Contrasting extreme runoff events in areas of continuous permafrost, Arctic Alaska

Douglas L. Kane, Larry D. Hinzman, Robert E. Gieck,
James P. McNamara, Emily K. Youcha and Jeffrey A. Oatley

ABSTRACT

Spring snowmelt floods in the Arctic are common and can be expected every year, mainly because of the extensive snow cover that ablates relatively quickly. However, documentation of extreme flows (both low and high) in the Arctic is lacking in part because extreme flows are relatively rare and gauging sites are very sparse, with most of short duration. In the nested Kuparuk River research watersheds on the North Slope of Alaska, two large summer floods have been observed (July 1999 and August 2002) in the headwaters; these high flows are contrasted to the low flows (drought conditions) observed in the summers of 2005 and 2007. It is clear that the continuous permafrost and the limited near-surface storage in the shallow active layer are responsible for both the high and low flow responses. Or, stated another way, the active layer is a poor buffer to both floods and droughts. When contrasting summer floods with snowmelt floods, it is clear from flood frequency analyses that the smaller, high-gradient headwater basins will be dominated by summer floods while those watersheds draining the low gradient coastal plain will be dominated by snowmelt floods. The two summer floods in the headwaters had flows that were three to four times greater than the largest measured snowmelt flood, while on the coastal plain the 2002 summer storm for the whole of the Kuparuk River only produced the maximum summer runoff of record that was about 1/4 of the maximum snowmelt flood. So, on the coastal plain and even for the Greater Kuparuk River that drains across the coastal plain, snowmelt floods dominate. Drought conditions prevail in summers when the limited surface water storage in the active layer and surface water bodies is depleted because evapotranspiration exceeds precipitation.

Key words | active layer, Alaska, Arctic, drought, floods, permafrost, runoff

Douglas L. Kane (corresponding author)
Robert E. Gieck
Emily K. Youcha
Water and Environmental Research Center,
University of Alaska Fairbanks,
Fairbanks, AK 99775,
USA
Tel.: +1 907 474 7808
Fax: +1 907 474 7979
E-mail: *ffdlk@uaf.edu*

Larry D. Hinzman
International Arctic Research Center,
University of Alaska Fairbanks,
Fairbanks, AK 99775,
USA

James P. McNamara
Department of Geosciences,
Boise State University,
Boise, ID 83725-1535,
USA

Jeffrey A. Oatley
Natural Resource Conservation Service,
USDA,
Fairbanks, AK 99709,
USA

INTRODUCTION

About 30–40% of the annual precipitation in the Alaskan Arctic occurs as snow during the winter months (7–9 months) and melts in 7–10 d any time between late April and the middle of June. It is common for the ablation to be interrupted by intermittent cold periods of a couple of days to several days. The runoff response primarily depends upon the snow water equivalent (SWE) of the snowpack and the pattern of ablation (sustained versus interrupted). On average, about two-thirds of the SWE leaves the catchments as runoff (Kane *et al.* 2000, 2004, 2008) and usually produces the maximum flood of the year.

Summer rainfall, on the other hand (or rain mixed with snow occasionally), accounts for the remainder of annual precipitation with an increasing trend of monthly precipitation from June through August. Snow is possible any day during the summer. The summer runoff response depends upon rainfall intensity and amount, plus antecedent soil moisture and precipitation. It is hypothesized that, for small

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and intermediate sized watersheds entirely contained in the Arctic, while most annual floods will be snowmelt-generated, the floods of record will be rainfall-generated (Kane *et al.* 2003). The exception to this hypothesis may be low gradient watersheds along the coast that lack any terrain to induce enhanced orographic precipitation like the Putuligayuk catchment on the North Slope of Alaska (Figure 1). However, snowmelt floods will always dominate large watersheds like the Ob, Lena, Yenisei and Mackenzie that extend far to the south into areas of no permafrost. The reasoning is that they are entirely snow covered at winter's end, but summer rainfall events only occur over a portion of these large basins. On a good day for ablation, 20–30 mm of meltwater can be released from the snowpack on optimum slopes and therefore not the entire watershed contributes at any given time (limited by available energy for melt). However, daily rainfall amounts can far exceed 30 mm (this depends upon the amount of moisture in atmosphere and cloud dynamics), particularly where orographic factors influence the amount of precipitation like the headwaters of the Kuparuk River.

With very few streams gauged in the Arctic, coupled with the lack of complementary hydrologic data (like precipitation, air temperature and soil moisture data), it is difficult to build a consensus for the circumpolar Arctic on hydrologic runoff response. There are a few documented precipitation events of significance in the Arctic. Thomas & Thompson (1962) reported on an extensive precipitation event in 1960 over the Canadian Arctic when 48 mm of precipitation fell at Mould Bay, Prince Patrick Island, NWT

