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Beaded streams of Arctic permafrost landscapes

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Abstract

Beaded streams are widespread in permafrost regions and are considered a common thermokarst landform. However, little is known about their distribution, how and under what conditions they form, and how their intriguing morphology translates to ecosystem functions and habitat. Here we report on a Circum-Arctic inventory of beaded streams and a watershed-scale analysis in northern Alaska using remote sensing and field studies. We mapped over 400 channel networks with beaded morphology throughout the continuous permafrost zone of northern Alaska, Canada, and Russia and found the highest abundance associated with medium- to high-ice content permafrost in moderately sloping terrain. In the Fish Creek watershed, beaded streams accounted for half of the drainage density, occurring primarily as low-order channels initiating from lakes and drained lake basins. Beaded streams predictably transition to alluvial channels with increasing drainage area and decreasing channel slope, although this transition is modified by local controls on water and sediment delivery. Comparison of one beaded channel using repeat photography between 1948 and 2013 indicate relatively stable form and ^{14}C dating of basal sediments suggest channel formation may be as early as the Pleistocene–Holocene transition. Contemporary processes, such as deep snow accumulation in stream gulches effectively insulates river ice and allows for perennial liquid water below most beaded stream pools. Because of this, mean annual temperatures in pool beds are greater than 2 °C, leading to the development of perennial thaw bulbs or taliks underlying these thermokarst features. In the summer, some pools stratify thermally, which reduces permafrost thaw and maintains coldwater habitats. Snowmelt generated peak-flows decrease rapidly by two or more orders of magnitude to summer low flows with slow reach-scale velocity distributions ranging from 0.1 to 0.01 m s^{-1}, yet channel runs still move water rapidly between pools. This repeating spatial pattern associated with beaded stream morphology and hydrological dynamics may provide abundant and optimal foraging habitat for fish. Thus, beaded streams may

BGD

11, 11391–11441, 2014

Beaded streams of Arctic permafrost landscapes

C. D. Arp et al.

create important ecosystem functions and habitat in many permafrost landscapes and their distribution and dynamics are only beginning to be recognized in Arctic research.

1 Introduction

Channels with regularly spaced deep and elliptical pools connected by narrow runs are a common form of many streams that drain Arctic permafrost foothills and lowlands. These channels are often referred to as "beaded" streams because during summer low flows, pools appear as *beads-on-a-string* of runs (Oswood et al., 1989). Beaded streams are generally treated in scientific textbooks on permafrost (e.g., Davis, 2001), hydrology (e.g., Woo, 2012), and aquatic ecology (e.g., McKnight et al., 2008), yet to our knowledge field investigations of these systems has been limited to only one site.

Beaded streams are thought to be a common Arctic thermokarst landform and occur mainly in association with ice-wedge networks of polygonized tundra (Pewe, 1966). The formation of channel drainage in these streams occurs along ice-wedge troughs with mature drainage channels resulting in complete degradation of ice wedges by thermal erosion (Lachenbruch, 1966). Classification of Arctic streams place beaded channels within the *tundra* class as compared to *springs* and *mountain* classes (Craig and McCart, 1975). In foothills watersheds, beaded streams are typically fed by linear hillslope water tracks (McNamara et al., 1999), while on the coastal plain these channels initiate mainly from thermokarst lakes and drained thermokarst lake basins (DTLBs) (Arp et al., 2012b; Whitman et al., 2011).

Our understanding of the physical and chemical character of beaded streams mainly comes from Imnavait Creek in the Arctic Foothills of Alaska (Oswood et al., 1989). Subsequent studies of this and adjacent systems suggest how beaded morphology functions in permafrost thaw (Brosten et al., 2006), hydrologic storage and hyporheic flow (Merck et al., 2012; Zarnetske et al., 2007), and thermal regimes (Merck and Neilson, 2012). Thermal stratification in pools up to 2 m deep often occurs in beaded channels during summer low flows (Oswood et al., 1989) and this may play a role in permafrost

BGD
11, 11391–11441, 2014

Beaded streams of Arctic permafrost landscapes

C. D. Arp et al.

thaw, hydrologic transport, and nutrient processing as the Arctic climate changes (Zarnetske et al., 2008; Merck and Neilson, 2012). In the winter, foothill streams freeze solid (Best et al., 2005) such that bed sediments thaw slowly and to a limited depth compared to adjacent alluvial channels (Brosten et al., 2006; Zarnetske et al., 2007). Winter analysis of multiple aquatic habitats on the Arctic Coastal Plain, however, shows that beaded streams can maintain liquid water under ice and potentially develop perennially thawed sediments (Jones et al., 2013). These physical regimes of water and energy flow in Arctic streams, coupled with channel morphology and drainage network organization likely dictate how these ecosystems also function as aquatic habitat and seasonal migration pathways for fish between river systems and headwater lakes (Craig and McCart, 1975).

Knowing where beaded streams occur in permafrost landscapes and how these fluvial forms are organized within drainage networks will help advance our understanding of their broader role in watershed, ecosystem, and biological functions across the Arctic. Such analyses will also help in predicting changes in these thermokarst fluvial systems with respect to climate and land-use changes and corresponding permafrost responses and hydrologic feedbacks. In this study, we (1) describe the distribution of beaded streams from Circum-Arctic to regional scales, (2) explore whether the distribution and variation in beaded morphology helps explain physical functioning, the evolution of beaded streams, and their responsiveness to external drivers, and (3) highlight the important role of these ecosystems serve in aquatic habitat. This work expands our understanding of beaded streams beyond the foothill regions of the Arctic where all previous work has been completed, both in terms of fundamental aspects of permafrost and fluvial processes as well as aspects relevant to fish and other aquatic biota.

BGD
11, 11391–11441, 2014

2 Methods

2.1 Study areas, distribution surveys, and classification

The distribution and abundance of beaded streams were determined by using a nested survey design and a range of survey methods. These nested domains ranged from a (1) Circum-Arctic assessment confined to the zone of continuous permafrost using imagery available for browsing in Google Earth (GE), (2) aerial transects across landscape gradients on the North Slope of Alaska, and (3) a census of the Fish Creek watershed (4700 km^2) using high resolution photography (Fig. 1). We also conducted field studies throughout this watershed and used data from an ongoing monitoring network at several streams in the lower portion the watershed.

The Circum-Arctic survey utilized imagery available in GE to identify channels with beaded morphology. This analysis focused on the continuous permafrost zone north of 66° latitude. We utilized the historical image browser function in GE to access the highest resolution imagery possible for a given region, which typically dates to between the early 2000's and 2013. This analysis focused on portions of Alaska (USA), Siberia (Russia), and northern Canada totaling approximately 4.5 million km^2. The resolution of imagery necessary to accurately identify streams with beaded morphology is about 10 m or finer depending on pool size and density and channel extent. Availability of snow-free imagery was also essential. Generally, imagery available for northern Alaska had consistently sufficient resolution to identify most streams with more expansive channel networks and larger pools, while imagery available for some parts of Russia and Canada was often too coarse to identify such stream channels. All point locations for this survey were placed near the downstream end of channel networks with consistent beaded morphology such that channels within single drainage areas were only counted once. Surface elevation, latitude, and classes of permafrost ground ice were attributed to each point using thematic datasets for panarctic (Brown et al., 1998) and Alaska-focused permafrost and ground ice distribution (Jorgenson et al., 2008) and surface elevation (Fig. 2).

BGD
11, 11391–11441, 2014

Regionally focused aerial surveys in a Cessna 185 were flown on 10 July 2011 on a clear day along three transects. One 270 km transect was from the Brooks Range divide north to the Colville River Delta, which moves from glaciated terrain in the upper foothills to vast areas north of the Pleistocene Glacial Maximum that were unglaciated (Fig. 1a). Another transect was 130 km from Prudhoe Bay to the lower Fish Creek Watershed on the Arctic Coastal Plain (ACP), and a third transect spanned 36 km of land area from Fish Creek to the lands north of Teshekpuk Lake representing an inner to outer ACP gradient. During the transect flights at approximately 150 m elevation, one observer had a sufficient view of approximately 500 m land surface to one side of the plane, thus covering approximately 220 km^2 of land surface in these surveys. During the flight each stream observed was marked with a GPS, photographed, and later these photographs were inspected to determine which streams could be classified as having beaded morphology.

The watershed census of beaded streams was conducted in the Fish Creek Watershed as part of a broader effort to map, classify, and understand watershed hydrography and its role in watershed runoff processes (Arp et al., 2012b). The Fish Creek Watershed is located in the northeastern portion of the National Petroleum Reserve – Alaska (NPRA) on the ACP (Figs. 1 and 3). Surface deposits grade from marine-alluvial silt with some pebbly substrates in the east to inactive eolian sand dune fields in the west (Carter, 1981; Carter and Galloway, 2005). The sand-bedded alluvial rivers, Fish Creek and its tributary Judy Creek, drain this area and form a delta in the Beaufort Sea just west of the Colville River Delta. Both rivers begin as beaded streams, Judy in a narrow arm extending into the foothills and Fish in the sand sea. The Ublutuoch River also starts as a beaded stream, but maintains this morphology for a longer distance before becoming a gravel-bedded alluvial channel near its confluence with Fish Creek. All perennial channels in the Fish Creek Watershed were delineated from 2002 mid-July CIR photography (2.5 m resolution) in a GIS environment. Streams with beaded morphology were quantified according pool density and size (measured as width perpendicular to the direction of flow) and valley gradient from a 5 m IfSAR DEM at a segment scale, typically 1–3 km length representative of individual drainage networks. These segments were also placed into four classes according to predominant pool (channel bead) shape and connectivity to runs as: (1) elliptical (round) pools separated by distinct connecting runs (Fig. 4b), (2) coalesced pools (elliptical pools merged together) without distinct connecting runs (Fig. 4c), (3) large irregularly shaped pools often connected by long runs (Fig. 4d), and (4) connected thaw pits in degrading polygonized tundra connected by perennial or ephemeral streams (Fig. 4e). In this last class, connected-thaw pits, these features often still show the geometry associated with ice-wedge junctions. We used this classification to help evaluate if pool form of beaded morphology was correlated with landscape position within the watershed and permafrost ice-content or other thermokarst landforms (e.g., thermokarst lakes and DTLBs). Additionally, we compared how well the size and form of these different beaded stream classes could be resolved using high resolution CIR photography compared to coarser resolution images in GE. We visited approximately 20 % of these stream channels in the Fish Creek Watershed during late July 2011 to verify beaded morphology and classification and to collect additional field measurements.

2.2 Geospatial and field measurements

A subset of stream channels mapped and classified in the Fish Creek Watershed (Arp et al., 2012b) were used for detailed geomorphic and hydrologic analysis in this study. Specifically, we targeted a set of each channel class representing beaded streams and alluvial channels (Fig. 4f), as well as points of channel initiation. During field visits, we measured stream discharge using the velocity-area method. Along stream reaches equaling 20 or more channel widths (typically 100–300 m), we surveyed the water surface elevation at 5–7 points with an engineer's level, stadia rod, and tape to measure the channel slope. At the same time, channel cross-sections that bisected pools were surveyed at 2–3 locations to measure gulch and pool geometry.

