Evidence of Hydrological Intensification and Regime Change From Northern Alaskan Watershed Runoff

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Key Points:
- Arctic Coastal Plain watershed runoff regimes are traditionally snowmelt-dominated
- Discharge records show increasing annual runoff over the past 19 years and much higher rainfall runoff contributions over the last 4 years
- Increasing ice-free ocean conditions correspond to higher rainfall runoff, yet attribution of hydrologic responses remain uncertain

Supporting Information:
- Supporting Information S1

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Abstract
Snowmelt-dominated runoff regimes have defined northern Alaskan rivers. Discharge records from three watersheds within the National Petroleum Reserve in Alaska (NPR-A) span 19 years and capture three notable periods of changing runoff. In the first, 2001–2008, mean annual runoff (MAR) averaged 90 mm, characterized by sharp snowmelt runoff and summer drought. Over the next 7 years, larger MAR averaged 120 mm driven by high and early snowmelt runoff. The most recent 4 years, 2016–2019, had even higher MAR of 163 mm with high and sustained late summer flows. Hydrograph analysis suggests a shift toward rainfall-dominated runoff in the most recent period compared to snowmelt-dominated hydrographs in the previous two. Declining sea ice appears closely linked to increasing late summer precipitation and a shift toward rainfall runoff. Future development in the NPR-A will require continued hydrological monitoring and planning to mitigate flood and erosion hazards, permafrost degradation, and ecosystem impairment.

Plain Language Summary
Water is expected to cycle more rapidly as the Arctic climate warms, yet it is uncertain whether conditions will get wetter or dryer. Watershed runoff, measured in the form of river flow, captures the balance of precipitation and evaporation over wide land areas to detect how the water cycle is changing. Historically, arctic river flows are supplied mainly by spring snowmelt and become quite low during summers with limited rainfall. River flow records from three watersheds in northern Alaska over the last 19 years provide evidence that total water inputs from snow and rain are increasing relative to water losses from evaporation. Most recently, contributions from rainfall have increased greatly, and this may be related to enhanced moisture supply from more ice-free conditions of the Arctic Ocean. Higher river flows that come later in the summer may affect erosion and sedimentation, frozen soils, fish habitat, and human infrastructure.

1. Introduction
Runoff from arctic coastal watersheds has long been characterized by a short season initiated by large snowmelt peakflows that decline rapidly to much lower runoff supplied by rainfall and storage in the active-layer and lake basins (Bowling et al., 2003; Kane & Yang, 2004; Marsh & Woo, 1981). Evapotranspiration (ET) can often exceed traditionally low rainfall amounts during the summer, leading to periods of extremely low flow and disconnectivity in smaller streams. While snowmelt-dominated runoff regimes and associated sharp peakflow events present hazards to infrastructure (Arp et al., 2020; Instanes et al., 2016), channel and floodplain soils are typically frozen and more resistant to erosion during this period (Beel et al., 2018; McNamara & Kane, 2009). Accordingly, most hydrologic monitoring programs have focused on capturing snowmelt runoff events relative to watershed snowpacks (Kane & Yang, 2004) with more recent interest in summer lowflows and effects on aquatic habitat connectivity relative to changing climate and expected intensification of the hydrologic cycle (Arp et al., 2019; Rawlins et al., 2010).

Large summer rainfall-runoff events are traditionally rare on the Arctic Coastal Plain of northern Alaska (ACP) (Kane et al., 2003) but are potentially most effective at moving sediment and reshaping channels (McNamara & Kane, 2009). Extreme rainfall-generated floods have occurred in arctic foothills watersheds, yet similar weather systems have failed to produce comparable responses in coastal watersheds (Kane et al., 2003). Coastal plain hydrological studies have focused on calculating watershed water balance from networks of intensive hydrometeorological stations, which are then compared to discharge records (Kane et al., 1991; Kane & Yang, 2004), suggesting that 60–80% of runoff typically comes from snowpack with
antecedent surface storage playing an important role in runoff efficiency from year to year (Bowling et al., 2003; Stuefer et al., 2017).