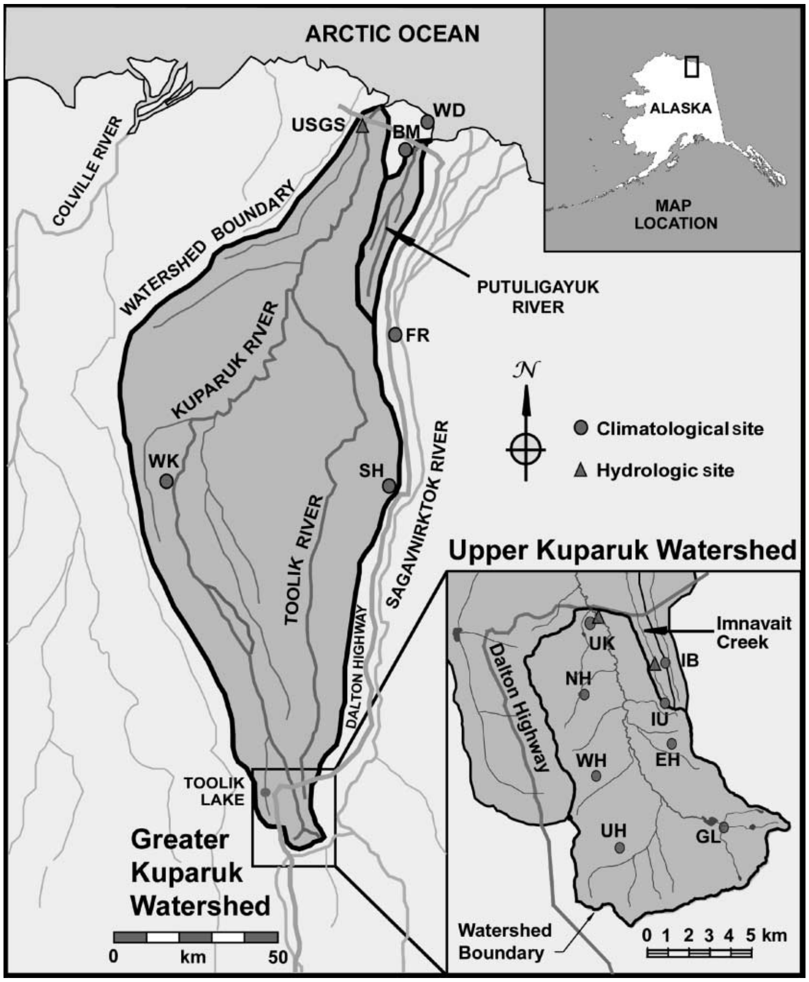

Figure 1 | Map of nested watersheds presently being studied with the location of various meteorological and hydrological measurement sites.

in a 24 h period. No runoff response was reported. The moisture arrived in this region by flowing along the eastern coast of Canada when driven by a low-pressure system centered over Hudson Bay. Cogley & McCann (1976) reported that 49 mm of rain fell on Vendom Fiord, Ellesmere Island, NWT on 22 July 1973. This storm appeared to arrive from the west and passed over several of the Queen Elizabeth Islands. Stage data was recorded on some streams; volume estimates of runoff were less than 10% of the precipitation. Kane *et al.* (2003) monitored the July 1999 flood, also on the Upper Kuparuk River, when in excess of 80 mm of rainfall fell in a 50 h period. Eight precipitation gauges recorded the spatial distribution of the rainfall over the Upper Kuparuk catchment. Continuous stage recording was made on the stream; 73% of the precipitation left the basin as runoff, the highest peak flow as of that date for the Upper Kuparuk River. Precipitation in the northern part of the entire Kuparuk basin was substantially less than in the headwaters.

There are indications that the Arctic is generally warming: how will this impact the annual precipitation pattern? Possible scenarios could be less snow and more rainfall due to longer summers and shorter winters, more extreme summer rainfall events, more extreme drought conditions and more frequent mid-winter melt or rain-on-snow events. We presently cannot confidently predict what this impact will be. There are at present large swings in the annual precipitation in this extreme environment; changes in the magnitude and timing of this hydrologic input could have very significant ecological impacts. This is a case study of both drought and flood conditions in an Arctic setting with continuous permafrost where floods mainly impact the stream channel and adjacent floodplain, while drought is pervasive throughout the watershed, impacting mainly the ecological system (vegetation, fish, etc.).

SETTING

In 1985, a study of a small watershed (Imnavait Creek, 2.2 km^2) was initiated on the North Slope of Alaska in the northern foothills of the Brooks Range (Figure 1). Gradually over the years three other watersheds were added to form a nested watershed study (Figure 1): Upper Kuparuk River (1993, 142 km^2), Kuparuk River (1993, 8,140 km^2) and Putuligayuk River (1999, 471 km^2). From the headwaters (Imnavait Creek and Upper Kuparuk catchments) there is a transition from small mountains and foothills (high to medium gradient) to the essentially flat coastal plain (low gradient). Imnavait Creek and the Upper Kuparuk River basins are representative of high gradient watersheds and the Putuligayuk River drainage of a low gradient watershed. The Kuparuk River basin is a combination of foothills and mountains (62%) and flat coastal plain (38%).

The area is treeless (except for some riparian areas with large shrubs and small trees) and underlain by continuous permafrost. Lakes (including shallow ponds and wetlands that can dry up during the summer) dominate the coastal plain landscape and the active layer reaches an average depth of thaw of about 50 cm in late August. Organic soils of varying depth (~20 cm) mantle mineral soils with alpine vegetation at higher elevations and tussock sedge tundra at lower elevations. Permafrost thickness varies from 250 m at the southern boundary to 600 m at the northern boundary. For more detailed information on these watersheds see Kane *et al.* (2000).

The hypsometric curves for the four nested streams monitored on the North Slope of Alaska are shown in Figure 2 along with the elevation of each meteorological

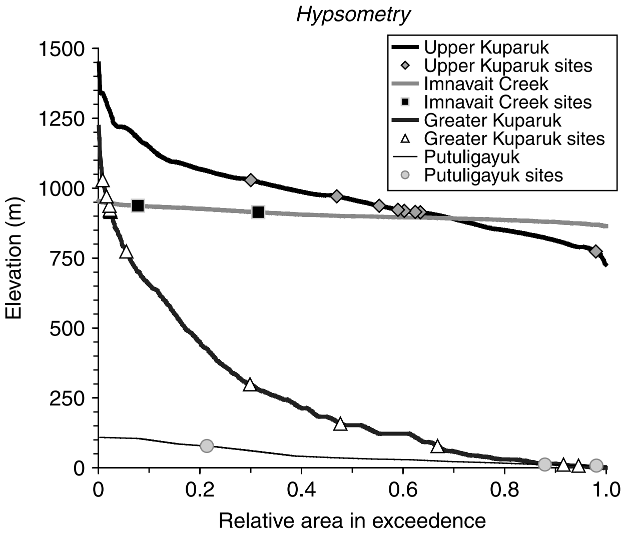

Figure 2 | Hypsometric curves for the four streams gauged on the North Slope of Alaska in and near the Kuparuk River basin, with the elevation location of precipitation gauges superimposed on the curves.

station that has a rain gauge in addition to other instrumentation.