In order to better understand controls on beaded stream morphology, we conducted similar surveys in the field and from geospatial data (CIR photography and DEMs)

BGD
11, 11391–11441, 2014

along a longitudinal gradient of Fish Creek and the Ublutuoch River from their headwaters downstream. For each fluvial system, at least three reaches were studied in the field where the channel had distinctly beaded form and three reaches were studied downstream where the channel had transitioned to an alluvial form. Additional locations were later selected to better refine this transition including identification of sediment sinks (flow-through lakes) or clear-water inputs (lake-fed tributaries) relative to potential sediment sources including contact points with hillslopes and sand dunes, and tributaries originating from drained lake basins or upland tundra. The total length of channels analyzed for Fish Creek was about 135 km and the total length of channels analyzed for the Ublutuoch River was about 70 km.

2.3 Analysis of channel change and history

To better understand the evolution of beaded channels we compared the position and morphology of one channel over a 64 year period using high resolution photography from 1948 (Black and White, Naval Arctic Research Laboratory (BW NARL)) and 2013 (color-infrared at 25 cm pixel size, Aerometric Inc) located in the Fish Creek Watershed. The 1948 BW NARL photographs were acquired from the University of Alaska Fairbanks GeoData Center and scanned at 1200 dpi. The scanned images were georeferenced with 20 ground control points (primarily ice-wedge intersections) to a light detection and ranging (LiDAR) dataset (detailed below) using a spline transformation and converted to a pixel-size of 0.5 m. The 2013 color photography was acquired, by Aerometric, Inc. on 4 September to compliment airborne LiDAR data. Manual analysis of both datasets was conducted in black and white to avoid any bias that may have arisen between the two datasets that were collected using different film types and separated by so many years of time. Particular attention was given to any changes in channel form (location and plan-view dimensions) relative to ambient polygonized tundra within a 100 m buffer of the channel and the presence and dynamics of thaw pits. This was done to examine the hypothesis that beaded streams evolve in a manner similar to observed degradation of ice-wedge intersections, but lacking channel

BGD
11, 11391–11441, 2014

connectivity. All stream channels in the 1948 image were delineated by hand and ice-wedge intersection with pits marked with a central point and then compared to 2013 photography to detect changes. We tracked individual pools (beads) and thaw-pits from 1948 to 2013 and also recorded those features that were observed in one time period but not the other. The channel gulch/riparian corridor was also delineated for both periods based primarily on the darker (greener) signature of taller sedges, willows, and dwarf birch and moister understory bryophyte communities.

In order to determine the timing of pool initiation, long-term sedimentation rates, the depositional environment of pools, we collected sediment cores to analyze sediment stratigraphy and estimate age-depth relationships using ^{14}C dating. In April 2012, two overlapping cores were collected from a large pool in Crea Creek to a depth of 75 cm (base of unfrozen talik) using a Russian Peat Corer. Cores were photographed, subsampled at 5 cm increments, and subsamples placed in whirl-pak bags. We sampled an individual twig from a basal organic sediment layer with fibrous, terrestrial organic remains that is directly above the organic-poor sand layer that extends down into the base of the talik. Several moss and sedge samples were also collected from above the basal layer the organic rich, sandy sediments that are similar to organic-rich *gyttja* deposited in lakes of the region. Another core was collected from a pool in 2013 at nearby Blackfish Creek and macrofossils collected from above several distinct sand horizons within the core. The plant macrofossils were prepped with an acid-base treatment and analyzed for ^{14}C content using standard acceleratory mass spectrometry techniques at the NOSAMS facility at Woods-Hole Oceanographic Institute. All radiocarbon dates were calibrated to calendar ages using the Intcal 13 curve (Reimer et al., 2013) and are reported as the mean and two-sigma ranges of the calibrated ages.

2.4 Hydrologic monitoring and habitat analysis

As part of an on-going monitoring program (Fish Creek Watershed Observatory; Whitman et al., 2011), streamflow, water temperature, and other water quality parameters have been recorded at hourly intervals at five stream-lake systems since 2008. These small catchments are being monitored by the Bureau of Land Management (BLM) Arctic Field Office to collect baseline data prior to expected changes in land use, primarily new oil development, and associated water extraction for ice roads and facility operations in the NE NPR-A. Stream gauging was conducted using autonomous pressure transducers (Onset U20-001-01) anchored to the bed of pools that when corrected to local atmospheric pressure to measure water height. Stream discharge was measured using the velocity-area method with either a ACDP (Flowtracker™) or electromagnetic (Hach™) velocity meter mounted to a top-setting wading rod. Approximately 20 velocity measurements were made per cross-section at increments spaced to not exceed 10 % of total discharge. Typically we made 3–4 measurements near the snowmelt peakflow in early to mid-June and 2–3 measurements during peakflow recession in late June or early July and 2–3 measurements again in late July and late August. Rating curves were fit with a log or power law equation to estimate continuous discharge during the ice-free season; separate high-flow and low-flow rating curves were often required. Based on temperature sensors placed in channel runs and comparison with time-lapse cameras set during several years, we assumed that streamflow ceased during October in most years.

In addition to pressure transducers anchored to pool beds that record temperature, thermistors (Onset U12-015) recorded hourly temperature near the surface of pools (30 cm below the surface) and in channel runs of each beaded stream. These paired temperature measurements were used to assess thermal regimes and timing and extent of stratification in pools as a ratio of surface temperature to bed temperature. Using this system, one pool and corresponding channel run have been monitored among these five streams year-round from 2009–2013. To assess variability in thermal regimes and particularly stratification within stream systems, we selected an additional three pools of varying depth and area in both Crea and Blackfish creeks in 2012 and instrumented these with additional bed and surface thermistors. These were retrieved and downloaded in late August 2013.

BGD
11, 11391–11441, 2014

During the late winters of 2010–2013, we visited several of these sites concurrent with lake-ice, snow, and water chemistry surveys. When opportunities existed, we measured snow depth either with a 3 m avalanche probe or by digging a pit, or both, above frozen pools located with a GPS. Holes were augered through the ice and ice thickness and below-ice water depth was measured using an ice-thickness gauge (Kovacs™). We also measured the depth of thawed sediment (talik) using multiple 1.2 m threaded stainless steel rods fitted with a blunt tip and driven with a slide-hammer to the depth of refusal (typically 10–20 pounds with no downward movement). When possible these late winter surveys were done repeatedly at the same pools and water chemistry measurements were made including dissolved oxygen.

We tested how contrasting beaded stream morphometry and watershed features affected hydrologic residence times and velocity distributions using tracer tests on two stream reaches with contrasting morphology and flow regimes. At Crea and Blackfish creeks, we identified a 325 m and 232 m reaches, respectively, starting and ending at channel runs and encompassing the pools with stratification monitoring sensors. Rhodamine WT (RWT), a pink fluorescent dye, was used as conservative water tracer because it has low biological reactivity and adsorbtion to organic matter, yet begins photodegrading after several days of sunlight exposure at low concentrations (Vasudevan et al., 2001). Based on targeted downstream peak concentrations of 30 ppb, we made pulse additions of RWT at reach heads and monitored concentration at the reach bottom using a YSI 6600 v2 data sonde with a RWT probe. This experiment typically lasted a day or longer to account for all tracer moving through the system. RWT tracer data was then analyzed using a One-dimensional Transport model with In-channel Storage and Parameterization (OTIS-P) using an inverse modeling approach to estimate advective channel area (A), storage zone area (A_S), dispersion (D), and the storage exchange coefficient (α) (Runkel, 2000). Tracer breakthrough curve data was plotted as normalized concentration per time following the injection were converted to velocity distributions by dividing the reach length by travel time. RWT injections were

BGD
11, 11391–11441, 2014

conducted at both Crea and Blackfish creeks in mid-June near peakflows, in early July (late peakflow recession), and late August (low summer baseflow).

3 Results and discussion

3.1 Beaded stream distribution

Using available high-resolution imagery in GE across the Circum-Arctic, we found 445 individual channel networks located in northern Alaska, Russia, and Canada with beaded morphology (Fig. 1b). This survey was restricted to land areas north of 66° latitude, which was mainly in the zone of continuous permafrost, though two streams were within areas classified as discontinuous and three within areas classified as sporadic permafrost.

In Siberia, 148 beaded streams were clustered mainly in six different locations (Figs. 1b and 2). From east to west these include a lakeless plain of the Chukchi Region, lake-rich valley bottoms along the Alazeya River west of the Kolyma Delta, mountainous headwaters of the Yakutiya Region, higher elevations of the Yana Delta and adjacent Buor Khaya Peninsula, and very high densities in the foothills of the Anabar River Watershed near the treeline. Comparatively fewer beaded streams were identified across the Canadian Arctic (22 total) (Fig. 1b). This is likely related to regional geology associated with the dominance of exposed bedrock and thin sediment cover and lack of ice wedges on the Canadian Shield. From west to east, small clusters of beaded streams were found on the coastal plain east of Herschel Island and south of the Mackenzie River Delta, the lake-rich Tuktoyaktuk Peninsula, the coastal plain around the Coronation Gulf and village of Kugluktuk, and the Banks Peninsula within Bathurst Inlet. Lower densities of beaded streams across Canada, and to a lesser extent Siberia, may partly be attributed to variation in GE image resolution. However, there were many low-order stream networks that we could clearly observe in these regions that simply lacked apparent beaded morphology.

BGD
11, 11391–11441, 2014

Over 60 % of the beaded streams we located were in Alaska even though this was a much smaller area surveyed compared to Siberia and northern Canada. The southernmost beaded streams in Alaska were found on the coastal plain of the Seward Peninsula and between Kivalina and Point Hope with an additional cluster higher in the Noatak River valley (Figs. 1b and 2). On Alaska's North Slope, beaded streams were dense and evenly distributed in the western foothills and Chukchi Coastal Plain. Lower densities of beaded streams were found in the central sand sea region and only a few beaded channels were found on the outer coastal plain of the Barrow Peninsula and north of Teshekpuk Lake. This lack of channels with beaded morphology on the outer coastal plain is somewhat perplexing. Most channels in this region tend to take a plane bed form without alluvial features, which may relate to very high pore ice content that in addition to wedge-ice makes soils in this regions extremely ice-rich, often exceeding 90 % by volume (Brown, 1968). The outer coastal plain is also extremely flat with very low drainage densities and very high coverage of thermokarst lakes and DTLBs (Grosse et al., 2012), such that all fluvial systems are in low abundance and the ones present are strongly lake-affected. On the inner coastal plain and foothills, channels likely develop along moderately sloping terrain with varying densities of ice wedges, but otherwise low pore-ice content. Thus bead morphology likely develops as ice-wedge networks thermally erode, yet expansion of pools and runs is confined to the original ice-wedge casts because ice-poor permafrost is more resistant to thermokarst erosion. High densities of beaded streams were also found throughout the Kuparuk River Watershed from the foothills to the coastal plain and on the narrower coastal plain east of the Sagavanirtok River to Barter Island (Fig. 1b).