Research into source-water contribution to runoff events shows that old storage water can accompany snowmelt according to both graphical and chemical tracer end-member hydrograph separation techniques (McNamara et al., 1997). Using natural tracers in arctic systems, such as hydrogen and oxygen isotopes or specific conductance, is often challenging because of similarities between snow, active layer, and permafrost water signatures and high variability in storm-track rainfall signatures. Graphical hydrograph separation in temperate watersheds with continuous baseflow is often considered subjective in isolating stormwater from groundwater contributions (Sujono et al., 2004). However, in small- to medium-sized continuous permafrost watersheds where flow initiates almost entirely from snowmelt, the removal of groundwater baseflow simplifies graphical separation approaches, allowing for useful analyses of hydrographs from year to year and among basins (Woo et al., 2008). This assumption of minor groundwater contributions to early season flows may become less viable, however, as recent arctic hydrology models suggest increasing groundwater contributions to foothills watersheds (Rawlins et al., 2019; Zheng et al., 2019) and from coastal plain active layers (Connolly et al., 2020).

Arctic watersheds are increasingly sensitive to hydrologic intensification in response to both cold and warm season climate change that is predicted to drive higher snowfall and rainfall (Déry et al., 2009; Rawlins et al., 2010). Watersheds integrate meteoric fluxes over large areas as runoff. Evidence of higher overall runoff has gradually emerged from several watersheds with long-term runoff records in the Canadian (Beel et al., 2018; Déry et al., 2009), Siberian (Berezovskaya et al., 2004; Makarieva et al., 2019; Peterson et al., 2002), and Alaskan (Stuefer et al., 2017) Arctic. Coincident with hydrologic intensification may be a shift from snowmelt-dominated to rainfall-dominated runoff regimes (Instanes et al., 2016), a pattern already observed in many boreal and mountain watersheds (Aksamit & Whitman, 2017). In the Arctic, increasing open-ocean extents with declining sea ice should provide an additional source of rainfall (Bintanja & Andry, 2017; Bintanja & Selten, 2014) and force such a regime shift. Understanding if and to what extent such hydrologic changes are occurring in the ACP, and particularly the National Petroleum Reserve in Alaska (NPR-A) where development is extending into new terrain, will help inform better design of infrastructure and management of natural resources in the future.

2. Study Area and Methods

The Fish Creek Watershed (FCW) covers a 4,600 km² area entirely with the zone of continuous permafrost on the central ACP approximately equal distance between Prudhoe Bay to the east and Utqiagvik (formerly Barrow) to the west (Figure 1). Lands of this hydrologic unit are managed as part of the NPR-A. Three alluvial rivers drain the FCW, representing varying geologic, hypsographic, and lake basin compositions (Arp et al., 2012). Upper Fish Creek (2,016 km²) drains mostly tundra set atop inactive eolian sand dunes with many large deep lakes. Judy Creek (1,647 km²) has its headwaters in lower bedrock-controlled foothills, is very elongate, and has intermediate densities of lakes and drained lake basins. The Ublutuoch River (483 km²) has a beaded channel through much of its course running through alluvial-marine silt terrain with high densities of thermokarst lake basins.

Beginning in 2000, river gauging stations were established near the confluence of each of these three rivers within the FCW by the Bureau of Land Management (BLM) primarily in response to planned oil development (Whitman et al., 2011). Stations consist of vented pressure transducers that log and transmit in near real-time via GOES telemetry system (Figure S1 and Text S1 in the supporting information). Velocity-area discharge measurements have been consistently collected through a full range of flows over this 19-year period to develop and update rating curves to compute hydrographs. During ice-affected flows, records were interpolated to rated flow peaks aided with point discharge measurements and time-lapse camera images for each station. Ice-affected late season records were also interpolated to flow minima aided by time-lapse cameras, water temperature sensors, and air temperature data. A complete description of BLM gauging methods and rating curve development are provided as supplementary information (Text S1), and data are archived with the Arctic Data Center (Kemnitz et al., 2018). For reporting and comparison, river discharge records from this study were standardized by each catchment’s area as mean annual runoff (MAR in mm). Simple linear regression was used to analyze trends in MAR for the full record of each catchment.
Hydrograph analysis was performed on mean daily flow data for each catchment to identify snowmelt and rainfall peaks and corresponding peak flow recessions by fitting an exponential decay function from the peak to the next event (McNamara et al., 1998). A detailed description of graphical hydrograph separation is provided as supplementary information (Text S2 and Figure S2). Briefly, snowmelt- and rainfall-event recessions curves were used to separate these contributions as the high and early and low and late portion of the seasonal hydrograph, respectively, with baseflow storage contributions estimated as the portion of the hydrograph in between snowmelt and rainfall runoff (Figure S2 and Figure 2). Our analysis did not attempt to quantify any contributions from permafrost melt-water or subpermafrost groundwater separately, though we expect such contributions are primarily within the baseflow-storage portion of the hydrograph. Additionally, snowmelt runoff may be overestimated in some years using this approach due to undetectable rainfall events during the snowmelt runoff rise and recession. Sensitivity analysis on runoff recession coefficients (±1 standard error) was performed on a subset of hydrographs (Figure 2) to better understand the limitations and potential errors using this technique.