STORM HYDROLOGY

Precipitation event

Low pressure systems laden with moisture do not presently develop in the Arctic because air masses are too cold and sources of water are limited. Also the pathways for moist air masses to reach the North Slope of Alaska are limited because of topographic barriers. The most likely pathway is for moist air from the Pacific Ocean to move northward between Russia and Alaska. In July 1999, a precipitation event (Figure 3(a)) took exactly this route and, once north of Alaska, it turned eastward and shortly after that it was pushed inland to the south where higher elevations prevail (Kane *et al.* 2003). In 2002, a similar storm provided substantial rainfall also mainly to the headwater basins. Both storms, that produced around 100 mm of precipitation, generated the two largest floods observed in these drainages. The distribution, over the headwater basins, of precipitation from the 10–17 August 2002 is shown in Figure 3(b). In 1999, the gauge at Green Cabin Lake (GL) experienced the greatest precipitation over the two watersheds; in 2002 the total precipitation at Green Cabin Lake was the lowest over the same area. The Green Cabin Lake gauge is tucked in at the base of the highest mountains in the Upper Kuparuk catchment.

For the Imnavait Creek meteorological station, the temporal distribution of the 110 mm of precipitation that fell at this site is shown (Figure 4) for the August 2002 event. The maximum intensity was 6 mm/h at the Imnavait meteorological station during the most intense period of the storm on the 15th. This can be compared with a maximum of 11.1 mm in one hour for the 1999 storm at the Imnavait meteorological station.

While most of the summer precipitation in the Alaskan Arctic comes as rain, snow is also common during this period. A plot of hourly precipitation and air temperature at one of the meteorological sites during the August 2002 storm shows that the air temperature was hovering around the freezing point, at or below in the early stages, above during the most intense middle part, and mostly below

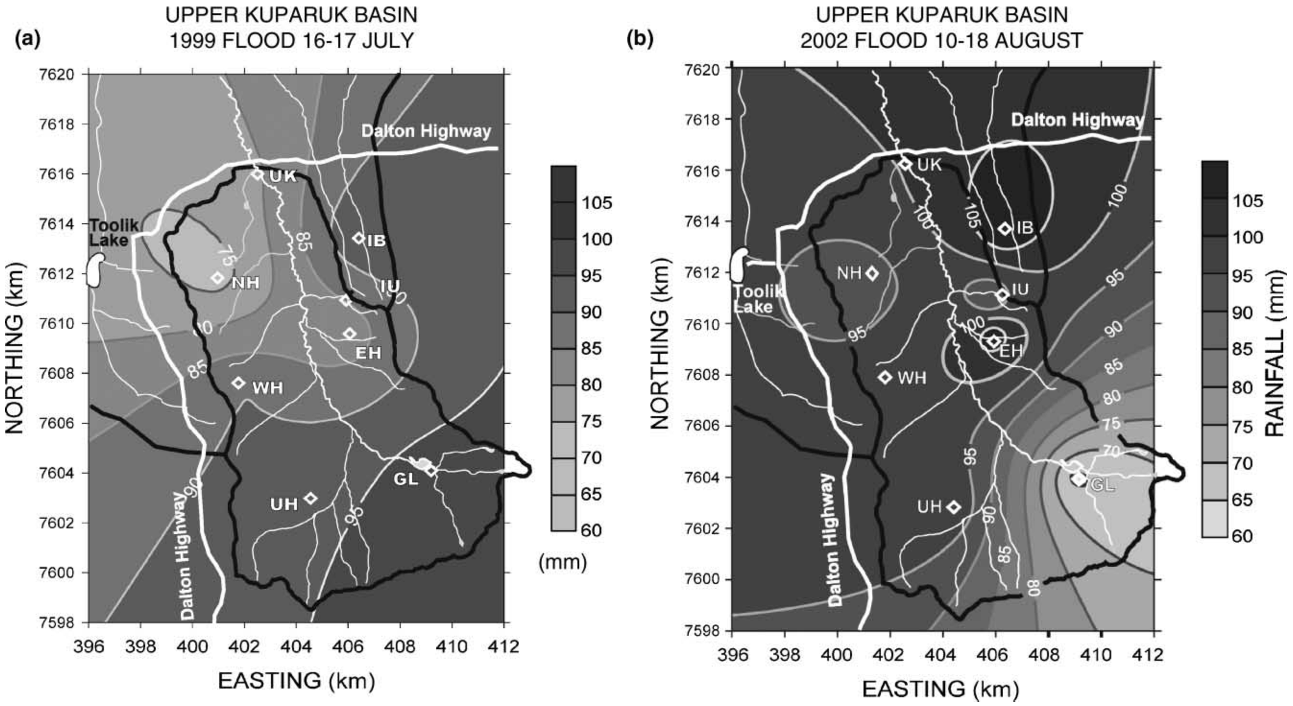

Figure 3 | Spatial distribution of total storm precipitation over the Upper Kuparuk and Imnavait catchments during the (a) July 1999 event and (b) August 2002 event. Diamonds represent the location of precipitation gauges.

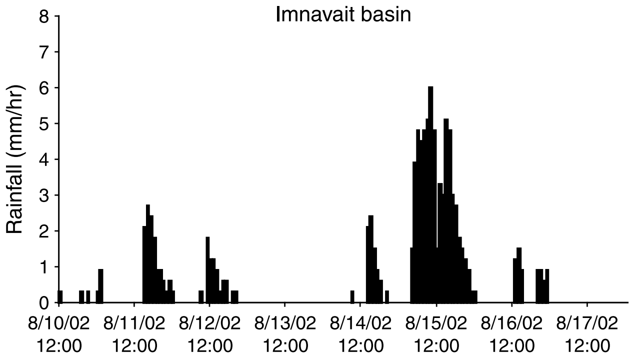

Figure 4 | Distribution of hourly precipitation at Imnavait Creek meteorological site during August 2002 storm (Alaska Standard Time). Almost all of the precipitation on 11, 12, 14 and after 16 August was snowfall.

freezing for the latter part of the storm (Figure 5). From a snow depth gauge that was operating over the summer in Imnavait Creek, it is clear that snow fell on three occasions: 10 August (depth of a few cm), late 11 August through early 13 August (tens of cm, snow seen on overflight on 14 August), and 16 and 17 August (a few cm). Observation by the lead author in a commercial jet on 14 August: "It looked like the area was in the middle of winter, except the lakes and rivers were all ice free". In the four days (11–14 August) preceding the majority of precipitation, approximately 27 mm water equivalent fell as snow and rain; this was followed by 55–60 mm during a 20 h period on 15 August. Another 20 mm or so fell during the period 16–20 August.