Looking at the full set of beaded streams in relation to permafrost ice-content, shows that half were found on high ice-content permafrost and 32 % on moderately ice-content and 18 % on low ice-content permafrost (Fig. 2). Regions of high ice-content typically were associated with either epigenetic permafrost along the coastal and syngenetic yedoma permafrost in foothills regions. Approximately half of all beaded streams were found below 60 m a.s.l. elevation and 90 % were below 210 m a.s.l. elevation (Fig. 2).

BGD
11, 11391–11441, 2014

Seven beaded streams were discovered above 500 m a.s.l.. These were found in both Alaska and Russia. Our survey did not identify the even higher elevation Imnavait Creek, 861 m elevation (Fig. 2), because the only high resolution GE imagery for this area was acquired during winter snowcover. Such snow-covered scenes were relatively rare in most imagery we used. Imnavait Creek, along with 12 beaded streams that were identified in our inventory, occur above the Pleistocene Glacial Maximum (Fig. 1a) indicating that streams with beaded morphology can readily form in glaciated terrain.

In our aerial surveys across the Alaskan North Slope, we located 43 beaded streams from three transects covering 436 km of flight lines or approximately 220 km^2, suggesting a density of 0.20 streams per km^2 or a drainage density of roughly 0.10 $km\,km^{-2}$. Comparing transect lines to landscape classification of permafrost shows that these surveys covered 29 % low-, 59 % moderate-, and 12 % high-ice content (Fig. 1a). However, of recognized beaded streams along these courses, a much higher proportion was associated with moderate ice-rich permafrost (76 %). Only three streams occurred on high ice-content permafrost, two on very flat outer coastal plain areas with glaciomarine sediments and one in yedoma deposits of the foothills (Fig. 1a). The majority of stream channels on the outer coastal plain, with very low drainage densities, would be generally classified as plane bed (Montgomery and Buffington, 1997) or F5-6 from Rosgen's Classification (Rosgen, 1994), and also have been termed lacustrine channels (Arp et al., 2012b) because they are nearly all fed by lakes. Still, polygonized tundra tends to be more pronounced and uniform in this region, and so a general lack of channels with beaded morphology was unexpected.

Beaded streams in the Fish Creek Watershed range from 6 to 125 m elevation and the full range of permafrost ice-contents (Jorgenson et al., 2008). We inventoried 126 beaded streams as individual catchments or drainage networks within this 4700 km^2 watershed located on the inner Arctic Coastal Plain of northern Alaska (Fig. 1a). Based on previous analysis of lakes, streams, and river channels here (Arp et al., 2012b),

BGD
11, 11391–11441, 2014

beaded streams represent 1168 km of channel length or 47 % of the entire fluvial system. The equivalent drainage density of beaded stream channels is 0.25 km km^{-2}.

Since the majority of beaded streams on the ACP initiate as 1st-order channels below thermokarst lakes or DTLBs (Arp et al., 2012b), their distribution throughout the Fish Creek Watershed is linked to lake distribution (Fig. 1a). The exception to this pattern is in the headwaters of Judy Creek that form a narrow arm extending into eolian silt deposits with bedrock outcrops. In this area lake densities are low and many streams initiate as colluvial channels (Arp et al., 2012b), which then transition to beaded morphology downstream, similar to patterns reported for the higher elevation foothills of the Kuparuk watershed (McNamara et al., 1999). Thirteen percent of all beaded streams in the Fish Creek Watershed are located within this region of ice-rich eolian loess. Relatively lower densities of beaded streams occur in the eolian sand sea regions (western half of Fish Creek Watershed) where permafrost is classified as having low ice-content (Fig. 1a) and most lakes formed between relict dunes and are up to 20 m deep (Jorgenson and Shur, 2007). The highest densities of beaded streams occur in the lower Fish Creek Watershed where surface geology is dominated by alluvial and marine silts and sands with some pebbly deposits and permafrost is moderately ice-rich (Carter and Galloway, 2005). Our results suggest some variation in beaded stream distribution within the inner coastal plain. However, we still find that beaded streams are the dominant form of low-order channels throughout a wide range of slopes (Fig. 5) and substrate characteristics.

3.2 Morphology in relation to landscape and watershed positions

Since abundant large deep pools are the defining characteristic of streams with beaded morphology, we initially classified and quantified these channels according to pool (bead) morphology and density (Fig. 3). On a reach scale (100's of meters) or segment scale (up to several km between tributary junctions), pool density, form, and size was often distinct. However, on a more extensive drainage network scale, which is the scale we used for classification, pool density varied to a greater extent. Counts

BGD
11, 11391–11441, 2014

of pools from high resolution CIR photography showed densities ranging from 2 pools per 100 m of channel up to 11 per 100 m (Fig. 3). Lachenbruch (1966) suggested that polygon spacings range from 5 m to 50 m based on variation in ground strength and the width of stress relief zones, which approximately matches the range of beaded densities reported here. This indicates that local controls, such as size, pattern, and form (i.e., low- and high-centered polygons) of tundra or broader-scale thermokarst landforms such as DTLBs (Frohn et al., 2005; Hinkel et al., 2005), may be the main cause of such variability in channel morphology. However, exact relationships have not yet been identified from our study.

Of the 126 individual beaded channel networks in the Fish Creek Watershed, 40 % were classified as elliptical with distinct connecting runs, 17 % had mostly coalesced pools and short or non-existent runs, 34 % predominantly had irregularly shaped pools, and the remaining 8 % were classified as connected thaw pits (Figs. 3 and 4). We originally hypothesized that these channel forms were related to variation in drainage area and slope, following general concepts of channel organization for other watersheds (Montgomery and Buffington, 1997). However, with the exception of much smaller drainage areas and steeper slopes feeding channels formed by connected thaw-pits (Fig. 5), there was a wide range of variation in these potential watershed controls on channel morphology. The majority of beaded channels are shown to initiate from either lakes or DTLBs (Arp et al., 2012b) and these took a wide range of pool forms downstream. In the Fish Creek Watershed, most channels with small elliptical pools were located in the higher elevation areas associated with eolian sand and loess deposits compared to lower elevation marine sand and silt deposits. Whether this pattern relates to size and form of ice-wedge networks that develop in sandy soils or how eroding sandy soils moderate expansion by infilling pools or interactions with vegetation deserves further consideration. This pattern makes the relationship to slope observed for small elliptical channels difficult to distinguish from factors related to substrate. The other channel classes were more evenly distributed throughout the watershed and by surficial geology (Fig. 3).

BGD
11, 11391–11441, 2014

Beaded streams of Arctic permafrost landscapes

C. D. Arp et al.

Comparing stream size according to mid-summer discharge across a wider range of channel types from initiation points (channel heads) to larger alluvial channels shows well organized patterns in relation to drainage area and channel slope (Fig. 5). This slope-area relationship is consistent with patterns more universally observed across a wide range of drainage networks (Montgomery and Buffington, 1997; Montgomery and Dietrich, 1989; Whiting and Bradley, 1993). In the Fish Creek Watershed, channels initiating from hillslopes are steepest with slopes averaging 2 % and with drainage areas < 1 km^2. Channels initiating from lakes had average slopes of 0.4 % and drainage areas > 1 km^2 (Fig. 5). Channels with connected thaw pits had drainage areas ranging from 1.3 to 3.5 km^2 and mid-summer flows ranging from 1 to 7 $L\,s^{-1}$. Because beaded channels compose approximately half of the drainage network in the Fish Creek Watershed (Arp et al., 2012b), they correspondingly have a wide range of drainage areas and slopes. Among 18 streams visited in mid-July 2011 with measured summer flows of 18 to 240 $L\,s^{-1}$, average drainage area was 20.5 km^2 and channel slope was 0.3 % (Fig. 5). We additionally note that unit runoff (Q/DA) often varied widely in reaches synoptically surveyed, as well as the catchments that we continuously gauge. This variation appears to be driven primarily by differing portions of lake and DTLB extent per catchment has been observed when comparing river runoff among larger rivers on the coastal plain (Arp et al., 2012b). Alluvial channels form the higher order portions of most drainage networks and in the Fish Creek Watershed typically begin at drainage areas > 40 km^2 and channel slopes less 0.03 % (Fig. 5).

To better understand how beaded streams fit within fluvial systems of the ACP and evaluate what controls their morphology, we selected two drainage networks for more detailed analysis of longitudinal channel dynamics from headwaters downstream. Fish Creek has its headwaters near the western divide of the watershed at 78 m a.s.l.. It is located entirely within the eolian sandsheet and initiates from a deep depression lake. This channel network first flows through several more depression lakes and in between maintains a classic beaded morphology (Fig. 6a). Over the next several km, the channel cuts through both vegetated and unvegetated sand dunes, which likely supply

BGD
11, 11391–11441, 2014

coarse sediment, and also the channel contacts steeper hillslopes that could contribute sediment as well. This portion of the channel appears transitional because reaches of beaded morphology are interspersed with more sinuous channels having point bars and meander cut-banks. At km 20 downstream, the channel steepens considerably below a tributary fed by a DTLB and then cuts through two more sand dunes, before taking a more even slope for the remaining 110 km with sand-bedded alluvial characteristics. Thus, Fish Creek quickly transitions from beaded to alluvial morphology likely because of ample sediment supply associated with the eolian sand landscape (Fig. 6a).

The other system we analyzed, the Ublutuoch River, begins at a lower elevation than Fish Creek, 58 m a.s.l., in the southern portion of the watershed at the eastern margin of the eolian sandsheet. The channel initiates from a large set of coalesced depression lakes, totaling about 5 km^2, seen as the flat profile in Fig. 6b. The first 12 km of this stream are relatively steep with regular density of pools typical of beaded morphology. Several oxbow lakes occur lower in this segment, indicative of channel migration, but the Ublutuoch then flows through several more lakes, likely trapping all sediment and resetting the system to a beaded form with a flatter slope. At km 24 downstream, a tributary from a large DTLB enters from the north, and at this point the channel starts taking a more sinuous form with oxbow lakes and other floodplain features. We suggest that this segment of stream from 24 to 56 km is transitional between beaded and alluvial morphology – a much longer transition than was observed along upper Fish Creek. Surrounding uplands here are entirely within the zone of marine silt and sand without distinct sediment contributions form adjacent sand dunes. Near the end of the segment, the channel becomes much more sinuous with oxbows and meander scares becoming evident, yet regular pools (beads) persist. At km 56, the stream contacts a distinctly higher hillslope that we think supplies sediment to the channel and afterwhich takes on a distinct alluvial form lacking any beaded morphology (Fig. 6b). During the entire transitional channel course, the stream's slope is nearly constant at about 0.02–0.04 %. It then flattens greatly to < 0.01 % over the last 5 km and becomes quite deep and very

BGD
11, 11391–11441, 2014

sinuous with high, regular banks before its confluence with Fish Creek. This lower segment of the Ublutuoch River is similar in form to tidally-affected channels or guts (Heim, 2014).