This 19-year discharge record was quantitatively separated into distinct periods to aid in analysis and summarizing results. Piecewise linear regression (Systat 13.0) of MAR over this period consistently and significantly ($r^2 = 0.53–0.59$, $p < 0.01$) segmented the records for all three watersheds between 2008 and 2009. Sequential Regime Shift Detection (SRSD) analysis (SRSD v6.2 in Excel) (Rodionov, 2004) was used to detect any changes in mean, variance, and correlation between MAR and runoff fractions, which consistently detected a shift between 2015 and 2016 for all three records in the proportion of rainfall runoff based on change in means ($p = 0.05$). Detecting a shift in means using this approach is sensitive to significance level $p$ and cutoff length $l$ (Rodionov, 2004), where using a lower level of significance ($p < 0.05$) or a longer cutoff length ($l > 4$) no longer detected this shift between 2015 and 2016 for these record. Based on piecewise regression and SRSD results, the 19-year record was compared and summarized for the periods 2001–2008, 2009–2015, and 2016–2019. To evaluate the relationship between open-water area in the Beaufort...
Sea relative to changes in FCW discharge records, mean monthly sea ice extent for August and September from 2001 to 2019 was acquired from the National Snow and Ice Data Center (NSIDC) as a sea ice index (Fetterer et al., 2017). Importing NSIDC-generated shapefiles in ArcGIS 10.5, we measured the open-water area for each month-year along a 100 km straightline length of shoreline centered and directly north of the FCW (Figure 1). These data are reported as average open-water distance from the coast by dividing polygon area by shoreline length.

3. Results and Discussion
MAR increased significantly in all three catchments from 2001 to 2019 (4.4–4.9 mm/yr, $r^2 = 0.38–0.43, p < 0.01$) despite very low runoff in 2007 and 2008 and relatively high runoff in 2004 (Figure 3). The lowest MAR was observed in the Ublutuoch River in 2007, 46 mm, which has entirely coastal plain drainage area, and the highest in the Judy Creek in 2019, 226 mm, which has headwaters reaching into the foothills (Figure 1). The largest catchment gauged, Upper Fish Creek at 2016 km$^2$ draining mostly eolian sand soils of the coastal plain with more and deeper lakes (Arp et al., 2012), had slightly higher average MAR of 119 mm over the entire 19-year record and lower interannual variability than the two smaller catchments. Interannual variation in MAR among the three catchments behaved coherently; average correlation among catchment runoff records was +0.91 ($p < 0.01$). Analysis of the longer and mostly overlapping record from the Putuligayuk River near Prudhoe Bay, a catchment similar in size to the Ublutuoch River and also entirely coastal plain, ended in 2015, identified a similar set of years with contrasting runoff extremes (Stuefer et al., 2017). These longer-term results from the Putuligayuk River showed a significant increase in MAR from 78 mm/yr (averaged from the period 1970–1986) to 122 mm/yr (averaged from the period 1999–2015). Runoff records from the FCW extend an additional 4 years and capture runoff from a much larger portion of the ACP and from three independent gauges. Here, MAR over the most recent period, 2016–2019, averaged 163 mm compared to 120 mm, averaged from 2009–2015, and 90 mm, averaged from 2001–2008 (Table 1).

