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Drainage Network Structure and Hydrologic Behavior of Three Lake-Rich Watersheds on the Arctic Coastal Plain, Alaska

C. D. Arp@*
M. S. Whitman†
B. M. Jones‡§
R. Kemnitz†
G. Grosse§ and
F. E. Urban#

*Water and Environmental Research Center, University of Alaska Fairbanks, 306 Tanana Loop, Fairbanks, Alaska 99775, U.S.A.
†Bureau of Land Management, Arctic Field Office, 1150 University Avenue, Fairbanks, Alaska 99709, U.S.A.
‡Alaska Science Center, U.S. Geological Survey, 4210 University Drive, Anchorage, Alaska 99508, U.S.A.
§Geophysical Institute, University of Alaska Fairbanks, 903 Koyukuk Drive, Fairbanks, Alaska 99775, U.S.A.
#Earth Surface Processes Team, U.S. Geological Survey, Denver Federal Center, Denver, Colorado 80225, U.S.A.
@Corresponding author: cdarp@alaska.edu

Abstract

Watersheds draining the Arctic Coastal Plain (ACP) of Alaska are dominated by permafrost and snowmelt runoff that create abundant surface storage in the form of lakes, wetlands, and beaded streams. These surface water elements compose complex drainage networks that affect aquatic ecosystem connectivity and hydrologic behavior. The 4676 km^2 Fish Creek drainage basin is composed of three watersheds that represent a gradient of the ACP landscape with varying extents of eolian, lacustrine, and fluvial landforms. In each watershed, we analyzed 2.5-m-resolution aerial photography, a 5-m digital elevation model, and river gauging and climate records to better understand ACP watershed structure and processes. We show that connected lakes accounted for 19 to 26% of drainage density among watersheds and most all channels initiate from lake basins in the form of beaded streams. Of the >2500 lakes in these watersheds, 33% have perennial streamflow connectivity, and these represent 66% of total lake area extent. Deeper lakes with over-wintering habitat were more abundant in the watershed with eolian sand deposits, while the watershed with marine silt deposits contained a greater extent of beaded streams and shallow thermokarst lakes that provide essential summer feeding habitat. Comparison of flow regimes among watersheds showed that higher lake extent and lower drained lake-basin extent corresponded with lower snowmelt and higher baseflow runoff. Variation in baseflow runoff among watersheds was most pronounced during drought conditions in 2007 with corresponding reduction in snowmelt peak flows the following year. Comparison with other Arctic watersheds indicates that lake area extent corresponds to slower recession of both snowmelt and baseflow runoff. These analyses help refine our understanding of how Arctic watersheds are structured and function hydrologically, emphasizing the important role of lake basins and suggesting how future lake change may impact hydrologic processes.

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Introduction

Many watersheds draining the Arctic Coastal Plain (ACP) of northern Alaska and northwest Canada have complex drainage patterns resulting from the interplay among permafrost soils, low-relief macro-topography and rough micro-topography, and abundant lakes and wetlands (Roulet and Woo, 1988; Bowling et al., 2003). The structure and organization of drainage networks provide the framework for understanding and predicting watershed hydrologic behavior (Tucker and Bras, 1998; McNamara et al., 1999) that is driven by strongly seasonal hydrologic fluxes, active-layer dynamics, and storage regimes that dominate the Arctic (Kane et al., 1991; McNamara et al., 1998; Woo and Guan, 2006). Arctic drainage networks also determine the nature of abundant and diverse aquatic ecosystems that provide habitat, migration corridors, and forage for fish and other wildlife (Hershey et al., 1999; Woo and Guan, 2006; Woo and Mielko, 2007; Lesack and Marsh, 2010; Whitman et al., 2011). Much interest is currently focused on understanding Arctic hydrologic processes, how these processes create and maintain aquatic habitat, and changes that are expected in the hydrologic cycle due to climate change (Martin et al., 2009; NSSI, 2009; Whitman et al., 2011). However, only a few Arctic watersheds have been monitored and described comprehensively to establish a conceptual framework applicable to ACP landscapes (e.g., (Bowling et al., 2003; Lesack and Marsh, 2010).

The Coastal Plain represents approximately half of Alaska's North Slope landscape and is dissected by numerous rivers systems that emanate from the Brooks Range, including the Colville, Kuparuk, Sagavanirktok, and Canning Rivers. These watersheds integrate the entire hydrologic response over a sharp climatic and physiographic gradient and contribute the majority of North Slope runoff to the Arctic Ocean. For instance, nested watershed studies from the Kuparuk River have described the importance of drainage network structure and active-layer dynamics in generating runoff regimes differentially influenced by snowmelt and rainfall along a gradient from the mountains to coastal plain (Kane et al., 1991; McNamara et al., 1998; Kane et al., 2003). Few hydrologic monitoring programs and watershed studies have been conducted on rivers systems with entirely ACP origins, however, with the main example being the Putuligayuk River where work by Bowling et al. (2003) highlights the important role of lake and wetland storage and connectivity in runoff generation. Yet given the known heterogeneity of ACP landscapes with lake area extents ranging from <10 to >30% (Sellmann et al., 1975; Grosse et al., 2012) and the potential for future lake and channel evolution in ACP environments (Smith et al., 2005; Jorgenson and Shur, 2007; McNamara and Kane, 2009), few systematic studies have analyzed how this variation in watershed structure relates to aquatic habitat and hydrological processes.

The Fish Creek drainage basin located on the central ACP of northern Alaska presents an important opportunity to understand this intra-ACP variability because it is drained by three river systems with distinct differences in the extent of eolian, lacustrine, and fluvial landforms in each watershed. We document the degree of this natural ACP gradient in relation to drainage network structure, particularly in terms of the form and connectivity of streams and lake basins that create mosaics of aquatic habitat. Existing climate and river discharge data from these three watersheds enabled us to examine how these differences in watershed morphology, particularly lake-basin type and extent, produced variable runoff responses in years ranging from extreme drought (2007) to relative deluge (2009). Thus, an analysis of these watersheds will help advance our understanding of Arctic landscapes and hydrologic processes in the present and also serve as a model for future changes in the Arctic with respect to lake expansion, drainage, or drying (Pohl et al., 2007; Arp et al., 2011; Jones et al., 2011) and hydrologic intensification resulting in uncertain runoff responses (Rawlins et al., 2010).

Study Area

The Fish Creek drainage basin drains an area of 4676 km^2 to the Beaufort Sea located at 70.39°N and 151.27°W, just west of the Colville River delta approximately midway between Barrow and Prudhoe Bay, Alaska (Fig. 1 and Table 1). These lands occur entirely within the National Petroleum Reserve–Alaska (NPR-A). The majority of this watershed is within the inner ACP, which is generally bounded from the outer ACP by an ancient shoreline of