Caution should be used for the indicated timing of snow precipitation measured during this storm. The snow was very heavy and wet: the tipping bucket rain gauges caught most of the precipitation, but some of it probably did not melt until the temperature rose above freezing or solar radiation melted it. The initial snow on the ground melted because of stored heat in soil and plants. Snow on the ground also partially melted when rain started falling; as the air temperature was very close to freezing, there was very little heat associated with the rain. Condensation melt is more likely. Snow fell again at the tail end of the storm and persisted on the ground for many days after the storm.

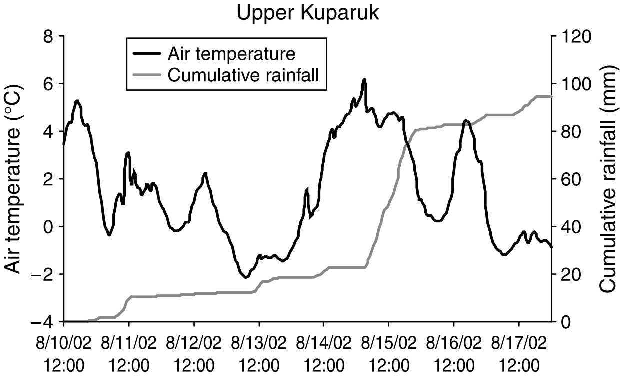

Figure 5 | Cumulative precipitation and air temperature distribution at Upper Kuparuk meteorological site during August 2002 storm (Alaska Standard Time). Snow fell during the periods that the air temperature was hovering around 0°C.

Thirteen rain gauges were located throughout the whole of the Kuparuk River basin at the time of the storm. Two are located in Imnavait Creek, six in the Upper Kuparuk watershed and five more in the northern segment of the Kuparuk River watershed. Three of these gauges are relatively close to the Putuligayuk catchment on the coastal plain. There were no additional gauges in neighboring watersheds at that time to the west or east of the Kuparuk watershed, so it is difficult to assess the areal extent of the storm other than reports of flooding where the Dalton Highway crosses numerous streams. Most of the detailed discussion in this paper will concentrate on the Upper Kuparuk River and Imnavait Creek where the storm was more intense.

Runoff response

All true Arctic catchments have a fairly significant runoff response to snowmelt; however, summer storm runoff responses are not generally impacted by the snowmelt hydrograph; this is the case here. Also, for precipitation events exceeding 12–15 mm, increased runoff is generally initiated in Imnavait Creek and Upper Kuparuk drainages (Kane *et al.* 1989), even for dry antecedent active layer conditions. This initial amount of precipitation goes into storage in the active layer. For the most part, these headwater basins have minimal surface storage, in contrast with the coastal plain. For a three-year period (1999–2001) during snowmelt for the Putuligayuk River on the coastal plain, 32, 30 and 37 mm were estimated to go into storage before runoff occurred (Bowling *et al.* 2003); these storage deficits resulted from evapotranspiration exceeding precipitation the previous summer. A large amount of this meltwater goes into storage in the extensive lakes, ponds and wetlands and the surrounding active layer.

Because of the shallow active layer, lack of storage in the high gradient headwaters and presence of areas with enhanced soil moisture (along water tracks), the runoff response is fairly rapid (McNamara *et al.* 1998). In this storm with temperatures near freezing, the initial precipitation was partly snowfall that also partially melted when it reached the ground. It appears from the gauges that 20–30 mm of precipitation fell over the watershed on the four days before the intense precipitation on 15 August. If about one-half of this was rain or melted, it would satisfy the typical storage (~15 mm) in the active layer. The fact that the streams reacted so fast to the intense precipitation on the 15th indicates that both Imnavait and Upper Kuparuk catchments were close to saturation.

The runoff response of the headwater catchments was impressive as both streams reached record high flows for the periods of observation. The flows were so high that both gauging stations received considerable damage. The stilling well on the Upper Kuparuk River washed away six hours after the peak flow. The data logger and memory module were recovered downstream buried in a gravel bar. We were able to extract all of the data from the memory module until the unit lost power when it toppled over in the stream. From our rating curve and also using indirect methods (also called the slope–area method) we were able to develop the complete runoff hydrograph.

Previous experience with selecting Manning's n values from the July 1999 flood (Kane *et al.* 2003) and the measurement of the water surface slope, hydraulic radius and cross-sectional area from high watermarks allowed us to estimate the peak Q. Manning's n in the channel was determined from high flow measurements of discharge with the channel near full. Since we did not have any values of the n factor in the tundra and shrubs on the bank of the floodplain, we estimated them from the results of other studies for both shrubs on the bank and the tundra (Barnes 1967; Arcement & Schneider 1984, 1989). Using our rating curve and recession values from previous storms, we were able to reconstruct an estimate of the entire hydrograph. The recession value was used to estimate the flow from 6 h after the peak (early in the morning of 16 August) to the time it was gauged again on 19 August. The peak flow was estimated at 120.8 m^3/s, or about 20% greater than the previous high flow in 1999. Today, it is still the largest runoff event after 15 years.