Annual peak discharge in all three catchments over the period of record was almost always snowmelt driven and occurred around 5 June on average and ranged from 22 May in 2002 and 2015, Ublutuoch River and Judy Creek, respectively, to 25 June in 2018, Upper Fish Creek. No significant trend in peakflow magnitude or timing was noted over this 19-year record. The highest flows on record occurred in 2010 when Judy Creek's mean daily discharge peaked at 246 m$^3$/s and the Ublutuoch River's mean daily discharge peaked at 91 m$^3$/s. The lowest peakflows occurred in 2016 when Judy Creek only reached 97 m$^3$/s and the Ublutuoch River only reached 25 m$^3$/s. Upper Fish Creek also consistently had slower snowmelt recession flows than Judy Creek or the Ublutuoch River over this 19-year record; a pattern also noted by Arp et al. (2012) and attributed to higher density of deep lakes.

In 2016, 2017, and 2018, several late summer rainfall peakflows approached 50% of snowmelt peakflows generated in the same year—still far from observations of rainstorm-driven peak flows that have occasionally exceeded snowmelt peaks in arctic foothills watersheds (Kane et al., 2003). In the most recent runoff season of 2019, a 22-mm rainfall event recorded in the lower watershed in late August generated a storm peak of 154 m$^3$/s at Judy Creek that exceeded its snowmelt peakflow of 134 m$^3$/s earlier that season. The other two catchments also generated very high rainfall peaks from this storm but did not exceed snowmelt runoff magnitudes. The steep and elongate nature of the Judy Creek's catchment that stretches into the foothills may have contributed to this higher magnitude rainfall response, though variation in rainstorm distribution amount and intensity over the 4,600 km$^2$ FCW area was also just as likely.

Figure 2. Examples of hydrograph separation for the Upper Fish Creek Watershed in 2007 (a), 2012 (b), and 2017 (c) representing years of contrasting runoff regimes and increasing rainfall-runoff contribution (hydrograph partition results are in parentheses including standard errors).
Hydrograph separation results suggest that snowmelt contributed 69% of total annual runoff averaged over the three catchments for the 19-year period, which is in the range typically reported for arctic watersheds (Kane & Yang, 2004). The highest snowmelt contributions among all three basins averaged 83% in 2008 and averaged as low as 40% in 2019. Rainfall runoff was estimated to contribute 19% of total annual runoff over the entire period, accounting for only 3% in 2007 and up to 51% in 2017 (Figure 2). Rainfall records from a station set lower in the FCW at the Upper Fish Creek gauge (Figure 1 and Figure S1) also showed very low total rainfall in 2007, 22 mm, and much higher rainfall in 2017, 140 mm. Estimated baseflow storage runoff averaged 12% of total runoff over the entire 19-year record with no significant trend. Storage contributions to runoff tended to be lower during years with higher rainfall runoff contributions, suggesting more storage recharge in these years and more storage discharge in years with lower rainfall runoff. This pattern of shifting storage excess and deficit follows results from process studies of other lake-rich watershed on the ACP (Bowling et al., 2003).

Comparing composite (all three catchments) runoff records together over 19 years suggests three periods with distinctive flow regimes based on quantitative breakpoint and regime shift analysis (Rodionov, 2004). The period from 2001 to 2008 had lower overall runoff driven in part by drought conditions in 2007 (Arp et al., 2012). Snowmelt peak discharge during this period was moderate in magnitude and timing compared to the next two periods (Table 1). Hydrograph separation results suggest snowmelt contributed 74% of runoff, rainfall contributed 13%, and storage another 13% on average over this earliest 8-year period. The middle 7 years (2009–2015) appeared distinct because of 30% higher MAR (120 mm on average) than the previous period. This increase in MAR was primarily driven by higher snowmelt peakflows, averaging 107 m³/s, compared to snowmelt peakflows of 82 m³/s averaged over the earlier and later periods across catchments (Table 1). Snowmelt and rainfall runoff contributions during the 2009–2015 period were similar to the previous 2001–2008 period, as were summer rainfall totals, though more rainfall was observed during the late summer (August–September) in this middle period compared to the first (Table 1).