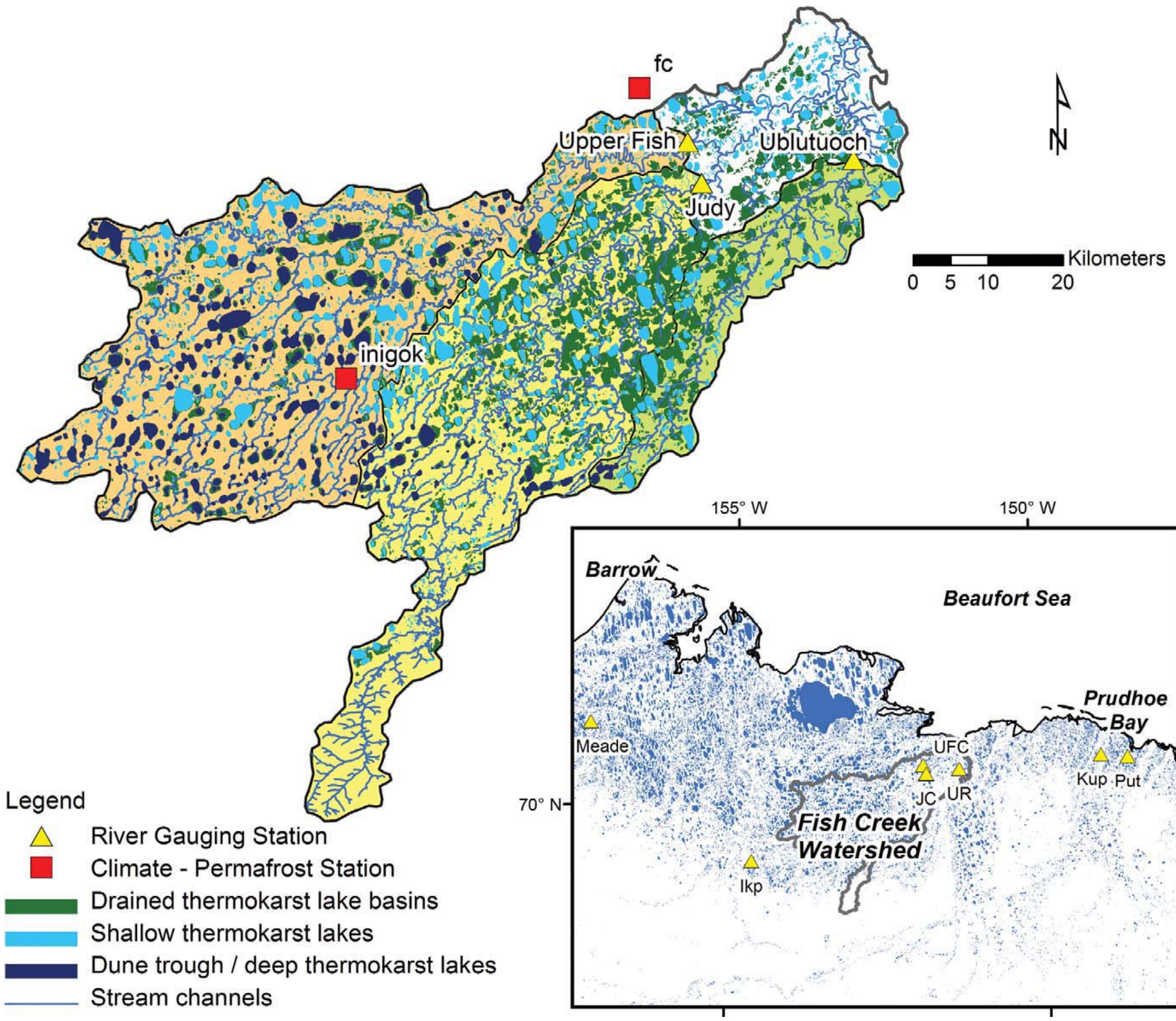

FIGURE 1. The Fish Creek drainage area, drainage network of stream channels and lake basins, and locations of river gauging and climate monitoring stations. Inset map shows the location of the Fish Creek drainage area in the Alaska Arctic Coastal Plain (ACP) and location of other gauging stations in ACP (UFC = Upper Fish Creek, JC = Judy Creek, UR = Ublutuoch River, Meade = Meade River, Ikp = Ikpikpuk River, Kup = Kuparuk River, and Put = Putuligayuk River).

TABLE 1

Characteristics of the three adjacent study watersheds of the Fish Creek drainage area.

Watershed	Drainage area (km^2)	Mean/Maximum Elevation (m a.s.l.)	Basin length (km)	Basin slope (%)	Lake area (%)	DTLB* area (%)	Dominant surficial geology
Upper Fish	2016	50/123	98.7	0.12	20.0	10.0	Eolian sand
Judy	1647	55/207	101.8	0.20	11.8	21.0	Alluvial and eolian sand
Ublutuoch	483	30/86	55.4	0.15	13.0	32.0	Marine sand and silt

*DTLB = drained thermokarst lake basin.

the Pelukian transgression (10–13 m a.s.l.) to the north and the Brooks Range foothills to the south (Williams et al., 1978). More generally, this landscape is classified as Beaufort Sea Coastal Plain ecoregion with surficial geology characterized by unconsolidated marine, glaciofluvial, and eolian deposits without bedrock control, and vegetation characterized by wet sedge tundra in drained lake basins, tussock-tundra uplands, and willow riparian corridors (Nowacki et al., 2001). Continuous permafrost occurs throughout this region reaching depths to 400 m, but with deep taliks under numerous lakes and river courses (Jorgenson et al., 2008). The active layer is shallow and typically thaws 30–60 cm by late summer. Near the surface (0–10 m), permafrost is very ice rich, often exceeding 80% volumetric ice content due to ice wedges associated with polygonized tundra and other forms of massive ground ice (Jorgenson et al., 2005, 2006). Thermokarst lakes and drained thermokarst lake basins (DTLBs) together cover >50% of the landscape with many deeper lakes occurring in stabilized dune troughs (Hinkel et al., 2005; Jorgenson and Shur, 2007) associated with the Pleistocene sand sea (Carter 1981). Mean annual air temperatures recorded at the Fish Creek and Inigok climate stations were –10.9 °C from 1999 to 2009. Runoff is dominated by snowmelt typically in early June. Relatively low summer precipitation is common on the ACP, averaging <200 mm (Table 2). At least 16 species of resident and migratory fish utilize lakes, rivers, and streams of the Fish Creek drainage basin (Whitman et al., 2011). Other important wildlife includes abundant and diverse migratory waterbirds, raptors, and passerines, the Teshekpuk Lake caribou herd, muskox, and brown and polar bears. Currently, land use is limited to petroleum exploration and subsistence activities mainly in the lower watershed.

TABLE 2

Summary of hydroclimatic and permafrost conditions for 1999–2009 compared to years used for hydrologic analysis in this study (2007–2009) for stations in the Fish Creek watershed (*MSAT* = mean summer (June–August) air temperature, *MAGT* = mean annual ground temperature at 120 cm depth, and *ALD* = active-layer depth measured in early fall; Snow depth is mean value for April, and Rainfall is from May to September).

Period/Station	*MSAT* (°C)	*MAGT* (°C)	*ALD* (cm)	Snow depth (cm)	Rainfall (mm)
1999–2009					
Fish Creek	6.5	–7.3	30	27	—
Inigok	7.6	–5.9	—	32	—
2007					
Fish Creek	8.1	–7.7	27	29	27
Inigok	8.9	–6.6	—	22	57
2008					
Fish Creek	8.8	–6.9	28	39	83
Inigok	8.3	–5.6	—	33	97
2009					
Fish Creek	6.8	–6.3	30	39	103
Inigok	8.3	–5.0	—	34	87

Three primary river systems form the Fish Creek drainage network; the more northwesterly Upper Fish Creek (UFC) is joined first by Judy Creek (JC) and then the more southeasterly Ublutuoch River (UR), both within 10 km of its delta along the Beaufort Sea coast (Fig. 1). River gauging programs were initiated in 2002 by the Bureau of Land Management (BLM) and in cooperation with the U.S. Geological Survey (USGS) from 2004 to 2009. Currently all three stations are jointly operated by BLM and the University of Alaska Fairbanks (UAF). Fortuitously for this and future studies, the watersheds draining above these three stations represent important differences within the inner ACP region primarily in terms of topography and surficial geology (Table 1 and Fig. 1). Of particular interest is a gradient in surficial geology from the UFC watershed, where 95% of the land area is classified as eolian sand, to the UR watershed, where 90% of the land area is classified as alluvial and marine sand and silt (Mull et al., 2004; Carter and Galloway, 2005; Jorgenson et al., 2008). The JC watershed shares a mixed composition of these eolian sand and alluvial and marine silt deposits with a narrow headwater portion composed of eolian loess and hillslope colluviums (Jorgenson et al., 2008) of the Schrader Bluff Formation (Mull et al., 2005). A number of differences among watersheds appears to be strongly related to this transition in surficial geology, the most apparent of which are the extent and types of lake basins and river channels.

Methods

DRAINAGE NETWORK MAPPING AND CLASSIFICATION

Because of the low-relief surface topography of the ACP, numerous lakes and DTLB, and complex channel networks, we elected to use a manual approach to delineating channel networks and connections to lakes. Algorithms and software packages for watershed analysis of digital elevation models (DEMs) (e.g., ArcHydro, Rivertools, and TauDEM) are commonly used for such analysis because they can provide efficient, comparable, and unbiased watershed and channel delineation. However, these approaches are inherently problematic for low-relief, lake-rich terrain (Tucker et al., 2001) such as the ACP, where even very high resolution DEMs, if available, may still require substantial post-processing, verification, and editing. Additionally, our goal was to classify channel form and lake connections, and thus using a manual approach for delineation allowed us to conduct this classification in concert with the network delineation process.