In 1985, a H-flume was installed on Imnavait Creek with wing walls extending out from the flume to ensure that flow did not go around the flume (particularly during snowmelt when slush flows along the main drainage are common). At the time that it was installed we had basically no idea of what flows could be expected. On several occasions, flows (both rain- and snow-generated) came close to exceeding the upper limit of the flume (~1 m^3/s). During this storm the flow exceeded the capacity of the flume (totally submerged) while part of the west wing wall was knocked down (with water flowing through the opening) and water was also flowing around both ends of the wing walls that extended out from the flume about 8–10 m on each side. From an abrupt change in the trend of the measured water stage, we can identify the time when part of the wing wall failed. We have occasionally lost our capabilities to measure the stage in the flume during snowmelt because of slush flows that impact the flume early in the runoff process. To guarantee that we have stage data immediately after slush flows (a period when the discharge is increasing very rapidly) we have a second stage recorder just upstream from the flume. The stage measurements at this site were continuous throughout the flood and a plot of the stage data with time showed no discontinuities (such as backwater effects or a drop in the water level when the wing wall failed). We used this stage data and again indirect methods using Manning's equation to develop a complete storm hydrograph. The peak flow was estimated to be 3.69 m^3/s.

For the four streams monitored in and adjacent to the Kuparuk River basin, the flows went from pre-flood flows to peak rates in the following manner: 0.0025 to 3.71 m^3/s (0.0011 to 54.6 $m^3/s/km^2$) for Imnavait Creek, 0.074 to 120.2 m^3/s (0.005 to 0.85 $m^3/s/km^2$) for Upper Kuparuk River, 10.1 to 951.4 m^3/s (0.0012 to 0.12 $m^3/s/km^2$) for the entire Kuparuk River and 0.94 to 5.44 m^3/s (0.002 to 0.012 $m^3/s/km^2$) for the Putuligayuk River. The increase in each case was by a factor of 1512, 1613, 94 and 5.8, respectively. Both the peak flows for Imnavait Creek and Upper Kuparuk were record flows (22 and 15 years, respectively, Figure 6). The peak flow for the entire Kuparuk (Figure 6) was the highest summer flow recorded over 37 years by the US Geological Survey (the previous high was 872 m^3/s in 1992). The fact that the flow in the Putuligayuk

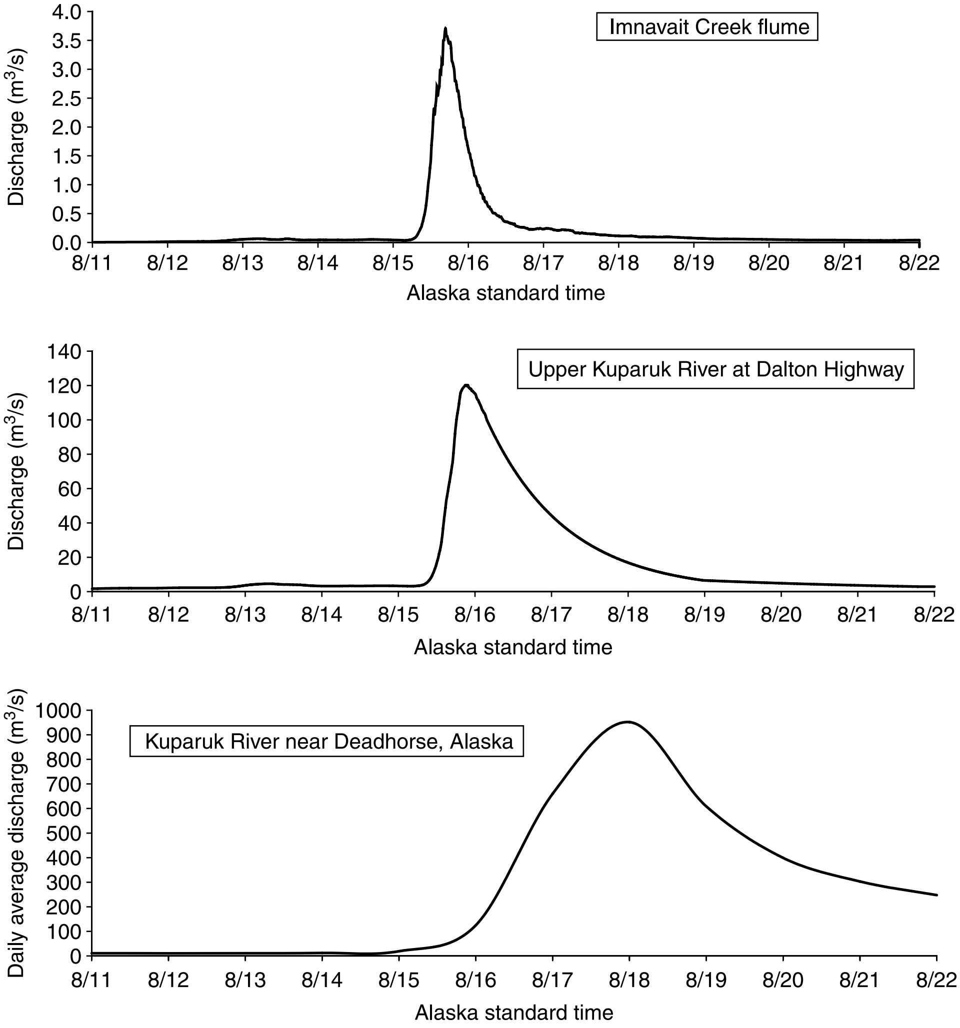

Figure 6 | Storm hydrographs progressing downstream for Imnavait Creek, Upper Kuparuk River and the entire Kuparuk River (gauged by the US Geological Survey), August 2002 (Alaska Standard Time).

River increased by a factor of 6 is impressive considering the past history of essentially no runoff response to summer precipitation for this low gradient coastal river.

DROUGHT HYDROLOGY

Contour plots of cumulative summer precipitation are shown (Figure 7) for an average summer, one of the wettest summers (2002) and two years (2005 and 2007) with low total summer precipitation over the Kuparuk and Putuligayuk basins (Figure 1). An average summer would have about 85 mm on the coast and increase to about 250 mm in the headwaters (Figure 7(a)). The extremes can be contrasted to these summer averages. In a wetter year along the coast (Figure 7(b)), almost 140 mm fell, while in a dry year (Figure 7(c)) just 50 mm and a very dry year (Figure 7(d)) only 15 mm. At the headwaters of the Kuparuk basin, the maximum summer precipitation has been in excess of 300 mm (1999), while the minimum summer precipitation is around 100 mm.