3.3 Channel change and formation

To evaluate the hypothesis that beaded streams form in ice-wedge networks and that pools progressively expand over time, more detailed studies were conducted in one system, Crea Creek, to look at decadal scale changes and determine its time of formation. Using remote sensing change detection over 64 years, we found no changes in the channel position along this 2.7 km segment (Fig. 7). The total number of pools in this segment remained relatively stable, though tracking individual beads showed that 18 % disappeared from 1948 to 2013 and a similar number of new pools (19 %) were identified in 2013 that were not detected in the 1948 imagery (Table 1). The mean pool size in 1948 was 60 m^2 compared to 62 m^2 in 2013. Tracking the size of pools found in both images showed that about one-third shrank by an average of 10.8 m^2 and about one-third expanded by an average of 19.7 m^2. Thus our comparison of this one representative beaded stream suggests relative stability of the channel within the accuracy of detection and seasonal variability.

We also delineated the riparian gulch of this beaded stream indicated in plan view by higher moisture and the contrasting zone between upland tussock tundra and vegetation composed of willows, tall sedges, and dwarf birch to see if these had changed over this time period. Such changes could correspond to progressive subsidence of ice-rich permafrost by thermokarst degradation or shrub expansion as has been noted throughout many areas of the Arctic (Sturm et al., 2001). Consistent with what can be observed in the shorter reaches in Fig. 7, the overall change in riparian gulch width was slight, a 9 % increase (Table 1). Analysis in this same area has shown a recent increase in degrading ice-wedge polygons to form thaw pits (Jorgenson et al., 2006). Thus we also recorded and tracked thaw pits (ice-wedge junctions with ponded water) between the two images within a 100 m zone on either side of the channel, but out-

BGD
11, 11391–11441, 2014

side of the riparian gulch. This showed a somewhat similar pattern as was found when tracking pools in the channel of Crea Creek. In total, we found 120 individual thaw pits or 1 pit per 2500 m^2, typically in clusters associated with high centered polygons. In 1948 we found 74 thaw pits, 55 of which were not observed in 2013, and in 2013 we found 66 thaw pits, 47 of which were not observed in 1948 (Table 2). This suggests that thaw pits may progress through a form of succession in which they degrade, collect water, paludify and/or partly drain or dry, such that detection is obscured after several decades. This is a similar sequence as demonstrated for denser networks of thaw pits of polygonized tundra in nearby upland areas in the Fish Creek Watershed (Jorgenson et al., 2006).

Analyzing the stratigraphy and geochronology of sediments in a large pool of Crea Creek vaguely attests to the timing of stream channel formation and the depositional environment since initiation. A fibrous organic-rich layer with abundant terrestrial plant remains separated the transition from organic-poor medium sand to organic-rich sediment that is the uppermost unit – we interpreted this layer as basal sediments that were dated to 10.1, and 13.6 ka cal years BP (Fig. 8). The terrestrial macrofossils (shrub twigs) in this fibrous unit and the two dates that span 4 ka suggests this layer may have been a terrestrial soil that persisted for millennia on top of eolian or alluvial sand deposits, but predated the initiation of the beaded stream pool. Alternatively, this layer may represent the depositional environment of an early stage of the beaded stream pool where terrestrial vegetation was overhanging and being deposited, and adjacent soils were being eroded by ice wedge degradation and supplying a range of reworked material with different ^{14}C ages to be deposited onto this fibrous layer. Regardless, we interpret the 9.0 ka moss macrofossil sampled from the upper portion of the fibrous layer to be a conservative upper limit age on the initiation of the beaded stream pool. At this time, we do not know whether the lower limit of this age estimate is near the 9.0 ka time period, or represents the late Holocene. The large age-gap from 9.0 ka at 42 cm to ~ 0.7 ka at 22 cm suggests that either there was a water-level lowering event caused a hiatus of sedimentation through much of the Holocene, or that high flow events or other processes eroded the sediment deposits representing most of the Holocene (Fig. 8). However, there was no preserved wetland or terrestrial soil layer interrupting the *gyttja* unit, which would have accompanied a water-lowering event. The Crea beaded stream pool we examined appears to have had episodic sedimentation during the Holocene that is periodically eroded by either high flow events, or ice scouring.

The stratigraphy and ^{14}C dates from a core in a deep pool in Blackfish Creek also suggest unconformities in sedimentation of beaded stream pools. The Blackfish pool had sandy organic-rich *gyttja* with several 3–6 cm bands of coarse sand that graded upward to fine sand. These suggested upstream scouring events that mobilized and transported high and coarse sediment loads episodically, potentially from the catastrophic drainage of upstream lakes. A number of DTLBs occur upstream of this site and their drainage dates are currently unknown, but may have corresponded to these events. The basal age of this unit from a sedge fragment yielded a date of 590 (±30) yrs BP, considerably younger than we found at Crea Creek (Fig. 8). A paired sedge and willow macro-fossils extracted from above a coarse sand horizon at 20–30 cm indicated ages of 1430 (±25) years BP and 125 (±25) years BP. Our interpretation of this core and analyzed ages is that the basal material was either not reached or had been remobilized and that a number of very high flow events in this stream's recent history had deposited material from upstream of varying ages. These flow events may have partially eroded some of the late-Holocene record and/or deposited reworked macrofossils, which gave dubious ^{14}C ages. The depositional environments of beaded streams seem discontinuous and difficult to interpret because of unconformities and reworked plant macrofossils. However, in the right situation may record upstream watershed events such as lake drainage. At this time, the typical lifespan of the beaded streams we studied remains an enigmatic, but still potentially place this channel's formation near the Pleistocene–Holocene transition.

BGD
11, 11391–11441, 2014

3.4 Physical processes affecting morphology and habitat

3.4.1 Winter Processes

Because winter is the dominant season in the Arctic and most beaded streams are ice-covered and likely stop flowing from October to late May or early June, understanding their state during this period is of great interest. An important characteristic of beaded stream channels on the ACP is that their often deep gulches, 0.5–2.0 m, rapidly fill with blowing snow early in the winter, effectively leveling the snow-surface topography with the surrounding tundra. This deep snow insulates ice on pool surfaces, reducing its rate of thickening, and impacting soil active-layer dynamics as well. Measured snow depths above beaded streams averaged 122 cm and ranged from 70 cm on a small pool in Crea Creek to 192 cm above a pool in Bill's Creek (both in the lower Fish Creek Watershed) (Fig. 9). In contrast, surrounding tundra snowpack rarely exceeds 40 cm depth by late winter. Not only does this thick snowpack insulate ice and soil, but it also persists much longer in the spring and contributes a much larger portion of snow-water per unit area directly to runoff (Arp et al., 2010). In 12 beads we surveyed from 2010 to 2013, only one was found to be entirely frozen solid by March or April (Fig. 9). A more detailed and extensive survey of water below ice were conducted in March and April of 2013 using ground-penetrating radar (GPR) and high resolution synthetic aperture radar (TerraSAR-X) in this area and found the majority of pools had liquid water below ice (Jones et al., 2013). Average ice thickness of pools surveyed was 106 cm and ranged from 89 cm to 129 cm (Fig. 9). For comparison, lake ice thickness in this same region and years ranged from 118 cm in 2010 to 171 cm in 2013 (Arp et al., 2012a; Jones et al., 2013). The average depth of water found below the ice was 44 cm and ranged from 4 cm up to 106 cm. This water was typically under pressure from ice expansion and the weight of snow, such that upon drilling through the ice, water typically floods the frozen pool surface. On at least two occasions live fish (Alaska blackfish, *Dallia pectoralis*) were pushed out of the drill hole to the surface by flowing water during these surveys. Monitored dissolved oxygen levels in one bead showed a rapid drop

BGD
11, 11391–11441, 2014

to hypoxic conditions by mid-January and measurements in March typically showed levels below 5 % of saturation or $< 1\,\mathrm{mg\,L^{-1}}$. However, Alaska blackfish are known to tolerate such conditions (Scott and Crossman, 1973; Crawford, 1974), providing evidence that some beaded stream pools can function as overwintering habitat for select Arctic fish species. While we suspect that these stream pools are not preferred overwintering locations for these fishes, these relatively warm unfrozen sediments may be important for invertebrate and microbial communities.

Despite the relatively small diameter of pools, thawed sediment underlie most of them and measured depths averaged 120 cm and were up to 170 cm in one pool with sand-gravel sediment (Fig. 9). This suggests that beaded stream channels further disrupt the ground thermal regimes of otherwise continuous permafrost landscapes similar to large river channels and lakes with floating ice where talik depths are thought to reach 10's of m deep or more (Brewer, 1958; Lachenbruch et al., 1962). The actually geometry of sub-pool taliks is an interesting shape to consider given their relatively small size. Since 2009 we have been monitoring bed temperatures in a set of pools within beaded stream systems in the lower Fish Creek Watershed. Typically winter temperatures rapidly approach the zero-degree curtain and average winter temperatures (November to April) consistently average 0 °C (±0.1). Similarly, mean annual bed temperatures (MABTs) fall within a narrow range averaging 2.9 °C and varying inter-annually almost entirely according to summer temperatures (Fig. 10a). Such MABTs above freezing suggest the presence of a talik (Burn, 2002; Ensom et al., 2012), as we confirmed with field measurements. The presence of year-round unfrozen sediment and some liquid water in pools may be an essential factor supporting microbial and invertebrate based food webs, which then feed summer productivity and the use of beaded streams as important foraging habitat. Additionally, perennially thawed sediment also likely enhances the survival and productivity of macrophytes that provide additional habitat and forage.

BGD
11, 11391–11441, 2014

3.4.2 Summer processes

Much of the variation in MABT of pools is also determined by whether pools become thermally stratified during the summer. Monitoring of surface temperatures relative to the pool beds and temperature in the channel runs suggests a wide range of mixing behaviors and stratification regimes among pools both between different stream systems and from pool to pool in a single stream. For example in three beaded streams monitored form 2009–2012, one 1.3 m pool never became stratified, another 1.4 m pool was stratified by 10 % or more (i.e., surface temperature/bed temperature > 1.1) for 13 days per summer on average, and a 2.1 m pool had a stratification ratio of 1.2 and was stratified for over a month on average (Fig. 10b). This generally suggests that deeper pools stratify to a greater degree and for longer periods. To assess interpool variability, we instrumented an additional three pools in Crea and Blackfish creeks from June 2013 through August 2013 with surface and bed thermistors. In Crea Creek with pools depths of 1.6, 1.7, and 2.0 m, corresponding average stratification ratios (and durations with ratios > 1.1) were 1.05 (5 days duration), 1.09 (23 days), and 1.03 (4 days), respectively (Fig. 10b). In Blackfish Creek with deeper and coalesced pools, instrumented pools were 1.5, 2.2, and 2.6 m depth and corresponding stratification ratios and durations were 1.04 (5 days), 1.16 (24 days), and 1.10 (19 days). Thus, there is as expected some relationship between pool depth and stratification, but this is generally weak and suggests other factors control how water mixes among different pools. A single densely instrumented pool in Imnavait Creek was shown to stratify in a complex and dynamic manner (Merck and Neilson, 2012), similar to more extensive work completed there originally (Oswood et al., 1989). The velocity of upstream runs and morphology of pools at run inflows is certainly one factor. A steeper run upstream of Bill's Creek (Fig. 10a) was likely the cause of continuous mixing during all flows, ambient air temperatures, and wind regimes. The extent and structure of emergent aquatic macrophytes in pools likely also plays a role, where some shallow beads have very dense macrophytes beds (*Potamogeton* spp., *Arctophila fulva*, and *Hippuris vulgaris* are the most common plants) that likely create a rough and thick boundary layer enhancing stratification. Adjacent pools of seemingly similar depth and surface area are often devoid of vegetation, creating interesting habitat heterogeneity within beaded stream systems. Variation in water color due to dissolved organic carbon may play some role, however rarely do beaded streams in this part of the ACP have highly stained water from organic acids as has been observed in other beaded stream systems (Merck and Neilson, 2012; Oswood et al., 1989).