We primarily relied on 2.5-m color infrared (CIR) aerial photography acquired on 18 July 2002 and a corresponding 5-m horizontal resolution (0.5-m vertical resolution) interferometric synthetic aperture radar (IFSAR) DEM to identify channel networks. All channels with perennial flowing water during the majority of the unfrozen season were delineated using tools in ArcGIS as individual segments at a scale of 1:3000. Our identification of channels from these digital data was informed by extensive ground observations in five smaller catchments ranging from 5 to 50 km^2. We also acquired high resolution videography of the channel networks in these five catchments in August 2009 during periods of stream baseflow that could be referenced during the delineation process. River and stream channels were classified as: (1) alluvial, characterized by meandering planform with cut banks and point bars and often with floodplain and oxbow lakes; (2) beaded, characterized by evenly spaced elliptical pools connected by narrow runs; (3) colluvial, characterized by straight planform, incised gulches, and initiating from and flowing across relatively steep hillslopes; and (4) undetermined, where the defining characteristics were not distinct or appeared mixed among the other classes. In terms of governing processes for these classes we expected the following: (1) alluvial channels are formed by fluvial sediment transport and deposition (Knighton, 1998); (2) beaded channels are formed due to thermokarst erosion of ice-wedge networks (Pewe, 1966); and (3) colluvial channels are formed by hillslope processes below hollows (Montgomery and Buffington, 1997) including water tracks or zones of mass wasting (e.g., active-layer detachments) (McNamara et al., 1997). Examples of these stream classes are provided in Figure 2, Parts A–C. This channel classification was verified by field visits to 33 (1.6%) of delineated stream segments, representing all classes, in July 2011.

Delineation and classification of the drainage network was extended to all stream-connected lake basins. These connected lake basins were classified first as either (1) lakes with wetted perimeter to the basin margin, or (2) DTLBs with dry basins and supporting terrestrial vegetation; the majority of both types has already been identified in the National Hydrological Dataset (NHD) and existing geospatial data based on Landsat satellite imagery (Frohn et al., 2005). Partly drained lake basins, which are relatively common, were classified as lakes if >50% of the original lake basin was full or wetted and as DTLB if <50% of the original lake basin was full or wetted. Second, lake basins were classified as either (1) flow-through, if stream channels entered at an inlet and left at an outlet, or (2) headwater, if the lake only drained to an outlet. For the purposes of delineating drainage network extent, flow paths for (1) flow-through lakes basins were drawn as straight lines from lake inlets to the lake centroid and to lake outlets, and (2) headwater lake basins were drawn only from the lake centroid to the lake outlet. Additionally, all lakes within these three watersheds, whether connected by stream channels or not, were categorized by depth based on lake ice analysis using synthetic aperture radar (SAR) imagery (RADARSAT-1) from 12 April 2007 following methods in Mellor (1982) and Jeffries et al. (1996) and detailed in Arp et al. (2011). Lake depth classes are (1) <2-m depth with bedfast ice, (2) 2–4 m depth with floating ice, and (3) >4-m depth with floating ice. The majority of the first two depth classes are thermokarst lakes, but with many smaller oxbow or floodplain lakes. The deepest class of lakes is commonly considered to be formed in dune troughs, but may be of thermokarst origin as well (Jorgenson and Shur, 2007). Examples of several of these lake classes based on connectivity and depth are provided in Figure 2, Parts D–F.

HYDROLOGIC MEASUREMENTS AND ANALYSIS

Streamflow was monitored by the USGS following standard methods described in Buchanan and Somers (1969). Briefly, this method uses continuous measurements of the river stage from a pressure transducer coupled with measurements of discharge with the area-velocity method to develop a rating curve for calculating continuous discharge. In cold regions, flow during much of the year is ice affected such that reliable measurements of streamflow are only available from river breakup to freeze-up. We obtained daily streamflow for FC (NWIS ID#15860000), JC (15861000), and UR (15862500) gauged from NWIS (http://waterdata.usgs.gov/ak/nwis) from mid-May through September in 2007 to 2009, a period when most measurements were not rated as ice affected. Higher temporal resolution data, collected at 15-minute intervals, were also obtained and used for comparison with rainfall and drought events. All streamflow data were standardized by watershed area and reported as runoff in mm day^{-1}. For the purposes of consistent comparison among years, we summarized discharge data from 1 May to 30 September and report runoff statistics for this period, including flow duration analysis.

Meteorological and permafrost conditions were monitored at stations developed and maintained by the USGS Arctic Alaska Permafrost and Climate Network (http://data.usgs.gov/climateMonitoring/region/show?region=alaska). A brief description of the meteorological variables measured in this study follows below for the Fish Creek and Inigok stations (Fig. 1). Air temperature was measured at 3-m height with a shielded thermistor, ground temperature was measured with a thermistor at 120-cm depth in permafrost, rainfall was measured with a tipping-bucket rain gauge, and snow depth was measured with downward-looking sonar; all recorded at hourly intervals. For analysis of rainfall-runoff responses, we did not attempt to distribute this precipitation across the three watersheds and use the average precipitation from the two stations located near the lower and middle portions the Fish Creek drainage basin, recognizing that storm tracks and rainfall events can vary considerably across this relatively large area with a coastal-to-inland gradient.

Hydrograph analysis consisted of summarizing runoff response for snowmelt, summer drought, and rain events for each study year. Mean daily discharge data were analyzed for snowmelt runoff responses and drought period responses, and hourly discharge data were analyzed for rain-event responses. Runoff recession analysis was used as the primary metric for comparing hydrologic behavior among watersheds and years. This analysis assumes an exponential decay of river discharge, as:

$$Q_t = Q_i exp\ (^{-t}/_{t*}), \qquad (1)$$

where Q_t is discharge at time t, and Q_i is discharge at the start of flow recession. The recession coefficient $t*$ is reported in days

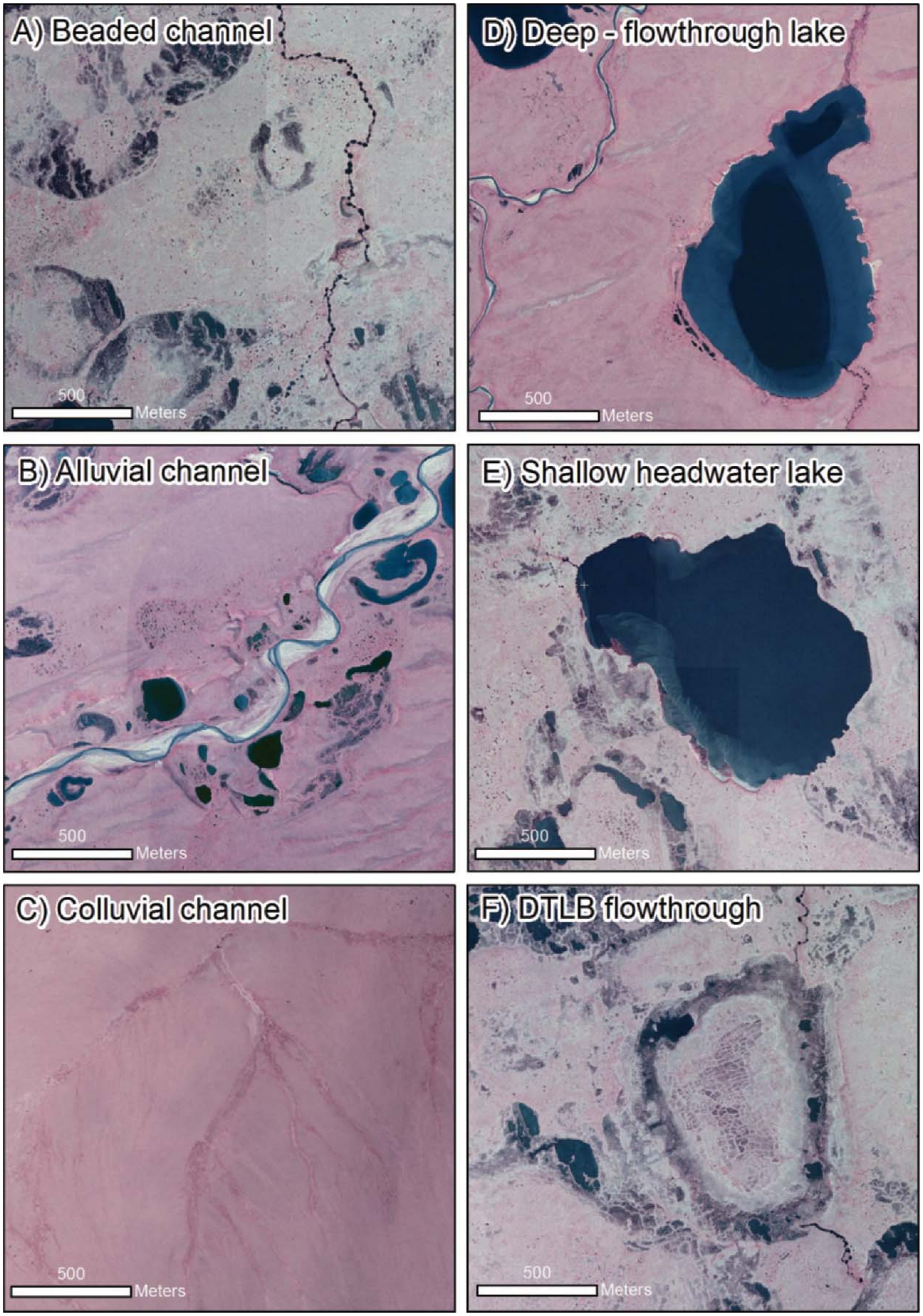

FIGURE 2. Examples of channel (A–C) and lake basin (D–F) classes from color-infrared photography (19 July 2002).

and represents the mean time of falling limb recession, the inverse of which is recession rate, k (McNamara et al., 1998). For snowmelt and rain-event peaks, we also report time-to-peak (T_c) and peak magnitude as peak discharge (Q_{pk}) relative to mean flow (MF) for snowmelt and Q_i for rainfall events.