The partitioning of this wide-ranging summer precipitation into runoff and evapotranspiration (ET) depends upon many factors, the most important being the timing of precipitation. For example, in the dry 2005 summer runoff had reached record lows in the Upper Kuparuk by the end of June. However, in early July a large storm resulted in

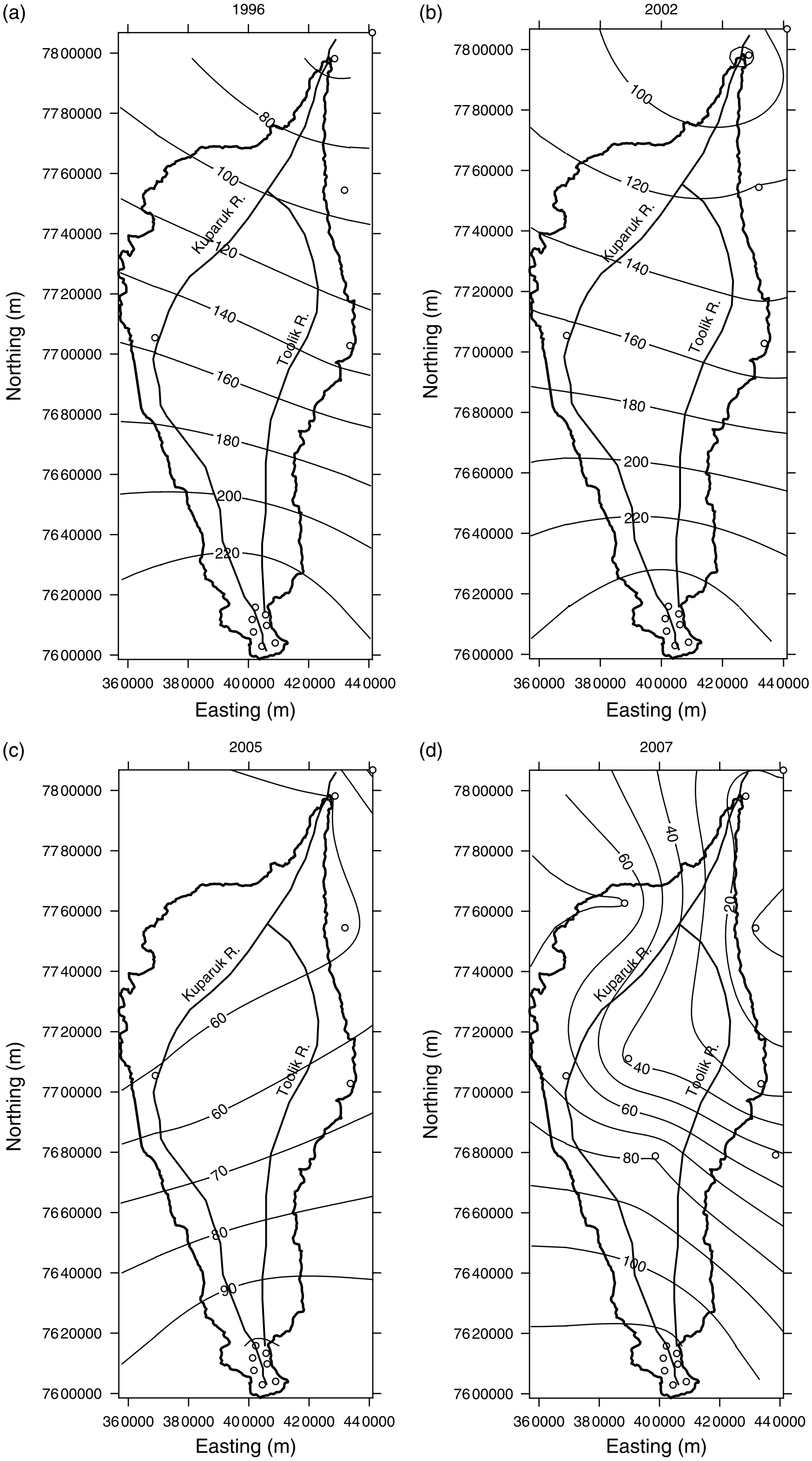

Figure 7 | Summer precipitation over the Greater Kuparuk River basin during (a) an average year, (b) a wet year, (c) a dry year and (d) a very dry year, especially in the northern part of the basin.

significant precipitation over the headwaters of the Kuparuk catchment that resulted in considerable runoff. This storm was followed by minimal precipitation during the remainder of the summer and flow recessed back to record lows. Had the precipitation from this event been more dispersed in time, most of the rainfall would have been returned to the atmosphere as ET and the runoff response would have been minimal.

In general, there is a trend of greater precipitation at higher elevations (Kane *et al.* 2000), particularly for the summer seasons. The general monthly pattern of summer precipitation is an increase from June through August and then a decline in September that continues into late winter. However, each summer month (June, July, August and September) has, for at least one of the years of record, been the wettest month.

Discharge in the streams during the summer months depends upon the timing and magnitude of summer precipitation. McNamara *et al.* (1998) described the typical summer runoff response of an Arctic stream as fast initial runoff response due to summer precipitation, long lag times between hyetograph and hydrograph centroids, an extended recession, low base flow due to lack of a deep groundwater system and high runoff/precipitation ratio. The continuous permafrost present here is primarily responsible for these odd runoff characteristics. Primarily the reduced storage in the watersheds due to the permafrost is responsible for both the peak and drought flows found in these basins. Recall that earlier it was reported that even after an extended period of time (~10 d) without summer precipitation, it only took about 15 mm to produce an increase in runoff. All of these watersheds (except summer for the Putuligayuk catchment) have high runoff ratios that range from 0.5 for summer rainfall events to higher values for snowmelt events (Kane *et al.* 2004, 2008) when compared with more temperate watersheds.