Ecologically, the important point in terms of fish habitat is that within a single beaded stream, varying degrees of mixing and thermal stratification from pool to pool likely create a range of temperature zones that can be utilized to either avoid thermal stress or optimize energetics for foraging and other activities. For example, some salmonids behaviorally thermoregulate by moving to warmer areas after foraging bouts in cooler water in order to accelerate metabolism and assimilate more quickly (Armstrong et al., 2013). Stratification within a single bead and heterogeneity in thermal characteristic of nearby beads within a network may provide similar opportunities to behaviorally optimize growth and foraging efficiency during summer. This thermal variability may also play a key role in the distribution of fish prey items, including the forage fish ninespine stickleback (*Pungitius pungitius*) as well as invertebrate and plankton communities (McFarland, 2014).

Similar to development of stratification in Arctic lakes, pools tend to stratify starting in early July once snowmelt runoff and associated cold temperature and turbulent mixing has slowed and during periods of intense warming of surface waters. Such regimes were clearly observed in pools at Crea and Blackfish creeks starting on 9 July 2013 when the water temperature rose rapidly from 8 to 16 °C over several days and two pools monitored in each stream develop varying degrees of stratification (Fig. 11). In Crea Creek, the mean daily temperature difference between the pool surface and bed was as high as 2.5 °C in one pool and only 0.9 °C in the other (Fig. 11a). For the same warming event in Blackfish Creek, levels of stratification are 1.1 °C in one pool and

BGD
11, 11391–11441, 2014

4.7 °C in the other (Fig. 11b). Another warming event in late July caused even higher amounts of stratification, up to 5 °C, among the pools in both streams.

In beaded streams on the ACP, we have observed that peak flows predictably occur only one to two days after the first detectable streamflow, which is first on top of the ice and often partly beneath the rapidly melting snowpack in stream gulches. Over five years of gauging on five separate beaded streams, the timing of peakflows ranged from 1 June to 10 June with peak hourly discharges of 1–10 $m^3 s^{-1}$, which typically exceeding summer flows by two orders of magnitude or more. This fast consistent response is similar with that observed for larger river systems of the ACP (Arp et al., 2012b; Bowling et al., 2003), which are fed predominantly by beaded streams and their source-water lakes. A related characteristic is that water temperatures are very near 0 °C at flow initiation and rise very rapidly directly following peak discharge, often warming to 10 °C or more over a 2–3 day period (Fig. 11). These rapid changes in flow and temperature regimes may provide important cues to fish migrating along larger river courses fed by beaded streams (Heim, 2014). Arctic grayling (*Thymallus arcticus*) are known to seek habitats that warm most rapidly in the spring to spawn, and the quickly rising temperatures of beaded streams may contribute to their importance as spawning habitats (Heim. 2014). In fact, we often see individual fish migrating up beaded channels with water flowing over bedfast ice just prior to peakflows, when the dark bodies of fish can be easily observed crossing the white ice surface. This is similar to Arctic grayling behavior observed in Interior Alaska, where pre-spawning migration has been correlated with water temperature first reaching 1 °C and includes swimming under ice and congregating in areas before ice conditions allow free passage (Beauchamp, 1990). Tracking studies of Arctic grayling tagged in Crea Creek, show a rapid pulse of upstream migration into the system during and after peakflow, suggesting that fish at the mouth until ice-breakup permits access (Heim, 2014). This early upstream migration may represent an adaption to maximize time spent in productive spawning habitats at the earliest possible time in order to provide a longer period of growth for offspring.

BGD
11, 11391–11441, 2014

More broadly, the period of peak flow across this hydrologic landscape represents a period of high connectivity among aquatic habitats, where fish can disperse from relatively limited deepwater overwintering habitats and move into shallow seasonally-flowing habitats like beaded streams. Again in late August through September, changes in flow and temperature may become important environmental cues that fish use to time migratory movements out of beaded streams (Heim, 2014). Migration out of Crea Creek in the fall was strongly correlated to decreases in stream temperature, as the channel connection to the Ublutuoch River became compromised due to ice formation. Low flows and colder temperatures increase the risks of utilizing Crea Creek (Arctic grayling were not found to overwinter within the drainage), yet persistence of fish within the drainage through September may be advantageous in terms of growth and acquisition of energy reserves prior to the onset of winter (Heim, 2014).

With respect to the basic physics of flow through stream systems characterized by multiple evenly spaced pools (storage zones), an important question is how rapidly water moves through these systems. This has implications for streamflow dynamics, movement and transformations of carbon, nutrients, and potentially contaminants, the transport of particles including mineral and organic sediment, plankton (both semi-mobile and drift), and the movement of fish. Because most beaded streams are set within a permafrost framework without interactions with groundwater systems, the development of any meaningful hyporheic flow through bed material or banks is unlikely. This process has been investigated in Imnavait Creek and adjacent beaded streams around Toolik Lake in Alaska where the glaciated setting and corresponding substrates may allow hyporheic storage to play a significant role in beaded stream hydrology (Merck et al., 2012; Zarnetske et al., 2007). Still we suggest that most if not all transient storage in beaded streams, in both glaciated and non-glaciated settings, occurs within in-channel dead zones (pools or beads).

Tracer tests conducted about two days after peakflows on each stream (Fig. 11) show a nearly equal distribution of the channel functioning in advective transport and storage (i.e., $A_S/A \sim 1$) (Fig. 12 and Table 2). Mean channel velocities for Crea Creek

BGD
11, 11391–11441, 2014

were about 40 % lower than for at least one run where we measured velocity profiles in cross-section, even though the flow was well out of its banks as is typical during high flows. The difference was even greater at Blackfish Creek, 65 % lower, likely due to more water exchanging with deep pool storage zones. Both streams have approximately the same drainage areas; Blackfish Creek usually has a higher peakflow and lower summer flows compared to Creak Creek potentially due to a higher proportion of DTLBs relative to lakes. The relative storage-area size (A_S/A) increased slightly at lower flows in Crea and was similar at Blackfish, yet the difference in mean reach velocities relative to run velocities was pronounced. Mean water velocities in Crea Creek decreased to 0.07 m s^{-1} in early July and were 0.01 m s^{-1} in late August compared with run velocities of 0.39 m s^{-1} and 0.33 m s^{-1}, respectively (Table 2). Blackfish Creek had much lower velocities in early July, 0.01 m s^{-1}, compared to the run, 0.33 m s^{-1}. The movement of RWT labeled water at Blackfish Creek was so slow in late August that less than half of the solute was detected 232 m downstream within 23 h after its release and full solute breakthrough was not achieved to facilitate inverse modeling of channel hydraulics. Needless to say, water was moving very slowly and the storage zone was exceptionally large given the flow rate, 26 L s^{-1}.

The increasing residence times of water in these two channels are shown more clearly in Fig. 12. At the start of peakflow recession over 10 % of the water in both channels was still moving at velocities lower than 0.1 m s^{-1}. During summer flows, the fastest reach-scale velocities did not exceed 0.2 m s^{-1} in Crea Creak and 0.05 m s^{-1} in Blackfish Creek (Fig. 12). Even though individual run velocities often exceed 0.5 m s^{-1} or greater, the water in the channel exchanges with storage zones (pools) sufficiently to slow the total movement of water by up to an order of magnitude or much more. Such slow transport rates of water in beaded stream systems may have important implications for maintaining in-stream flow during dry summers when evapotranspiration far exceeds rainfall on daily to weekly time-scales. The major source of water to these channels is thought to be upstream lakes (Arp et al., 2012b; Bowling et al., 2003), and the evenly spaced storage-rich nature of these streams may function importantly

BGD
11, 11391–11441, 2014

to maintain relatively constant flows and reduce evaporative losses during summer drought periods.

The summer of 2013 when these experiments were conducted was a relatively wet and rainy compared to previous years when we have monitored discharge in these streams. Still in five years of monitoring, starting in the summer of 2008, we have not yet observed interruptions in flow during summer drought periods in five gauged streams. At least some alluvial streams in the Arctic foothills of Alaska have experienced prolonged periods of no flow over certain reaches during drought conditions when only minimal flows continue through interstitial gravels and disrupt migration of Arctic grayling (Betts and Kane, 2011). In some instances, individual Arctic grayling have been observed traveling over 160 km within a year visiting different key habitats within a "migratory circuit" (West et al., 1992). Thus, connectivity among spatially separated habitats is critical to this life history strategy, and beaded streams may function importantly in maintaining hydrologic connectivity and fish passage between alluvial rivers and tundra lakes and ponds. Extreme drought conditions occurred on the ACP and foothills during the summer of 2007 and the hydrologic response has been well documented in rivers (Betts and Kane, 2011; Arp et al., 2012b), thermokarst lakes (Jones et al., 2009a), and upland tundra (Jones et al., 2009b) in this region. Whether beaded streams in this area maintained hydrologic connectivity between river and lake systems through this dry summer was undocumented and warrants reconstruction through hindcast modeling.

The other key function that the hydraulics of beaded streams provides is productive foraging habitat for Arctic fishes. This stems from the observation that larger foraging fishes (e.g., Arctic grayling) spend much of their time holding in channel runs downstream of pools, where they efficiently ambush drifting zooplankton, invertebrates, and nine-spine stickleback (McFarland, 2014). The rapid shift in velocities from pools to runs may function as a key delivery system of forage that either resides primarily in beaded stream pools (i.e., ninespine stickleback and aquatic macroinvertebrates) or comes downstream as drift from lakes (i.e. zooplankton) or riparian vegetation (i.e.

terrestrial invertebrates). Such a setting may in part be the same reason why lake inlets and outlets are such productive ecosystems (Jones, 2010). The difference here is that along the course of beaded streams, this lake outlet delivery system is replicated multiple times over a short distance (i.e., 5 times per 100 m on average, Fig. 3). Approximately half of the Fish Creek drainage network is composed of beaded streams, the equivalent of 1200 km stream length (Arp et al., 2012b). If we assume a pool density of 5 per 100 m, this gives us an estimated 60 000 pools (beads) throughout this watershed. Recent Fish Creek Watershed classification of lakes > 1 ha shows 4362 lakes, of which 45 % have perennial stream outlets and another 30 % have at least ephemeral outlets (B.M. Jones, unpublished data). In terms of potential fish habitat for summer foraging, this comparison suggest that pools in beaded stream increase the number of potential fish habitat zones for ambush foraging by18-fold across the landscape.