Results and Discussion

DRAINAGE NETWORK STRUCTURE

Drainage Density and Classification

Watershed drainage density is a function of both hydrologic flux and the physiographic influence on runoff and erodibility (Knighton, 1998) and for subarctic basins is shown to decrease greatly with peatland extent and corresponding basin relief (Luoto, 2007). The drainage density for the entire Fish Creek watershed is 0.65 km/km^2 (Table 3), a value that is low, but within those reported for other Arctic watersheds ranging from 0.28 km/km^2 to 2.07 km/km^2 (Kitover, 2005). Of this reported set relative to the Fish Creek watershed, Trail Valley Creek in the lower Mackenzie Valley in Canada is likely most similar physiographically with a value of 0.83 km/km^2, and the Upper Kuparuk is most proximate with a value of 0.34 km/km^2. However, we report drainage density to include all perennially connected surface waters, and it is unclear whether other analyses of drainage density commonly include non-channelized water courses, as automated terrain analysis methods of DEMs would likely include depression storage, while ''blue-line'' approaches from topographic maps likely only include perennial channels (Tucker et al., 2001). We found that in the Fish Creek drainage basin, 77% of its length is stream and river channels and the other 23% are lakes and DTLB (Table 3). Thus, for comparison with other studies, the fluvial drainage density for Fish Creek watershed is 0.50 km/km^2 (Table 3).

For the fluvial portion of the drainage network, channels were classified as alluvial, beaded, colluvial, or undetermined. We found that nearly an equal proportion of the fluvial network is composed of beaded streams (primarily as 1st- to 3rd-order channels) as alluvial streams and rivers (primarily 4th-order and higher channels) (Figs. 3 and 4). Beaded streams are a common, but seemingly an understudied, form of streams on the ACP (Oswood et al., 1989) and on other permafrost-affected landscapes with ice-wedge networks (Pewe, 1966). Other known systems of organizing Arctic streams (Craig and McCart, 1975) use the stream classes of ''mountain,'' ''spring,'' and ''tundra'' based primarily on source-water and water-quality characteristics. No doubt all streams and rivers in our study area would fit into the tundra class, of which beaded streams are specifically noted in Craig and McCart (1975). Our classification system is more generally based on channel form and corresponding formative processes, and besides the beaded stream class that is likely Arctic specific, the alluvial and colluvial classes broadly represent formative processes that are generally recognized in most drainage networks (Montgomery and Buffington, 1997).

An interesting observation from this analysis is that nearly all 1st-order channels were beaded streams, and of these 61% initiated from lakes, 29% from DTLB, and only a few from hillslopes or hillslope water tracks. Colluvial channels, which typically form 1st-order channels in most drainage networks (Montgomery and Dietrich, 1989), were only observed in the upper headwater portion of the JC watershed with steeper valleys, loess deposits, and few lakes (Figs. 1 and 4). Thus, lakes appear to be the dominant control on channel initiation on the ACP, whereas water tracks often control this process in Arctic foothills watersheds (McNamara et al., 1998, 1999). Whether this dominance of channel initiation from lakes in the Fish Creek watershed is primarily controlled by lake abundance and corresponding high ground-ice content, or simply how the degradation of ice-wedge networks behaves in very low-relief landscapes, warrants further consideration.

TABLE 3

Drainage density for the three study watersheds in the Fish Creek drainage area partitioned by streams and lake basins and respective classes.

Network Elements / Classes	Drainage Density (km/km2) Upper Fish	Judy	Ublutuoch
Streams	**0.47**	**0.61**	**0.50**
beaded	0.12	0.31	0.41
colluvial	0.00	0.03	0.00
alluvial	0.29	0.23	0.09
unclassified	0.07	0.04	0.00
Lake Basins	**0.16**	**0.14**	**0.13**
Lake	*0.16*	*0.10*	*0.07*
flowthrough	0.11	0.08	0.05
headwater	0.04	0.03	0.02
Drained Lake	*0.01*	*0.04*	*0.06*
flowthrough	0.00	0.02	0.03
headwater	0.01	0.02	0.03
All	**0.63**	**0.75**	**0.63**

Lakes and Network Connectivity

The remaining 23% of the Fish Creek drainage network is composed of headwater or flow-through lakes. These hydrologically connected lakes represent 35% of the total 2886 lakes with >0.1 ha surface area in the Fish Creek watershed, but they are typically larger lakes that cover 17% of the land surface (Table 4). The majority of these connected lakes are classified as depression lakes (Jorgenson and Shur, 2007) and represent 79% of connected lakes by number and 92% by area. Though classified as depression lakes that occur in dune troughs, many of these should also be considered thermokarst in origin due to expanding shorelines (Grosse et al., 2012). Other lakes are classified as riverine (Jorgenson and Shur, 2007) and primarily occur along the alluvial floodplain of UFC and JC and the delta plain before it reaches the Beaufort Sea. Numerically, a majority of all lakes in the Fish Creek drainage basin were classified as isolated (65%) without perennial channel outlets or inlets (Table 4); however, based on field observations from several sites, it is very likely that many of these lakes have ephemeral or even perennial connectivity that was not resolved or otherwise recognized in our analysis using a single period of mid-summer aerial photography. This expectation is supported by the results of monitoring of stream-lake connectivity for individual lake systems (Lesack and Marsh. 2007; Woo and Mielko. 2007; Lesack and Marsh. 2010) and across watersheds using remote sensing (Bowling et al., 2003), which describes the strongly seasonal and interannually variable nature of surface-water systems in the ACP. Such variation in connectivity is more generally recognized

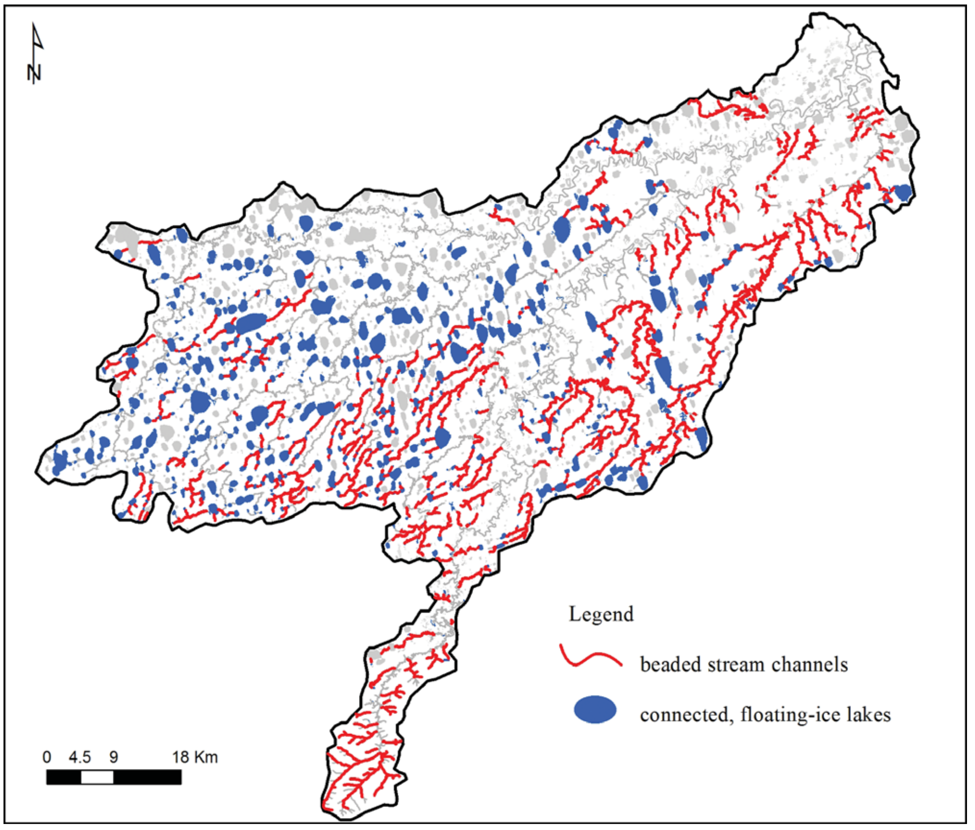

FIGURE 3. Distribution of beaded stream channels (summer foraging and migration habitat) and connected floating-ice lakes (over-winter habitat) in the Fish Creek drainage area.

as dynamic drainage density (Tucker and Bras, 1998; Spence, 2007) or as variable source-area contributions to streamflow and is a critical watershed process for understanding runoff response in the Arctic (Dunne et al., 1975; Roulet and Woo, 1988), as well as how aquatic ecosystems function in terms of fish migration and colonization and in terms of water, nutrient, and sediment exchange (Lesack and Marsh, 2010).

