences in nitrification rates observed in the Arctic tundra streams studied here illustrate the influence of these controls, particularly that of substrate conditions.

Peterson et al. [39] found that dissolved organic carbon is the largest fraction of the dissolved carbon flux in the Kuparuk River. Subsequent sampling and analysis shows that dissolved organic nitrogen (DON) concentrations are much higher than either NH_4 or NO_3 concentrations (Bowden, unpublished data). Thus, DON entrained in the hyporheic zone may serve as a key source of nitrogen for mineralization.

The data collected here for Oksrukuyik Creek and the Kuparuk River suggest that while dissolved oxygen is reduced in transit through the hyporheic zone, it is typically not depleted resulting in conditions conducive to nitrification. Nitrification rates were particularly high in Oksrukuyik Creek because channel concentrations of ammonium were artificially elevated by a fertilization experiment that was in progress at that time see [18]. Additionally, the opportunity for burial of large pools of organic matter was higher in Oksrukuyik Creek due to the proliferation of filamentous algae that grew as a consequence of the fertilizer additions.

Within the four intensively studied reaches, there was a net gain in phosphate along interstitial flowpaths. Although PO_4 production was typically low, in Oksrukuyik Creek it was very high. This may have been due to one hyporheic sampler for which the dissolved oxygen was reduced to 1.2 $mg\,l^{-1}$. High productivity in interstitial waters of Oksrukuyik Creek likely results in anaerobic micro-zones which may mobilize PO_4.

Kling et al. [28] sampled lakes and rivers of the North Slope and found that every water body tested was a source of CO_2 to the atmosphere. Similarly, for all of the reaches studied here, the hyporheic zone was a source of CO_2 to streams. Production rates varied from 3.36 to 3.81 $mmol\,C\,m^{-2}\,h^{-1}$ at the upper portion of the Kuparuk River to 1.69 $mmol\,C\,m^{-2}\,h^{-1}$ at the mouth of the Kuparuk River.

A combination of measured hyporheic nutrient concentrations, half of the modeled storage areas, and exchange rate was used to estimate the net hyporheic flux. Estimated flux rates of NO_3, NH_4, and PO_4, from hyporheic exchange and lateral-inflows were similar. However, the flux of CO_2 from lateral inflow was 3–123 times greater than that from hyporheic exchange. The combined nutrient input from hyporheic regeneration and lateral inflows is sufficient to meet the demands of the benthic community and keep channel nutrient concentrations constant.

Within the fourth-order reach of the Kuparuk River hyporheic upwelling of NO_3-N and NH_4-N is potentially equivalent to 14–16% of the N uptake by the benthic community. Within the fifth-order portion of the Kuparuk River the net flux of NO_3-N and NH_4-N to the stream channel is equivalent to 162% of the benthic community's nitrogen needs. Within the P- and N-fertilized Oksrukuyik Creek, hyporheic upwelling of NH_4-N is potentially equivalent to 42% of the benthic communities needs. It is not possible to determine from these data alone, whether the regenerated N from hyporheic zones is taken up directly by epilithic algae, in preference to N that is in the open channel flow. Long-term ^{15}N addition experiments in the Kuparuk River showed that the uptake length for $^{15}NH_4$ added to the open channel flow was about 0.454 km in the reference reach [37,56] and 5.360 km at the fifth-order mouth of the Kuparuk River. Therefore, N in the open channel is clearly taken up, although a portion of this N may have passed through hyporheic zones first before being utilized by epilithic algae.

5.5. Temperature dynamics

Temperature patterns of the hyporheic zone remain a simple and effective method of determining the location of upwelling and downwelling sites within a system. In the Arctic, interstitial water has the potential for intimate contact with permafrost or cooled sediments. Consequently, upwelling water will be colder than channel water during the first half of the ice-free season. Parafluvial temperature patterns were indicative of flowpath direction. Additionally, for both the hyporheic and parafluvial zones, temperature was indicative of water residence time in the interstitial environment. It is important to recognize particular behaviors of the system that is being observed. Unlike Sycamore Creek [47], air temperature and solar radiation were insufficient to warm up the exposed gravel bars and elevate the parafluvial water temperatures at the mouth of the Kuparuk River.

6. Conclusion

Hyporheic exchange in Arctic tundra streams does not appear to be limited by the presence of continuous permafrost during the ice-free season, although it may be limited during the spring thaw. The primary location of modeled storage was a function of stream morphology and stage height. Storage within the peat-bottomed stream was within the bead itself while in the gravel- and cobble-bottomed streams the interstitial zone was an important storage location. The decrease in A_s/A with increasing discharge often seen in temperate systems was only marginally apparent in the Arctic tundra streams studied. However, the average relative size of storage zones in Arctic tundra streams was similar to the size observed in temperate streams.

The patterns of upwelling and downwelling sites in pool–riffle–pool sequences, as well as the associated thermal and chemical patterns, were similar to those seen in temperate streams. The velocity of interstitial flow was similar to rates measured in temperate streams. Interstitial waters served as sources of NO_3, NH_4, PO_4, and CO_2 to all streams. Higher nitrification rates in Oksrukuyik Creek than in the other three reaches studied were due to channel water enriched with NH_4, potential for organic-matter burial, and high dissolved oxygen concentrations. Dissolved oxygen was lower in upwelling sites than in downwelling sites and interstitial concentrations were always lower than in the channel. Interstitial temperature was inversely related to both the VHG and residence time in the hyporheic and parafluvial zones.

A combination of hyporheic sampling and OTIS-P modeling was useful in estimating the contribution of the hyporheic zone to benthic uptake requirements. While the relative flux of nutrients from the hyporheic zone was small compared to through-flow it has the potential to be very important to the benthic community. Even with the potential restrictions in size and reduced temperature by permafrost, interstitial exchanges are important to stream channel nutrient dynamics in the Arctic streams studied.

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