4 Conclusions

The coupled biophysical processes of beaded stream systems that we see as most interesting and important in terms of ecosystem functions are described conceptually in Fig. 13. We found high spatial and temporal thermal variability among pools, which likely play an important role in permafrost thaw and coldwater habitat (Fig. 13a). Beaded morphology appears to also play an important role in summer feeding habitats and hydrologic connectivity for migrating fish, the quality and availability of which is critical during short Arctic summers. During long Arctic winters, beaded stream gulches fill with deep snow that effectively insulates ice and permafrost and plays a role in creating taliks and providing overwintering habitats for certain fishes and invertebrate communities (Fig. 13b). This conceptual understanding of beaded stream systems helps summarize seasonal and reach-scale ecosystem functions of interest to physical and biological scientists and particularly managers concerned with changing human uses of Arctic lands and waters in the context of changing climate.

BGD
11, 11391–11441, 2014

This body of research on beaded streams in continuous permafrost landscapes documents a wide and varied distribution across the Circum-Arctic in relation to permafrost ice-content, topography, and elevation. On the inner coastal plain of northern Alaska, our surveys indicate that beaded streams compose the majority of drainage networks and most channels initiate from and are fed by lakes. At least in northern Alaska, lakes supply water for new development in the form of ice roads and other industrial and municipal uses. Knowing how such practices affect downstream ecosystems warrants investigation. Channels with beaded morphology are maintained downstream, eventually forming alluvial channels in relation to varied water and sediment supply. This suggests that new land disturbances, such as road construction or thermokarst processes that can alter these watershed fluxes, will factor into future drainage network changes. It also appears that beaded stream channels are relatively stable over time and potentially very old, such that any observations of rapid channel change may be indicative of more extreme forcing agents, either anthropogenic or climate driven. Given these concerns and the high density of beaded stream systems in many Arctic landscapes, expanded research into the role of these ecosystems in permafrost, hydrological, and biological processes will be essential.

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BGD
11, 11391–11441, 2014

Beaded streams of Arctic permafrost landscapes

C. D. Arp et al.

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BGD
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Table 1. Comparison of beaded stream morphology and ambient thermokarst features between black and white photography acquired in 1948 and 2013 for a 2.7 km segment of Crea Creek in the lower Fish Creek Watershed.

Attribute Compared	1948	2013
Pools		
number	132	134
total area (m^2)	7861	8334
mean area (m^2)	59.6	62.2
number unique	23	25
Gulch/Riparian Zone		
total area (m^2)	221 802	241 247
mean width (m)	82.1	89.4
Thaw pits		
total number	74	66
number unique	55	47

BGD
11, 11391–11441, 2014

Table 2. Results from reach-scale tracer injections in Crea (325 m) and Blackfish (232 m) creeks during the summer of 2013 (RWT is rhodamine WT, Q is stream discharge, A is the advective cross-sectional area, U is advective zone velocity, D is the dispersion coefficient, A_S is the storage zone cross-sectional area, A_S/A is the relative storage zone area, α is the storage zone exchange coefficient, A_R and U_R are the cross-sectional area and velocity, respectively, of a single channel run).

Experiment Data			Total Channel Hydraulics				Channel Storage Zone			Channel Run (single)	
Site	Date	Solute Added (RWT, g)	Q ($m^3 s^{-1}$)	A (m^2)	U ($m s^{-1}$)	D ($m^2 s^{-1}$)	A_S (m^2)	A_S/A (s^{-1})	α (m^2)	A_R ($m s^{-1}$)	U_R
Crea	14 Jun	70.4	1.172	5.29	0.22	3.33	5.32	1.01	1.9E-03	2.48	0.54
Crea	5 Jul	49.9	0.129	1.89	0.07	0.88	2.71	1.43	5.9E-04	0.43	0.39
Crea	25 Aug	19.9	0.027	1.95	0.01	0.38	2.55	1.31	1.2E-03	0.10	0.33
Blackfish	13 Jun	92.4	1.730	9.81	0.18	1.90	9.08	0.93	3.2E-03	2.90	0.70
Blackfish	6 Jul	41.4	0.085	7.00	0.01	0.45	6.60	0.94	1.5E-03	0.52	0.33
Blackfish	24 Aug	19.1	0.026	–	–	–	–	–	–	0.36	0.15

BGD
11, 11391–11441, 2014
Beaded streams of Arctic permafrost landscapes
C. D. Arp et al.

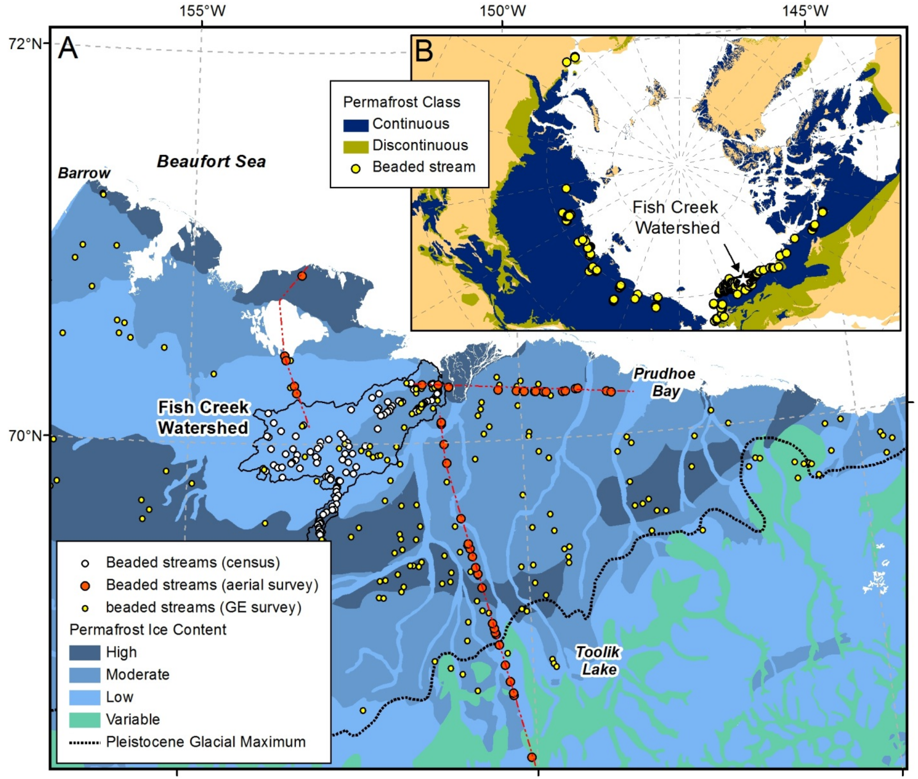

Figure 1. Beaded streams and thermokarst channels are distributed across the Alaskan North Slope in relation to permafrost ice content (NICOP, Jorgenson et al., 2008) and the Pleistocene glacial maximum (Manley and Kaufman, 2002) with all beaded stream locations indicated within the Fish Creek watershed (main location for this study) and several aerial survey transects from the Brooks Range to the Beaufort Coastal Plan **(A)**. The panel in the upper right corner shows the location of this study area within the circumarctic zone of continuous permafrost and locations of beaded stream channels that could be identified from imagery in Google Earth **(B)**.

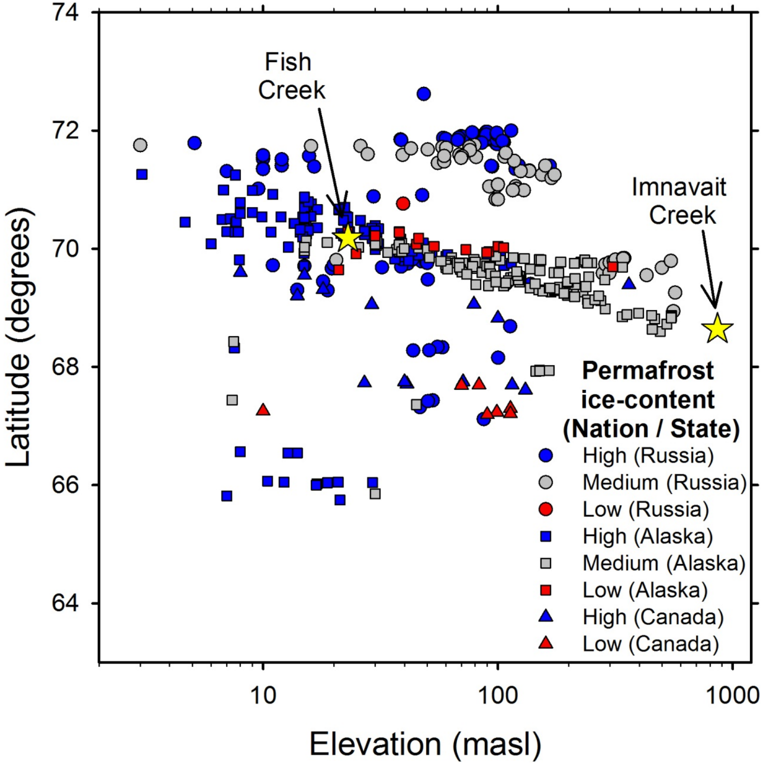

Figure 2. The distribution of beaded stream channels throughout the circumarctic in relation to latitude and elevation. These channels were identified using imagery in Google Earth primarily within the zone of continuous permafrost (grouped according to country and ice-content classes of permafrost). The location of streams in the Fish Creek (this study) and Imnavait Creek (location of majority of past beaded stream research) are indicated with yellow stars.

BGD
11, 11391–11441, 2014

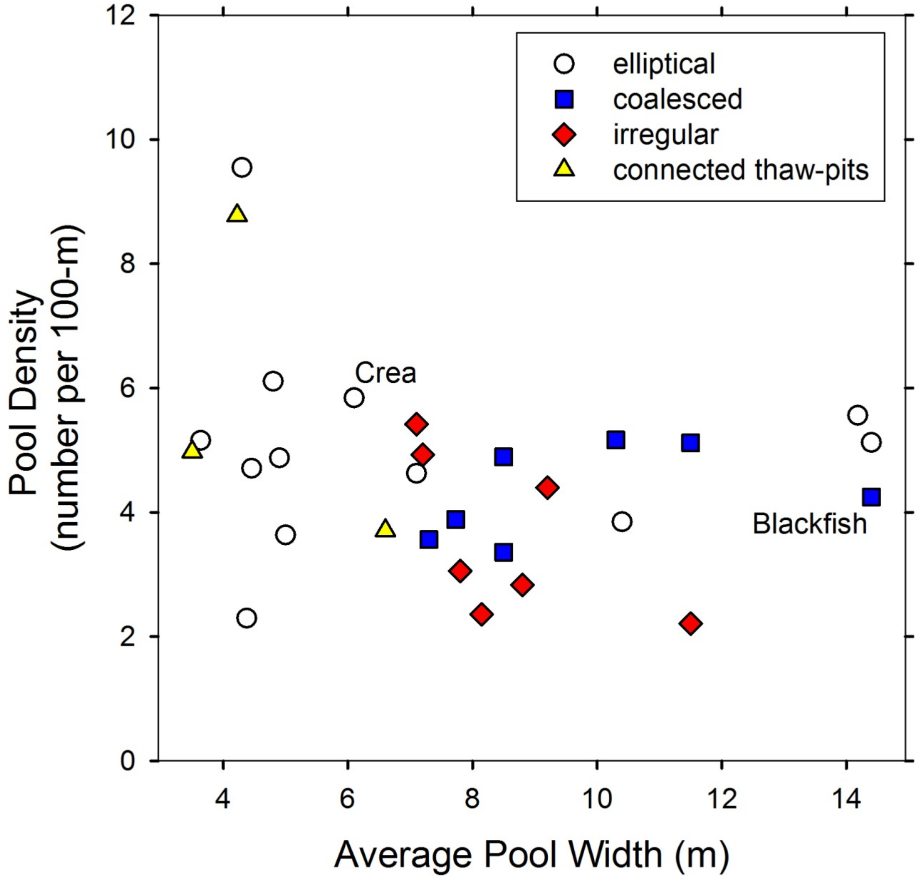

Figure 3. Morphological characteristics of beaded stream channels classified by pool shape in compared by pool density and pool size measured using 2.5 m CIR photography at the segment scale (1–3 km) in the Fish Creek Watershed.