Typically, lakes are not explicitly considered in analysis of watershed drainage density, but in the case of ACP watersheds where extant lakes often cover >25% of the land surface, they are a critical component. Hydrologically connected lake basins (lakes and DTLB) accounted for 19% and 26% of the JC and UFC drainage network, respectively (Fig. 5). This variation in lake drainage density also generally corresponded to total lake area extent in each watershed (Tables 1 and 4). In the UFC watershed, most of the lake-basin extent within the drainage network was contemporary lakes (81%), with very few DTLB (19%) (Fig. 5). In the UR watershed, a much higher proportion of the lake basin drainage network consisted of DTLBs (44%). An interesting and consistent pattern among all three watersheds is that flow-through lakes with

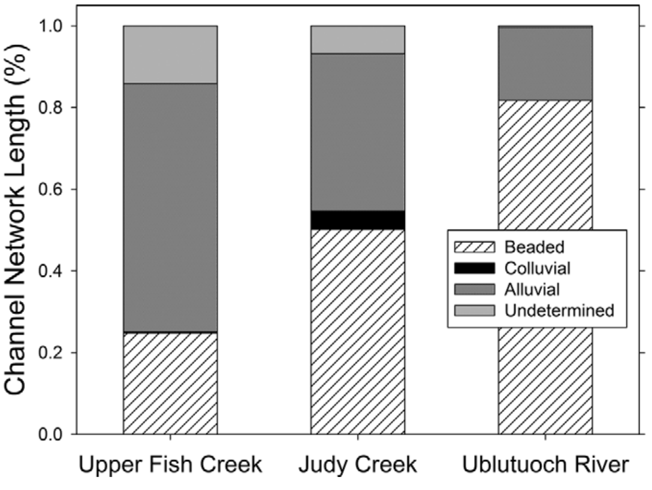

FIGURE 4. Proportional composition of the fluvial drainage network for watersheds in the Fish Creek drainage area.

TABLE 4

Characteristics of lakes (>0.1 ha) in the three study watersheds of the Fish Creek drainage area (Area is in % and Density is number per km^2).

	Upper Fish		Judy		Ublutuoch	
Lake classes	Area	Density	Area	Density	Area	Density
Lake depth/ice regime						
Very shallow (<2 m), bedfast ice	0.6	0.20	0.6	0.22	0.6	0.18
Shallow (2–4 m), floating ice	8.4	0.30	9.2	0.32	11.3	0.24
Deep (>4 m), floating ice	11.0	0.13	2.0	0.03	1.1	0.00
Surface connectivity						
Stream connected	13.6	0.19	7.6	0.18	9.1	0.15
Isolated	6.4	0.44	4.2	0.38	3.9	0.29

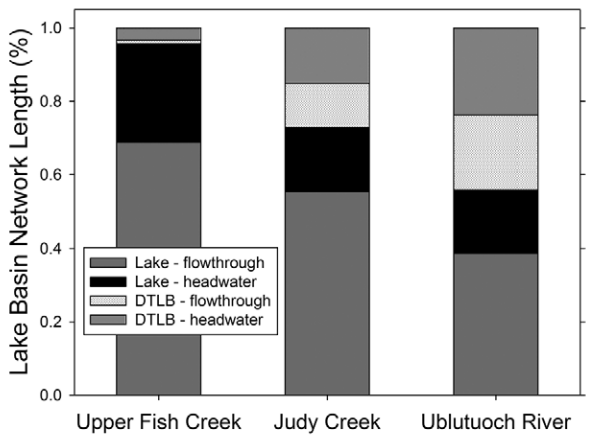

FIGURE 5. Proportional composition of lake basins within the drainage network for each watershed in the Fish Creek drainage area (DTLB = drained thaw lake basins).

surface inlets and outlets are 2.5 times more common in drainage networks than headwater lakes (outlet only). However, connected DTLB exhibited the opposite pattern averaging 2 times as many headwater basins than flow-through basins (Table 4 and Fig. 5). This pattern was most notable in the JC watershed where 78% of connected DTLB were at headwater positions. Does this suggest that lake drainage commonly initiates stream channels, or that the outlets of lakes are channel heads that initiate because of large and stable contributing areas that persist after drainage, or both? This finding also begs the question, Are headwater lakes more prone to drainage?

Comparing all lakes, both connected and isolated, among these watersheds showed that moderate-to-deep lakes with floating-ice regimes accounted for the majority of larger lakes (>0.1 ha). Deeper lakes, those classified as >4-m depth, accounted for 55% of lakes by surface area in the UFC watershed compared to 17% and 8% in the JC and UR watersheds, respectively (Table 4). These deeper lakes, particularly those with a large surface area which often reach maximum depths exceeding 12 m (Jones et al., 2009a), typically occur in dune troughs associated with the eolian sand deposits that dominate the UFC watershed. Shallow lakes with bedfast-ice regimes had relatively low abundance by surface area extent throughout all watersheds (averaging 4.2%). These lakes are individually smaller in surface area but have a relatively high density, particularly in the UR watershed where 43% of lakes freeze to the bed in most years (Table 4). The abundance and distribution of these lake classes have significance to aquatic habitat because lakes with floating-ice regimes can provide overwinter habitat for fish and other aquatic life (Fig. 3), whereas lakes with bedfast ice only provide open-water summer fish habitat (Sibley et al., 2008; Jones et al., 2009a), albeit potentially important for foraging and reproduction. With respect to hydrological processes, lakes with bedfast-ice regimes tend to have much earlier ice-out timing and correspondingly higher evaporative losses (Arp et al., 2011) such that variable distribution among watersheds may reduce baseflow runoff. Another important difference among watersheds is that the extent and abundance of DTLB mapped by Frohn et al. (2005) show a strong gradient in DTLB area from UFC with 10.0%, to JC with 21.0%, and UR with 32.0%. Interestingly, these proportions of DTLB appear to be inversely correlated with lake area extent or more directly related to the extent of shallow floating-ice lakes and bedfast-ice lakes that are most prevalent in the UR watershed. Whether lake drainage is less common in the area affected by the eolian sand sea or that fewer DTLB are recognized in this area is uncertain. In either case, however, this variation across these watersheds also appears to correspond to differences in drainage density and channel forms.

Overall, this variation in drainage network structure in terms of stream and lake basin types and the order in which they are connected along network flow paths should translate to varying distributions of aquatic ecosystems and habitat among these watersheds. Similarly, we expected that this variation in watershed structure should produce differing responses to hydrologic fluxes as observed in runoff regimes at each watershed outlet.

HYDROLOGIC BEHAVIOR

Water Yield and Flow Regimes

River discharge records averaged from 2007 to 2009 show *MF* of 5.0 $m^3 s^{-1}$ from UFC, 3.1 $m^3 s^{-1}$ from JC, and 1.2 $m^3 s^{-1}$ from UR. We note, however, that USGS flow records for these stations mainly include open-water periods, and winter baseflow is often reported as zero during ice-covered periods, even though March field surveys revealed flowing water in lower Fish Creek (M.S. Whitman, unpublished data). More spatially extensive analysis of the Kuparuk River found lower segments of the channels also support winter baseflow (Best et al., 2005). Interestingly, comparing mean runoff (*MR*) among watersheds showed a water yield of 78 mm from the largest watershed (UFC) and 75 mm from the smallest watershed (UR), with lower runoff of 60 mm from JC of intermediate size (Fig. 6). Comparison with the Putuliagiyuk River, which also is entirely within the ACP, showed *MR* averaged 108 mm from 1999 to 2007 and the lowest amount during the 2007 drought year of 55 mm (Kane et al., 2008). Unfortunately, a lack of comprehensive late spring snow surveys and adequately distributed precipitation monitoring did not allow us to calculate runoff ratios for these watersheds as is commonly reported in other studies (Kane and Yang, 2004).