When the low flows are occurring due to the lack of precipitation, the amount of flow in the channel versus subsurface flow immediately beneath the channel depends upon the distribution of permafrost in the vicinity of the stream. For example, all through the summer of 2007, continuous flow occurred at our gauging site on the Upper Kuparuk River (142 km^2) and at the gauging site run by the US Geological Survey just upstream of the mouth at the Arctic Ocean (8140 km^2). However, there were several sections of the Kuparuk River that had no flow in the channel; this was true above the gauging site in the Upper Kuparuk and between the two gauges. At the end of the summer of 2007, the US Geological Survey reported the lowest end of summer stage at the Lower Kuparuk gauging site since it was installed in 1971.

FLOW FREQUENCY ANALYSES

Analyses of the annual flow extremes, both peak rainfall and snowmelt and low flow, were carried out for the four streams in this study. Methods used are those described in the report by the Interagency Advisory Committee on Water Data, Hydrology Subcommittee (1981). Traditionally these analyses are carried out to make predictions of flood magnitudes for various probabilities or return periods. Here we are using the Log-Pearson III method to compare the different mechanisms for runoff response of four Arctic drainages and to also compare flood conditions with those associated with drought. The estimated flows (flood and low flow) and the upper and lower confidence limits are shown. Clearly the hydrologic runoff response of a watershed will differ for an equal amount of precipitation input into a catchment from either snowmelt or rainfall (Waylen & Woo 1982).

First we will look at the probability of snowmelt and summer precipitation floods for Imnavait Creek (Figure 8(a)). No analysis of low flow probabilities is made for this small, headwater catchment (2.2 km^2) as the flows usually ceases at least once during the summer. When comparing the snowmelt ($n = 23$ years, Table 1(c)) and summer precipitation ($n = 22$, Table 1(c)) flood frequency results of the catchment runoff, it is clear that most of the smaller floods of high probability are snowmelt floods and the large floods of low probability are from summer precipitation storms (Figure 8(a)). The controlling factor here is that the amount of energy available for snowmelt is limiting; an examination of ablation curves for a 16 yr period (Kane *et al.* 2000) shows that the maximum slope of this curve is very similar most years. The other consideration is that for this region (headwaters), maximum rainfall rates can (and do) exceed maximum ablation rates. Note

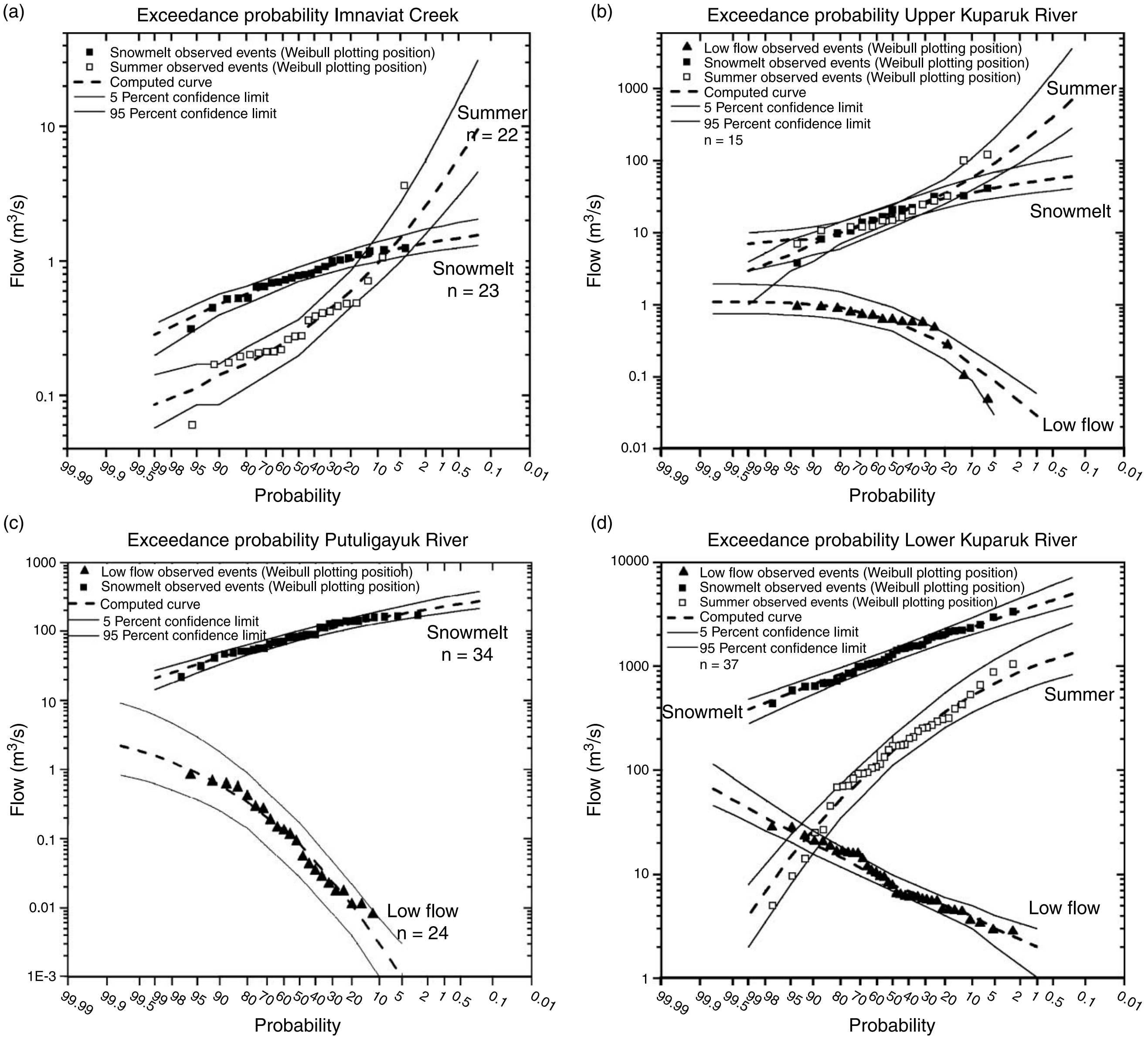

Figure 8 | (a) Flood frequency analyses for Imnavait Creek showing results for snowmelt and rainfall floods (no low flow analysis is shown as this small drainage ceases to flow during most of the summers); (b) Flood frequency analyses for the Upper Kuparuk River for high flows (both rain and snowmelt) and low flows; (c) Flow frequency analyses for snowmelt and summer low flows of the Putuligayuk River; no analysis of summer floods were performed because of the complete lack of them in this low gradient watershed; (d) Flow frequency analyses for the entire Kuparuk River, including snowmelt and summer high and low flows.