Table 1
Hydrologic, Climatic, and Sea Ice Data Summarized Relevant to the Fish Creek Watershed According to Distinct Periods With Differing Patterns of Discharge and Runoff Contributions

| Variable                          | 2001–2008 | 2009–2015 | 2016–2019 |
|-----------------------------------|-----------|-----------|-----------|
| Mean annual runoff (mm)           | 90 ± 29   | 120 ± 26  | 163 ± 42  |
| Annual peak discharge (cms)       | 87 ± 42   | 107 ± 54  | 80 ± 36   |
| Time of peak discharge            | 6-Jun ± 6 | 4-Jun ± 7 | 6-Jun ± 12|
| Annual flow duration (days)       | 150 ± 32  | 187 ± 15  | 177 ± 30  |
| Annual # of rainfall peaks        | 4 ± 2     | 4 ± 2     | 6 ± 1     |
| Snowmelt runoff (%)               | 74.2 ± 9.7| 75.5 ± 6.8| 47.1 ± 7.5|
| Storage runoff (%)                | 12.6 ± 7.4| 11.3 ± 4.4| 13.8 ± 6.8|
| Rainfall runoff (%)               | 13.3 ± 8.2| 13.3 ± 4.3| 39.1 ± 10.2|
| Annual rainfalla (mm)             | 69 ± 24   | 72 ± 29   | 136 ± 23  |
| Seasonal rainfalla (Aug–Sep, mm)  | 28 ± 16   | 41 ± 22   | 84 ± 15   |
| Mean air temperature (Aug–Sep, °C)| 6.8 ± 2.2 | 6.3 ± 1.1 | 6.1 ± 1.3 |
| Open-ocean extentb (km)           | 360 ± 240 | 536 ± 201 | 746 ± 141 |

Note. All values are averaged across three study catchments with reported standard deviations.  
*Record only spans from 2003 to 2019.  
*bData from NSIDC Sea Ice Index averaged for August and September.
The last runoff period identified, 2016–2019, is shorter in comparison to the previous two but had distinctly higher rainfall runoff contributions, 48% on average, and corresponding higher rainfall totals, 136 mm. The majority of this additional rainfall was recorded during the late summer, which was twice as high, on average, compared to the previous two periods (Table 1). Snowmelt peakflows were lower in this last period, 76 m³/s on average over the three catchments, and also slightly later on average. Late summer temperature was also slightly cooler during these last 4 years in comparison the previous record (Table 1), likely corresponding to lower ET losses as well and contributing to higher runoff. Stuefer et al. (2017) also identified a very recent pattern of higher runoff for a much longer ACP watershed record (Putuligayuk River), which terminated in 2015 and was already suggestive of hydrologic intensification through increasing runoff and variability. Our analyses that extends to 2019 shows even wetter, more rainfall-dominated conditions, leading to what we see as mounting evidence of hydrologic intensification and even a hydrologic regime shift for ACP rivers in northern Alaska. A longer period of rainfall-dominated runoff response is needed to evaluate a hydrologic regime shift with more certainty. Arctic discharge records are notoriously challenging to maintain long term for making important assessments of system changes (Bring et al., 2017), yet we are hopeful that support for such programs as river gauging in the NPR-A continues.

The most wide-scale and striking arctic response to warming climate is decreasing sea ice extent and much larger extents of open-water persisting into late fall (Serreze & Barry, 2011; Wendler et al., 2014), which is expected to supply enhanced moisture to the terrestrial hydrologic cycle (Bintanja & Selten, 2014). To evaluate this potential linkage to observed runoff changes in this study, we compared the extent of ice-free open ocean north of the FCW in August and September from sea ice concentration data sets (Fetterer et al., 2017). Over the same three periods of increasing runoff identified in this study, open-water extent also increased from 360 km in the 2001–2008 period to 536 km in the 2009–2015 period and to 746 km in the 2016–2019 period (Table 1). Late summer rainfall, which may have been partially marine-sourced depending on storm tracks, followed this increase in open-water ocean north of our study watersheds (Figure 4). This correlation is suggestive of enhanced ocean moisture supply fueling higher terrestrial rainfall as has been predicted (Bintanja & Andry, 2017; Bintanja & Selten, 2014). Whether from marine or inland tracking storms, this increasing late summer rainfall certainly corresponded to observed higher late season runoff over these three periods (Figure 4b). Perhaps more importantly, this analysis suggests higher rainfall runoff efficiency in this most recent period. Consecutive years of higher runoff should be fully recharging active-layer, lake, and wetland storage zones and allowing higher runoff ratios over this period, as has been intermittently observed in arctic watersheds following unusually wet seasons with diminished storage deficit (Bowling et al., 2003; Stuefer et al., 2017). Enhanced runoff efficiency of low-gradient hydrologic systems may be a key outcome of watershed responses to hydrologic intensification driven by sea ice decline in the Arctic.