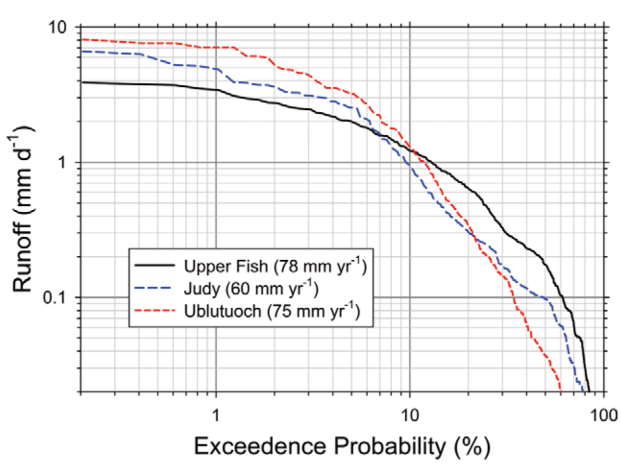

FIGURE 6. Flow durations curves for the three watersheds in the Fish Creek drainage area for 2007–2009 and mean runoff (*MR*) listed for this same period.

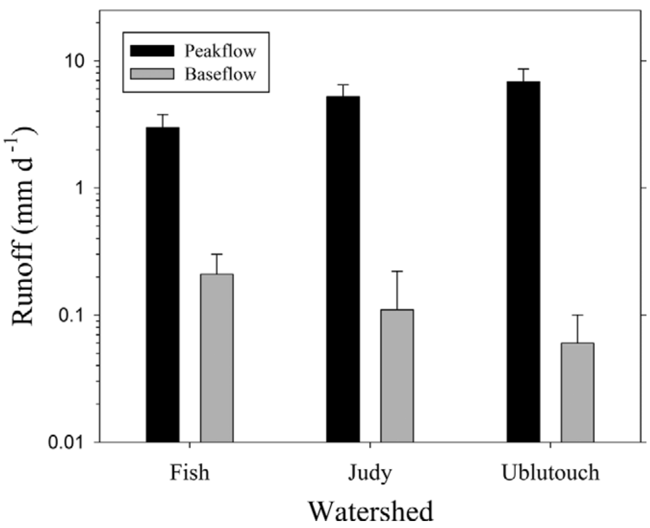

FIGURE 7. Comparison of peakflow runoff (mean daily value for day of peak) and baseflow (July and August) for the three watersheds in the Fish Creek drainage area.

Analysis of flow duration curves for this period show *MR* was exceeded 15% of the time for the Judy and Ublutuoch watersheds, but 26% of the time for the largest watershed, UFC (Fig. 6). This pattern of variation in flow regimes is also described for snowmelt peak and baseflow runoff among watersheds, with lower peak flow and higher baseflow from UFC compared to JC and UR (Fig. 7). This comparison of 3-year combined flow regimes indicates that relative storage capacity increases with watershed area and results in higher and sustained baseflow conditions in the UFC watershed than in JC and UR. Whether this apparent shift towards greater relative storage relates to the greater areal extent of lakes, abundance of deeper lakes, active-layer depths, and porosity of sand soils, or some combination of these factors is of great interest and warrants more detailed future analysis. Another important consideration in this analysis, which cannot be addressed yet for this drainage basin, is how variation in precipitation patterns and snowfall redistribution and ablation across this region impact observed differences in runoff regimes.

Next we analyzed how these flow regimes varied interannually among watersheds from 2007 to 2009. April snow depth, summer rainfall, and summer air temperatures measured at the Fish Creek station (lower elevation, 31 m a.s.l.) and Inigok station (middle elevation, 53 m a.s.l.) provide the best available summary of hydroclimatic conditions in the Fish Creek drainage area for these years (Table 2). An interesting pattern of interannual variability was observed in runoff from all three watersheds that totaled 140 mm in 2007, 167 mm in 2008, and 335 mm in 2009. The summer of 2007 was characterized by extreme drought conditions across much of Alaska's North Slope (Jones et al., 2009b) with an average of only 42 mm of rainfall recorded from the two study area weather stations. The summer of 2008 started with slightly larger snowpack than normal and relatively high rainfall and high air temperatures. The relatively low runoff in 2008 may be a consequence of reduced lake, DTLB, and other wetland (i.e. low-centered polygons) water storage or rather increased storage capacity from the preceding summer and fall drought conditions. The role of storage deficit from the preceding season is an important process for ACP watersheds suggested by Bowling et al. (2003) and observed in Landsat time-series analysis of lake area extent for this region (Jorgenson et al., 2005; Jones et al., 2009a) and other ACP landscapes (Plug et al., 2008; Arp et al., 2011). The summer of 2009 was considered very wet and relatively cool and cloudy; the lower storage deficit from 2008 conditions combined with relatively large snowpack likely resulted in the much higher water yield. This interannual variation in hydroclimatic conditions presented a good opportunity to further analyze watershed behavior in terms of snowmelt peak flow, mid-summer drought, and rain-event responses.

Interannual Variability and Runoff Responses

The timing of snowmelt-generated peak flows were relatively consistent among years, but varied among watersheds with average occurrence on 1 June in JC and UR and 6 June in UFC (Table 5, Fig. 8). The later peak flows in UFC were also relatively smaller in magnitude with slower rising and falling limbs with consistent behavior among years. Thus, peak-flow magnitude, time-to-peak (T_c), and recession coefficients (t^*) were relatively similar between JC and UR, averaging 13× *MF*, and lasting 11 days and 8 days, respectively, but with relatively higher peak flows in 2007 and longer T_c in 2009 (Table 5, Fig. 8). In 2008, rain events during the rising limb of snowmelt runoff may have been responsible for double peaks in the UFC and JC, but with no apparent response for UR. During the snowmelt peak-flow recession in 2009, a secondary peak was also noted for JC, to a lesser extent at UR, and not at all for UFC (Fig. 8). These comparisons of snowmelt runoff suggest greater storage in UFC and variable responses to rain-on-snow events.

Drought response was analyzed by selecting a 10-day mostly rain-free period during each study year with very warm temperatures necessary for high evaporative losses occurring at least during the first half of this period. Flow responses to these conditions were relatively moderate and similar in UFC and JC with an average flow reduction of 59% and 66%, respectively, and average t^* of 20 days for both watersheds (Table 5). Baseflow recession was much more rapid at UR with an average flow reduction of 196% and t^* of 8 days. Drought affects on baseflow were strongest in 2008 for UR and JC when mean daily temperature averaged 14 °C for 10 days, and <1 mm for rainfall was recorded. These watersheds have a larger portion of shallow lakes and DTLBs that would experience higher evaporative losses and complete drying, respectively, than might have occurred in UFC with many deep lakes and few DTLBs. In UFC, drought response was strongest in 2007 when mean daily temperature averaged 8 °C and little rainfall was recorded (Table 5).

Baseflow responses during drought conditions provide the basis for evaluating the likelihood of no flow conditions and spatial patterns of interrupted connectivity throughout drainage networks. Understanding the impacts of droughts on shrinkage of drainage density and the temporal and spatial dynamics of this process may allow development of a valuable framework for understanding fish migration and distribution patterns in Arctic watersheds. Such an analysis of stream-lake hydrologic connectivity was recently demonstrated for the Mackenzie River delta based on long-term monitoring records of lake outlets (Lesack and Marsh, 2010). Because

TABLE 5

Results of hydrograph analysis for the three study watersheds in the Fish Creek drainage area summarized by snowmelt, drought, and rain-event responses from 2007 to 2009 (*Tc* = time-to-peak, *Tlc* = hyetograph peak to hydrography peak, and *t = recession coefficient all in days; *Qpk* is runoff peak, *Qo* is pre-event discharge, *Qi* = initial discharge, *Qf* = final discharge, *MF* = mean flow).**