also that the sign of the coefficient of skewness changes between snowmelt and summer rainfall generated runoff events (Table 1(a)).

For the neighboring Upper Kuparuk catchment ($142\,\mathrm{km}^2$) we have 15 yr of runoff data that was initiated in 1993 (Table 1). The flow characteristics are quite similar to the Imnavait drainage, as the coefficient of skewness has similar signs for snowmelt and summer runoff (Figure 8(b)). Also, they show the same relationship for summer flow versus snowmelt; most annual floods are snowmelt and the floods of record are rainfall. At the Upper Kuparuk gauge we did determine low flow characteristics; at no time during the period of observation did the surface flow completely cease (although it did both upstream and downstream of the gauging site at least twice during the period of record). The shape of the low frequency curve shows that at high return

Table 1 | The period of record and length of flow measurements used in the flow analyses are shown in parts (b) and (c); part (a) gives the coefficient of skewness for each flow condition and stream

(a) Coefficient of skewness

Watershed	Coefficient of skewness, snow	Coefficient of skewness, rain	Coefficient of skewness, low flow
Imnavait Creek	−0.6683	1.0618	n/a
Upper Kuparuk River	−0.8423	1.3383	−1.988
Kuparuk River	−0.0958	−0.8314	0.1862
Putuligayuk River	−0.5065	n/a	−1.0339

(b) Number of events in analysis

Watershed	Number of events, snow	Number of events, summer	Number of events, low flow
Imnavait Creek	23	22	n/a
Upper Kuparuk River	15	15	15
Kuparuk River	37	37	37
Putuligayuk River	34	n/a	24

(c) Period of record in analyses

Watershed	Period of record, snow	Period of record, summer	Period of record, low flow
Imnavait Creek	1985–2007	1986–2007	n/a
Upper Kuparuk River	1993–2007	1993–2007	1993–2007
Kuparuk River	1971–2007	1971–2007	1971–2007
Putuligayuk River	1970–1980, 1982–1995, 1999–2007	n/a	1970–1979, 1982–1986, 1999–2007

periods (lower probabilities, $<1\%$) the flow is rapidly approaching no flow.

The third drainage, the low gradient Putuligayuk (471 km^2) on the coastal plain, is unique in that we do not have any summer floods that even come close to the snowmelt flood. So, we have only analyzed the snowmelt floods ($n = 34$) and the low flows ($n = 24$). The computed curve (Figure 8(c)) for the snowmelt has the same negative coefficient of skewness as the other drainages, indicating that the amount of energy available for snowmelt limits the snowmelt flood peak. This stream also has the propensity to cease flowing in the summer. This is essentially what happened late in the summer of 2007.

The Kuparuk basin (8120 km^2) gauged near the Arctic Ocean has somewhat different responses to peak flow (Figure 8(d)). It should be noted that this gauging site, operated by the US Geological Survey, is the longest continually operated site in Arctic Alaska ($n = 37$). First, the snowmelt runoff characteristics are similar to the three watersheds in that the coefficient of skewness is negative. However, that is where all similarity ends. Unlike Imnavait and Upper Kuparuk with positive values for rain-generated floods, the Kuparuk has a negative value for these summer floods. The other interesting feature is that the computed curve for the snowmelt floods is higher than that for the summer floods for all probabilities. There are several reasons for this but the main one is that, during snowmelt, the entire Kuparuk has the potential to contribute runoff while in the summer there is never significant rainfall over the entire basin (particularly the lower basin) to contribute to runoff. Finally, another distinguishing feature is that the sign of the coefficient of skewness for low flow is the opposite for both the Upper Kuparuk and Putuligayuk (note that no low flow determination was made for Imnavait) and resembles the typical recession curve.

SUMMARY

Long-term hydrologic monitoring in the Arctic is severely lacking: therefore flood estimates of low probability (high return periods) events have some uncertainty. Some of this uncertainty is due to the sparse, short duration and poor quality precipitation data we have in the Arctic. Collectively, the flow frequency analyses for the four streams portray a hydrologic response that is physically explainable, such as the sign of the coefficient of skewness. The flood frequency analyses of the two floods for the Upper Kuparuk River would indicate that these two floods had a return period in the 30–40 year range: recall that there are only 15 years of data for this stream. Both storms (1999 and 2002) also took essentially the same storm path from the Pacific Ocean to the North Slope of Alaska, probably the only route that will result in warm air masses capable of delivering significant amounts of precipitation. From measured runoff data, the ratio of the largest rainfall–runoff-generated flood to snowmelt-generated flood is about 4 for both Imnavait Creek and the Upper Kuparuk River. For the entire Kuparuk River basin this ratio is about $\frac{1}{4}$ or a factor of 16 times less than the headwater drainages. The Putuligayuk River, which is totally contained on the coastal plain, does not have any significant summer flows.

From the low flow frequency analyses, it is clear that these streams can have very low flows or even no flow, as observed in the summer of 2007. It was not expected that the stream would have alternating sections with and without flow; this highlights the fact that we do not truly understand permafrost distribution in the vicinity of the stream and that subsurface flow is more prevalent than thought. It is also clear that the concept of base flow has limited application in Arctic rivers, even for a river as large as the entire Kuparuk River.

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