Warming temperatures and hydrologic intensification in arctic coastal watersheds is expected to result in both enhanced precipitation (P) and ET, making runoff outcomes less certain (Rawlins et al., 2010). A key issue when evaluating changing meteoric fluxes in the Arctic is the sparsity and representativeness of weather stations that capture these fluxes. Watershed runoff integrates P-ET over large areas, which helps even out spatial heterogeneity of snowpacks and rainfall events typically represented by snow survey and weather station data, respectively. This underscores the efficiency of gauging rivers draining moderate sized watershed units (100–10,000 km²) as an effective means to observe changes in the Arctic hydrologic cycle.
Such river discharge records are additionally relevant to both hazard and habitat assessment. Several analyses of even larger arctic watersheds also show increasing runoff contributions (Déry et al., 2009; Makarieva et al., 2019; Peterson et al., 2002), though attribution of changing fluxes and water sources often remains uncertain. Results from this study suggest that increasing late summer rainfall and enhanced runoff efficiency is a primary driver in NPR-A watersheds. Moisture supply from larger and more persistent open-water areas of the Beaufort Sea are likely partially responsible for this large-scale watershed response and the emergence of a new flow regime for arctic rivers. Permafrost degradation and its contribution to total water yield and runoff timing through ground-ice melt and altered flowpaths are also a distinct consideration, where enhanced rainfall runoff may exacerbate permafrost thaw and generate even higher runoff.

4. Conclusions and Implications

Snowmelt-driven flow regimes have been a defining characteristic of many arctic watersheds. This dominant hydrologic pattern has formed the basis for planning, designing, and maintaining infrastructure, resource management, municipal and industrial operations, and understanding how ecosystems function in arctic coastal plains. The emergence of a rainfall-dominated hydrologic regime in the NPR-A, as evidenced by three independently gauged catchments, has implications for a range of social-ecological systems. The most immediate social-ecological impacts of higher late season river flows may be enhanced erosion of permafrost river channels, potential damage to riverside infrastructure, and alteration of subsistence resources and subsistence harvest practices. Rainfall-dominated hydrologic regimes are more common elsewhere, and thus human and ecosystem adaptation to this pattern has many examples. However, the rate of change that will drive landscape, river corridor, and ecosystem responses in the Arctic is uncertain. Adaptation will need to be proactive and dynamic to keep pace with the rapid shift in arctic coastal climates to a more maritime regime in which enhanced late season river flows, high lake levels, and saturated soil interact with already degrading permafrost landforms. Perhaps the most obvious form of adaptation may be in design and placement of new infrastructure relative to river channels, which is directly relevant to eminent expansion of petroleum extraction facilities in the NPR-A. Predicting how current and future freshwater fisheries resources respond to changing hydrology may be more challenging but perhaps more important to social-ecological sustainability in this region. Farsighted programs of consistent environmental monitoring, such as BLM's hydrologic monitoring program in the NPR-A, are providing reliable long-term data to understand such complex changes. Policy makers, land managers, and other stakeholders in the FCW and ACP should be aware of these valuable programs and ensure their continuance in the future.

Data Availability Statement

Data sets for this research are available in these in-text data citation references: Kemnitz et al., 2018 (https://arcticdata.io/catalog/view/doi%3A10.18739%2FA2G44HIQ8W) and Fetterer et al., 2017 (https://nsidc.org/data/g02135).

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