Year	Upper Fish				Judy				Ublutuoch			
					Snowmelt Peakflow and Recession							
	Date	*Tc*	*Qpk/MF*	*t**	Date	*Tc*	*Qpk/MF*	*t**	Date	*Tc*	*Qpk/MF*	*t**
2007	10-Jun	18	8.8	12.3	5-Jun	12	21.0	5.3	5-Jun	5	18.7	6.4
2008	6-Jun	16	8.0	12.9	29-May	8	12.7	8.6	29-May	7	12.4	9.2
2009	3-Jun	19	5.7	16.1	2-Jun	16	6.9	9.3	2-Jun	16	9.0	7.7
					Drought Period							
	Period of Drought		*Qi/Qf*	*t**	Period of Drought		*Qi/Qf*	*t**	Period of Drought		*Qi/Qf*	*t**
2007	17-Jul to 24-Jul		1.6	18.2	17-Jul to 24-Jul		1.6	21.1	17-Jul to 24-Jul		2.4	10.2
2008	7-Jul to 16-Jul		1.6	18.8	7-Jul to 16-Jul		1.9	14.9	7-Jul to 16-Jul		3.4	7.3
2009	13-Jul to 22-Jul		1.5	22.8	13-Jul to 22-Jul		1.5	23.9	13-Jul to 22-Jul		3.1	7.8
					Rain Event							
	Date	*Tlc*	*Qpk/Qo*	*t**		*Tlc*	*Qpk/Qo*	*t**		*Tlc*	*Qpk/Qo*	*t**
2007	13-Aug	—	—	—		—	—	—		—	—	—
2008	4-Aug	1.3	1.1	24.5		3.7	1.5	16		—	—	—
2009	29-Aug	9.6	1.4	34.7		6.1	6.6	7.2		6.8	2.6	19.8

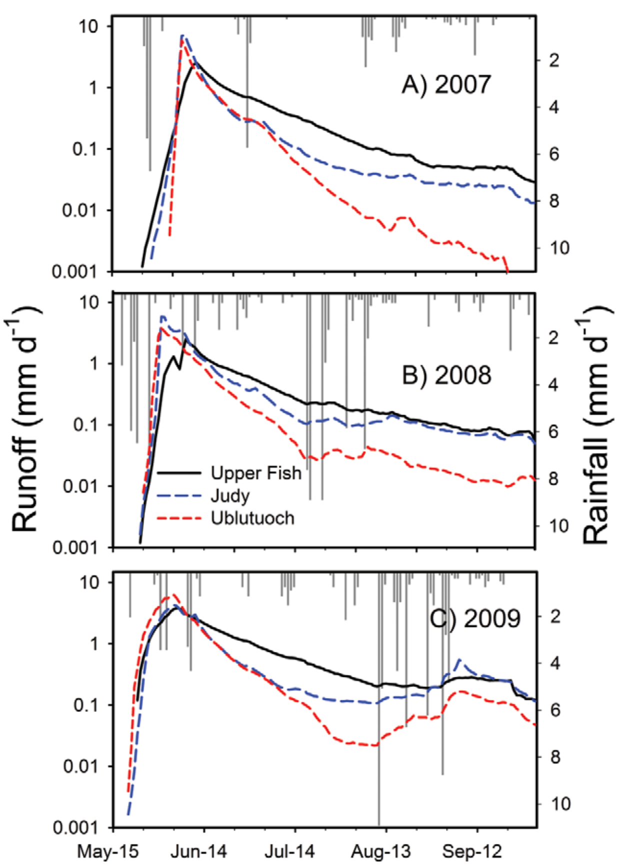

FIGURE 8. Runoff regimes and rainfall (mean daily values) for 2007 (A), 2008 (B), and 2009 (C) for each watershed in the Fish Creek drainage area.

most streams in the Fish Creek drainage basin initiate from lakes, important questions are whether certain lakes become hydraulically disconnected during drought conditions and how this may impact fish migration. Our analysis here also suggests greater storage in UFC for sustaining baseflow during brief drought periods than was observed for the other watersheds, but otherwise provides little information about the degree of connectivity within individual watersheds.

Runoff responses to rainfall events were difficult to detect in streamflow records for the Fish Creek watersheds, which is consistent with studies of other coastal plain streams with snowmelt-dominated runoff regimes that are generally subject only to low intensity and intermittent rain events (Roulet and Woo, 1986; Rovansek et al., 1996). For rainfall-runoff analysis, we selected the most intense rain event each summer with a preceding rain-free period such that recession response could be evaluated. In 2007, the only event meeting these criteria produced 1.1 mm over a 7-h period and no response was observed at any watershed gauging station. In 2008, a relatively strong weather system affecting much of the ACP (Arp et al., 2010) produced 6.7 mm of rainfall over an 18-h period with peak-flow responses detected in both the UFC and JC watersheds, but not UR (Table 5). The 2009 rainfall event analyzed was the largest within the 3-year observation period with 11 mm of rainfall over a 12-h period on 29 August and another event of 4.6 mm over a 10-h period on 31 August, the most isolated rain event available for analysis during this relatively wet summer. Flow peaks generated from this event were detected at all stations and runoff was slow to accumulate, with an average T_c of 7.5 days for all watersheds. Runoff responses, however, varied considerably among watersheds with a high peak of about 6 times baseflow with a quick recession (*t** of 7 days) at JC, a moderate peak of about 2 times baseflow with moderate recession (*t** of 20 days) at UR, and small peak of 1.4 times baseflow with a very long recession (*t** of 35 days) at UFC (Table 5). For comparison, several storm events in the Upper Kuparuk and Kuparuk rivers analyzed in 1994 and 1995 had average t^* of 3.1 and 7.0 days, respectively (McNamara et al., 1998), about 3 to 5 times faster flow recession than in the Fish Creek watersheds. The lack of rain event responses seen in the Fish Creek watersheds are typical for the ACP due to low relief and high depression storage, but also due to generally low intensity rainfall patterns compared to North Slope foothills climate. However, the variable responses to rainfall observed among these watersheds also underscore the role that differing lake basin types (i.e., deep lakes, shallow lakes, and DTLB) play in contributing, storing, or attenuating runoff. The lack of rainfall response in the UR may be due to extensive DTLBs with large storage deficit in mid-summer that would need to be overcome before runoff can initiate. In contrast, rainfall at UFC with extensive lake area and fewer DTLB would likely cause immediate contribution of runoff to stream-connected lakes because storage deficit may be minimal during most summers.

Overall, comparisons of hydrographs and the results of hydrograph analysis among years helps confirm the pattern of higher baseflow and storage in UFC and lower baseflow and storage in UR with intermediate behavior at JC. During 2007, late summer baseflow recession was very rapid in the UR compared to 2008 and 2009 when July and August rains raised baseflow considerably (Fig. 8). The shape of the UFC hydrograph was very consistent among years (Fig. 8) with relatively small snowmelt peak flow, slow baseflow recession during drought periods, and minimal response to later summer rain events (Table 5). JC also showed moderate early baseflow recession in 2007, but more sustained flows late in the summer. Mid- and late-summer rainy periods in 2008 and 2009, respectively, produced higher and more rapid responses at JC than the other watersheds. It is very likely that some of this variation in JC is due runoff generated in the small but steeper headwaters that may have had different precipitation and snowmelt patterns and intensity not captured by the lower elevation weather stations.

LINKING WATERSHED STRUCTURE WITH HYDROLOGIC FUNCTION

To place our results on hydrologic behavior of these three lake-rich ACP watersheds into a broader landscape context, we compared snowmelt and baseflow recession coefficients (t^*) with four other North Slope watersheds with available discharge records from 2007 to 2009. These watersheds include the Kuparuk River (8107 km^2) that originates in the Brooks Range and flows to the Beaufort Sea, the Meade (4618 km^2) and Ikpikpuk (4395 km^2) Rivers that originate in the foothills and are gauged within the inner coastal plain, and the Putuligayuk River (471 km^2) that is entirely within the ACP. These basins have mean elevation and lake area extents that correspond well with mountain-to-ACP gradients (Fig. 9, part A). An analysis of nested watersheds of the Kuparuk Basin showed slower recession responses as storm-event t^* with increasing drainage area across 5 orders of magnitude (McNamara et al., 1998). Making a similar comparison across these Arctic Alaska watersheds including the three Fish Creek watersheds found no relationship between drainage area and either snowmelt and baseflow t^* (Fig. 9, part B), most likely because of the relatively small gradient in drainage area ($<$2 orders of magnitude) and also differing climate regimes and physiography among watersheds. Besides variation in hydrologic fluxes and topography, another important variable differentiating these watersheds is lake and wetland extent with ACP watersheds having $>$10% lake area extent and the larger, higher elevation watersheds having $<$5% lake area extent (Fig. 9, part A). Plotting total lake area extent instead of drainage area provided a reasonably good fit for both snowmelt and baseflow recession (Fig. 9, part C), suggesting that lake area explains a portion of how runoff processes vary across a diverse gradient of Arctic watersheds. Whether lake extent in this analysis directly represents the impact of depression storage on runoff characteristics or whether lake extent simply corresponds to different sets of interrelated watershed characteristics that differentiate ACP from foothills from mountain landscapes is uncertain, but warrants more thorough consideration and analysis.