BGD
11, 11391–11441, 2014

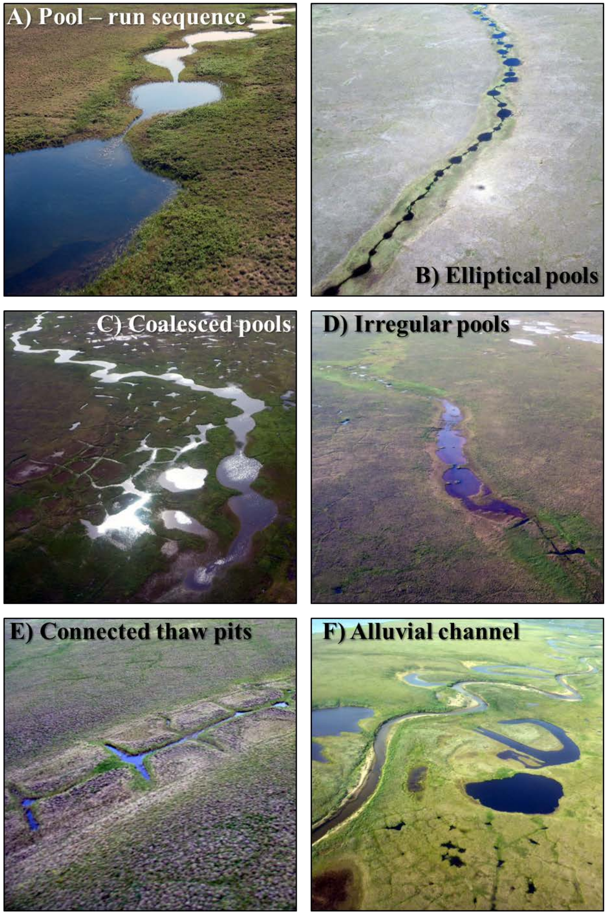

Figure 4. Oblique photographs showing typical pool-run morphology **(A)** and of examples beaded channels forms **(B–E)** compared to alluvial channel **(F)** morphology.

BGD
11, 11391–11441, 2014

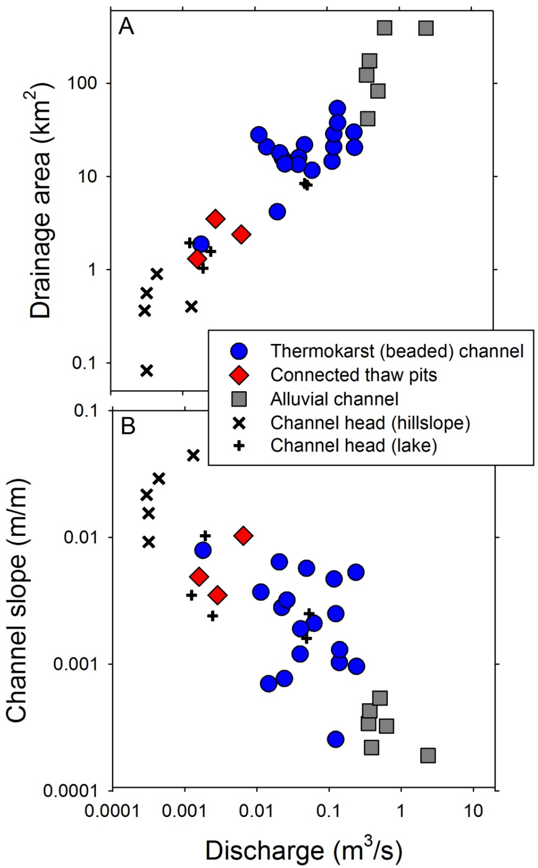

Figure 5. Stream channels in the Fish Creek Watershed organized by drainage area **(A)** and slope **(B)** in relationships of streamflow (discharge during mid-July 2011).

BGD

11, 11391–11441, 2014

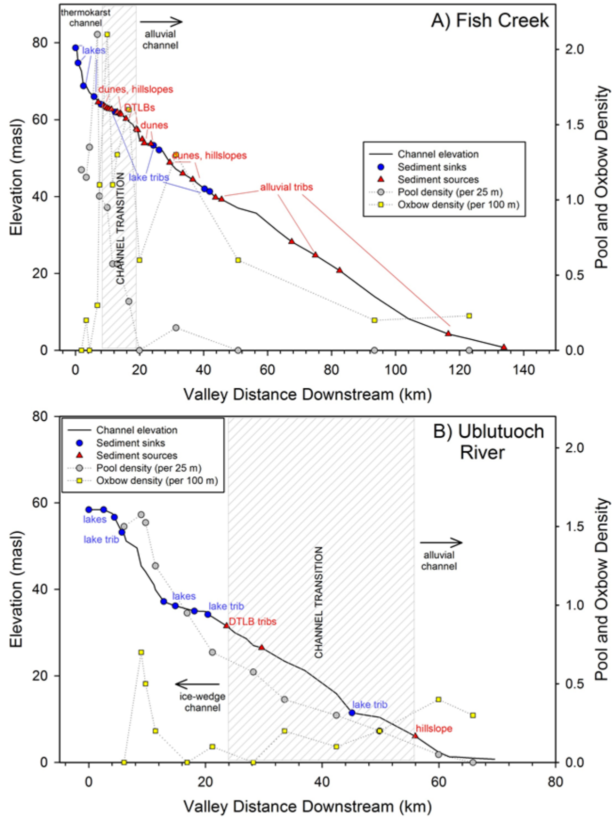

Figure 6. Headwater to downstream patterns of a beaded stream originating in the eolian sand deposits, Fish Creek **(A)**, compared with a beaded stream originating in alluvial-marine deposits, Ublutuoch River **(B)** showing changes in channel elevation and the density of pools and oxbow (meander-cutoff) lakes relative to sediment sources and sinks.

BGD
11, 11391–11441, 2014

Beaded streams of Arctic permafrost landscapes

C. D. Arp et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◂ ▸
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

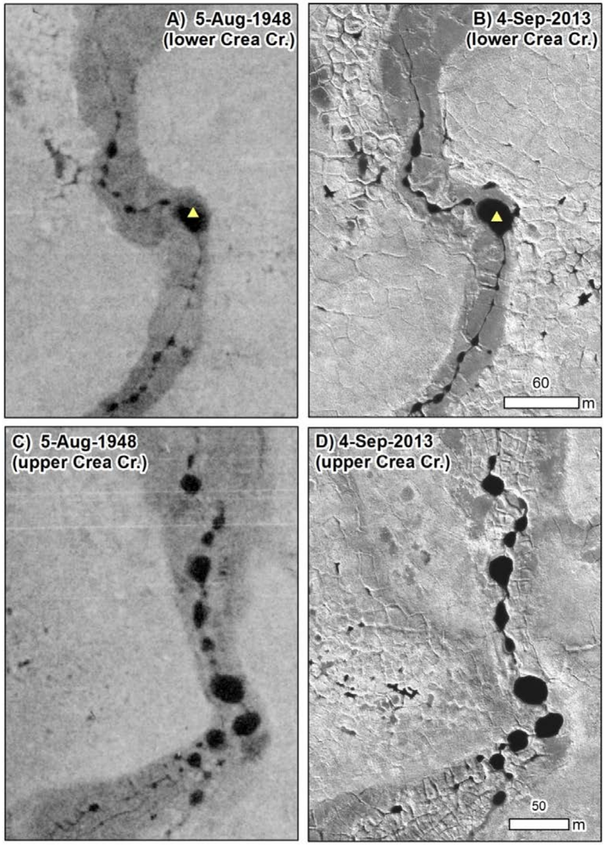

Figure 7. Comparison of two segments of the Crea Creek channel in 1948 **(A, C)** and 2013 **(B, D)** showing that pools, the riparian gulch, and adjacent thaw pits can be clearly observed in each image. The location of a sediment core collected for ^{14}C dating is indicated with a yellow triangle.

BGD
11, 11391–11441, 2014

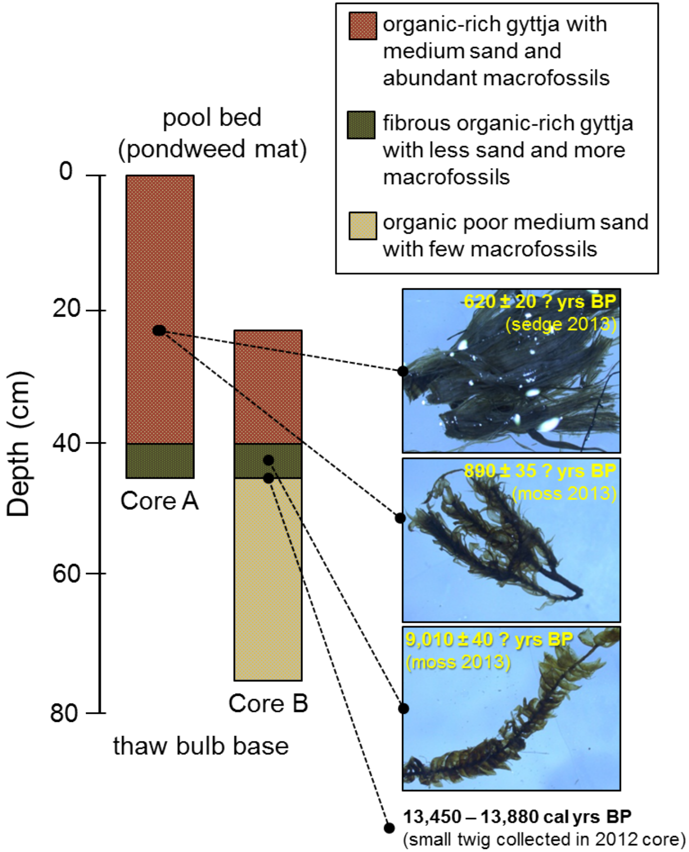

Figure 8. Sediment core stratigraphy showing of repeat cores collected in 2012 and 2013 from a large pool in Crea Creek (indicated in Fig. 7) showing location of macrofossil fragments collected and radiocarbon dates. The sharp transition from organic-rich *gytta* to medium sand is interpreted to be the base of the pool at its time of formation.

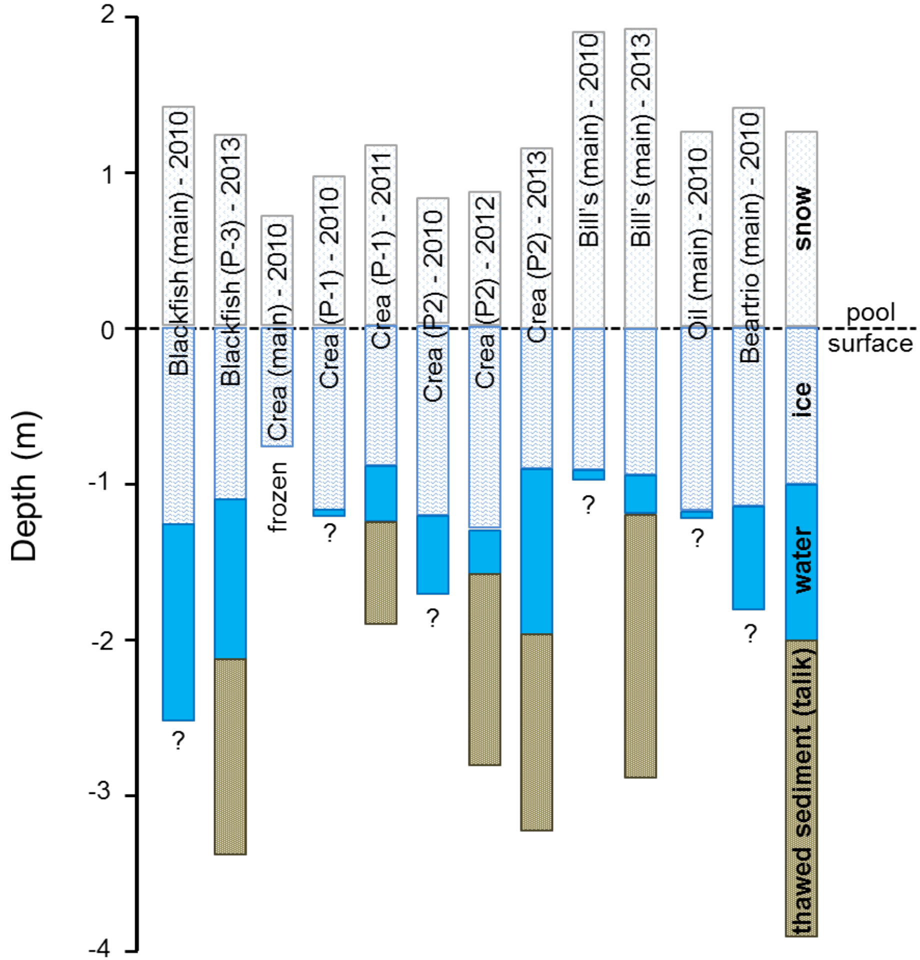

Figure 9. Winter profiles of several pools in beaded streams surveyed in early March to early April from 2010 to 2013 (no measurement of thawed sediment depth is indicated with "?").

BGD
11, 11391–11441, 2014

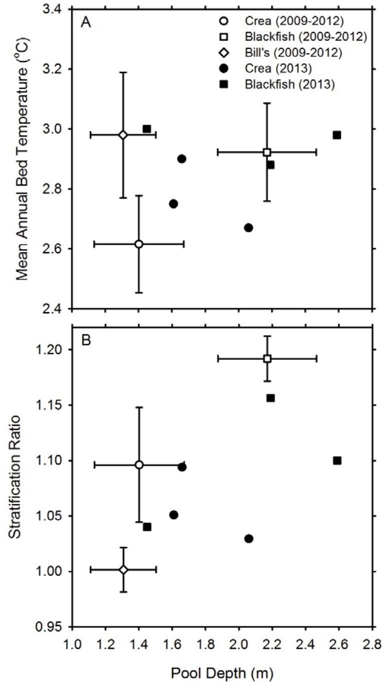

Figure 10. Thermal regime characteristics of single pools at three beaded streams averaged over fours year (error bars are standard deviations) with an thermal data shown for an additional three pools within two of these beaded streams in 2013. Annual temperatures at pool beds are averaged from hourly intervals **(A)** and stratification ratio is the average ratio of surface temperature to bed temperature during July through mid-August each year **(B)**. Pool depths in each are mean values from hourly measurements during the period temperatures are summarized in each plot.

BGD
11, 11391–11441, 2014

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂◂ | ▸▸
◂ | ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

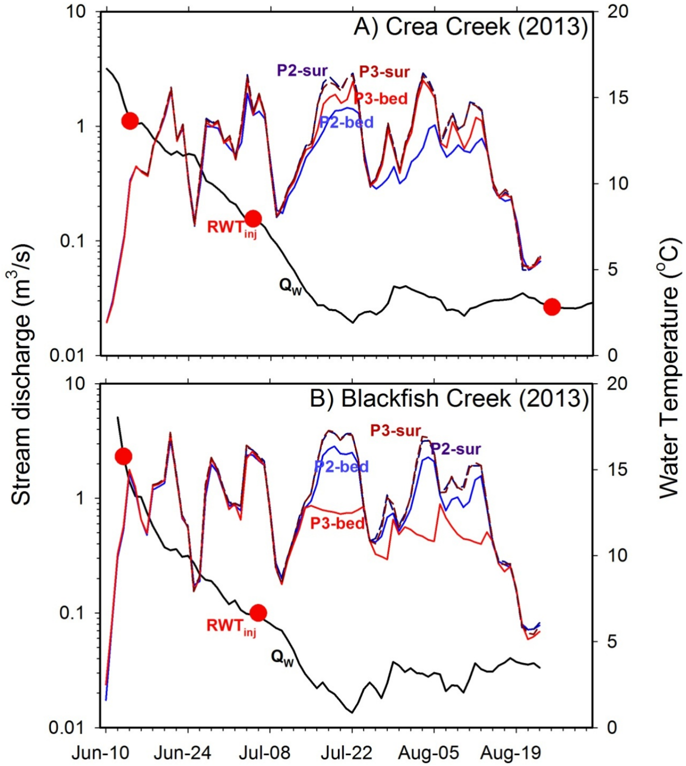

Figure 11. Streamflow hydrographs of Crea **(A)** and Blackfish **(B)** creeks with contrasting channel and watershed morphology. Bed and surface temperature was monitored in multiple pools within each reach to document the timing and extent of stratification and data from the two pools with the largest variation in stratification are shown for each stream (Timing of water tracer injections studies are indicated with red circles (RWT_{inj}), streamflow (Q_W), and pool bed (P_{bed}) and pool surface temperature (P_{sur}); all data are mean daily values from hourly measurements).

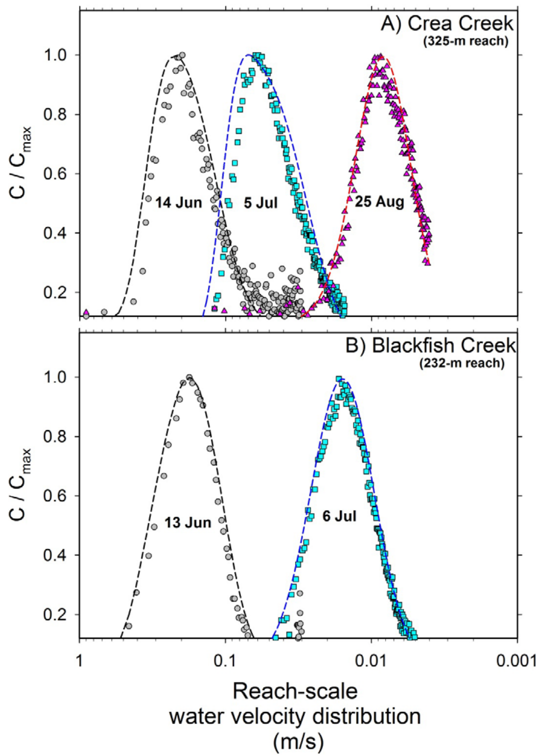

Figure 12. Water velocity distributions measured using conservative hydrologic tracer tests (rhodamine WT pulse additions) shown as concentration **(C)** relative to maximum concentration (C_{max}) measured at the downstream point of Crea Creek with shallow elliptical pools **(A)** and Blackfish Creek with deep coalesced pools **(B)** at differing flows in 2013. Dashed lines are modeled breakthrough curves fit to tracer data using OTIS-P (experimental data and model results shown in Table 2).

BGD
11, 11391–11441, 2014

Beaded streams of Arctic permafrost landscapes

C. D. Arp et al.

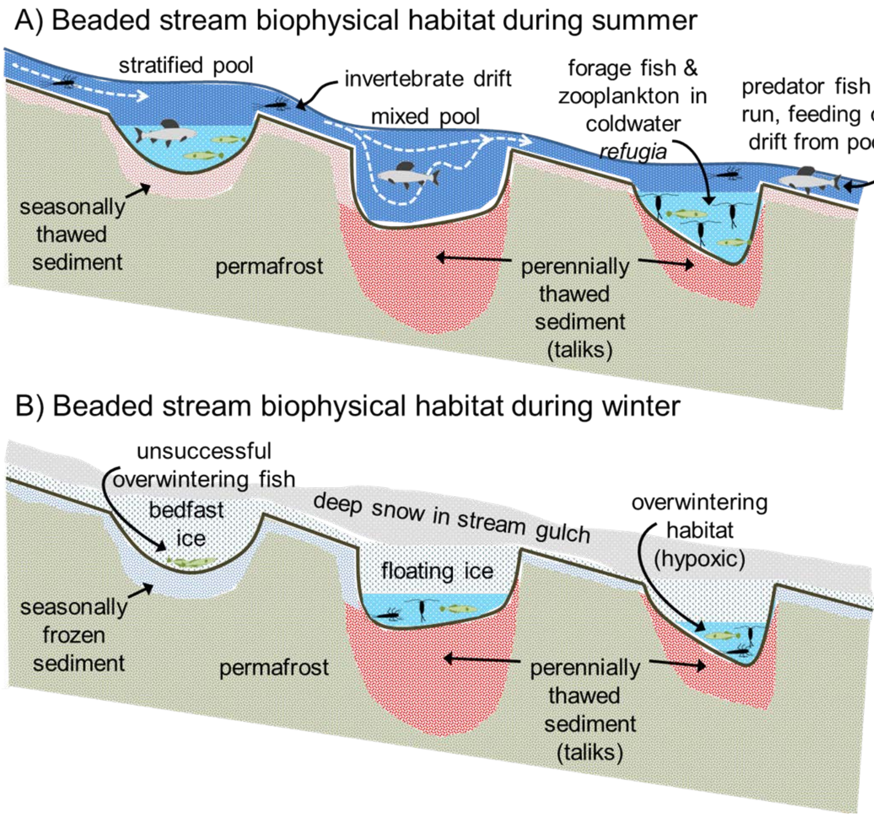

Figure 13. Conceptual diagram showing morphology, physical regimes, habitats, and organisms of a hypothetical pool-run system in the summer **(A)** and winter **(B)** based on observations and monitoring studies in multiple beaded stream systems during these time periods over many years.

BGD
11, 11391–11441, 2014