The contributing source-area concept provides a fundamental framework for understanding watershed hydrologic connectivity and runoff behavior (Dunne et al., 1975; Spence, 2007) that is applicable to a wide range of watershed sizes and physiographic and climatic provinces. In ACP watersheds, the extreme seasonality in wetland extent is a well documented phenomena that controls watershed water balance and runoff (Roulet and Woo, 1988; Bowling et al., 2003). Interannual variability in ACP lake-area extent is also strongly tied to precipitation (Plug et al., 2008; Jones et al., 2009a) and evaporation (Roulet and Woo, 1988; Rovansek et al., 1996; Kane et al., 2008) regimes. Additionally, thermokarst lakes, which form in ice-rich permafrost and are the dominant lake type on the ACP and other Arctic landscapes, expand by shoreline erosion with detectable increases in surface area for individual lakes (Arp et al., 2011) and regionally (Smith et al., 2005) at decadal time scales. The same process of thermokarst lake expansion can also lead to catastrophic lake drainage (Brewer et al., 1993; Hinkel et al., 2007; Marsh et al., 2009), which over the Holocene has affected major portions of the ACP landscape (Hinkel et al., 2003) resulting in complex and dynamic storage and drainage networks that evolved during the Holocene and may have expanded and contracted on various time scales. Thus, the linkage between hydrologic behavior and lake area extent (Fig. 9, part C) might be strengthened considerably by accounting for seasonality and interannual variability of lake area extent, as well as lake and DTLB storage. Accounting for lake-basin change over longer periods of time may prove to be an essential predictor of future shifts in hydrologic connectivity and runoff behavior for the Arctic landscape.

Paleo-reconstructions of hydrologic change on Alaska's North Slope suggest several relatively brief periods of alluviation driven by warm, wet summers and degradation of permafrost by active-layer detachment and retrogressive thaw slides (Mann et al., 2010). Such Arctic watershed responses to climate change may dominate steeper environments, but what are the long-term responses to climate change that can be expected in low-relief ACP watersheds where lakes and other depression storage dominate runoff behavior? Research that identifies mechanisms of thermokarst lake expansion and drainage linked to historic climate reconstructions (Marsh et al., 2009; Arp et al., 2011; Jones et al., 2011) and future GCM predictions (Pohl et al., 2007) may provide an important basis for such understanding. Refining measurements and predictions of

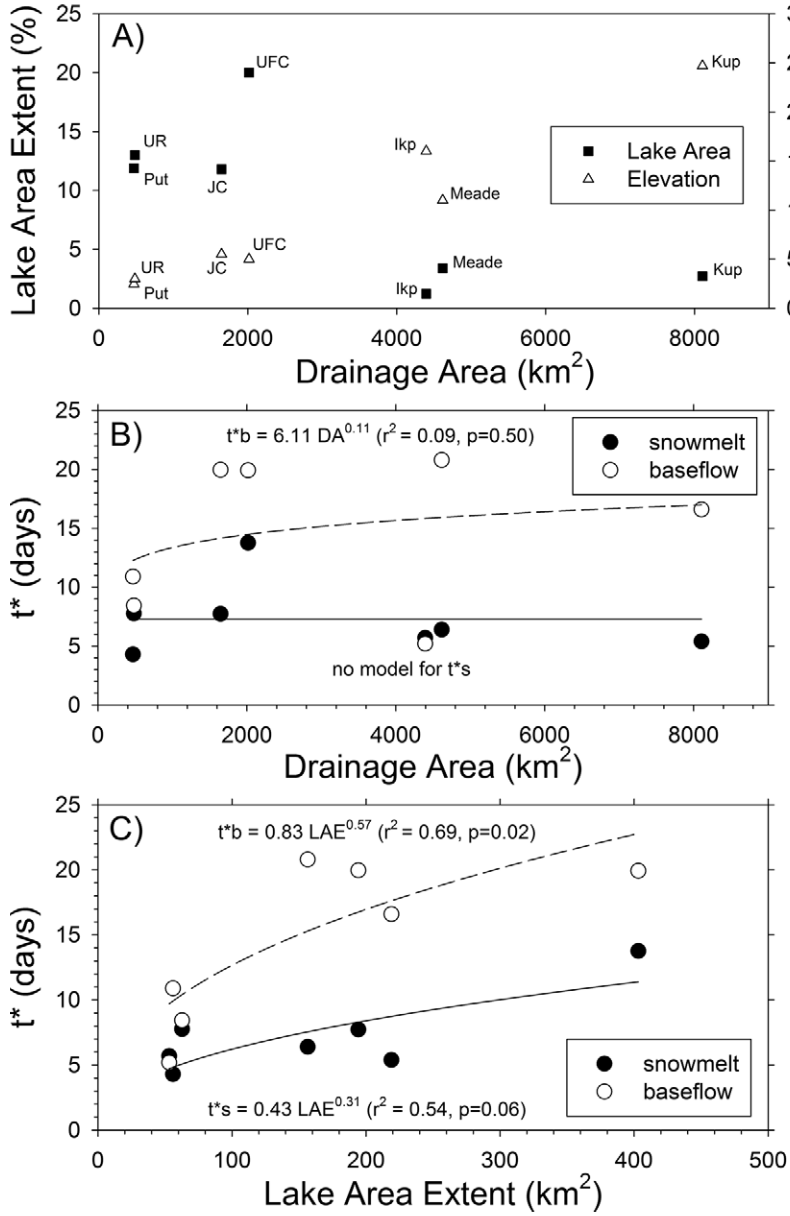

FIGURE 9. Comparison among major Alaskan Arctic Coastal Plain watersheds according to lake area, elevation, and size (A), recession coefficients (*t) and drainage area (B), and recession coefficients (*t**) and lake area extent (C) (UFC = Upper Fish Creek, JC = Judy Creek, UR = Ublutuoch River, Meade = Meade River, Ikp = Ikpikpuk River, Kup = Kuparuk River, and Put = Putuligayuk River).**

Arctic hydrologic intensification is a key aspect towards comprehending Arctic landscape responses to climate change (Rawlins et al., 2010), yet a more essential component maybe understanding land surface mechanisms that control drainage network structure and ultimately watershed function (Woo et al., 2008; McNamara and Kane, 2009).

Conclusions

We show the degree of variation in drainage network structure and hydrologic behavior in three adjacent watersheds within the Fish Creek drainage basin as a function of geologic gradients across the Alaskan ACP landscape. The transition from eolian sand to marine silt deposits corresponded with decreasing lake area and depth, increasing DTLB extent, and a higher proportion of beaded stream channels composing the drainage network. The majority of streams in these watersheds initiate from lake basins, approximately one-third of lakes are connected to the fluvial drainage network, and between 17 and 26% of watershed drainage density is through lake basins. This high and varied level of stream-lake connectivity most certainly plays a critical role in the distribution of aquatic ecosystems and fish communities across this landscape. The remaining two-thirds of lakes without observed perennial connectivity to the drainage network may also be connected, however briefly, during snowmelt and a better understanding of such ephemeral stream-lake connectivity and its role in aquatic ecosystems warrants higher resolution analysis.

As described in previous ACP studies, snowmelt runoff is a consistent and dominant hydrologic event in these watersheds, and runoff from rain events is minimal to undetectable. Differences in watershed storage were most evident by comparing watersheds of varying size and lake basin extent and from drought conditions in 2007 to wet conditions in 2009. The impact of 2007 on storage deficit was evident in 2008 snowmelt runoff and annual water yield, particularly in the larger watershed with the highest lake area extent, suggesting the importance of lake controls on runoff behavior. Rainfall runoff and drought responses were also affected by the proportion of the landscape covered by lakes relative to DTLBs. Comparison of both snowmelt and baseflow recession from a broader set of Alaskan North Slope watersheds showed little relationship to drainage area, but significant variation was accounted for by static lake area extent. Whether lake area extent directly controls variation in hydrologic regimes among these diverse watersheds or represents a suite of physiographic and climatic differences is uncertain, but deserves more careful analysis. The role of lake basins in Arctic watershed hydrology is particularly evident in light of dramatic landscape-scale changes in Arctic lakes that may be occurring due to both hydrologic intensification and thermokarst lake expansion and drainage. At smaller catchment scales in locations of intense industrial activity and winter water use, such as portions of the NPR-A, a better understanding of how lakes modify runoff regimes will also be essential for improved watershed management and accounting for impacts to downstream aquatic ecosystems.

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