Linking North Slope of Alaska climate, hydrology, and fish migration

Erica D. Betts and Douglas L. Kane

ABSTRACT

Arctic grayling (*Thymallus arcticus*) have a life-history strategy specifically adapted to the extreme climate of the North. These fish migrate to spawning grounds just after breakup in the spring, then migrate to feeding sites in early summer, and finally in the fall migrate back to their overwintering sites. The Kuparuk River is a perennial stream originating in the northern foothills of the Brooks Range on the North Slope of Alaska. Sections of the Kuparuk are periodically intermittent in that, during low flows in the system, these channel reaches appear dry. The flow varies between surface and subsurface in this permafrost-dominated environment, with subsurface flow being limited to the unfrozen thaw bulb around the stream. These dry reaches create a barrier to fish migration due to the lack of surface channel flow. The impacts of a warming Arctic may have implications for the partitioning of flow within the Kuparuk and consequently affect the ability of fish to move within the system at critical times. The timing and duration of these barriers are sporadic, occurring with almost equal probability throughout the summer, with fall dry spells creating the biggest impact on Arctic grayling fitness.

Key words | Alaska, Arctic grayling, fish migration, hyporheic flow, North Slope, overwintering

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INTRODUCTION

Climate change is expected to occur at a higher rate in the Arctic than in the lower latitudes (Prowse *et al.* 2006a). The Arctic Climate Impact Assessment found that the Arctic is experiencing a higher rate of climate warming, 0.09 versus the 0.06 °C/decade increase as averaged over the Northern Hemisphere (McBean *et al.* 2005), and that the projected mean annual temperature increase for the area north of 60 °N will be approximately twice the projected increase in the global mean annual temperature (Kattsov *et al.* 2005). The Arctic is already experiencing evidence of these changes as witnessed by changes in precipitation and rates of evapotranspiration (ET) (Hinzman *et al.* 2005; White *et al.* 2007).

A simple surface water balance is defined as precipitation (P) minus ET equals runoff plus storage. Precipitation minus evapotranspiration (P – ET) represents the net moisture input to the surface from the atmosphere (Walsh *et al.* 2005). Figure 1 shows the average surface water balance as measured at Imnavait Creek on the North Slope of Alaska and was recreated from data reported in Kane *et al.* (2004). This figure highlights the surface water deficit that exists in the system until sometime in mid to late summer. This pattern is typical of other Arctic watersheds that have low to negative values of P – ET in early to mid summer and then increase, becoming positive in late summer/early fall (Walsh *et al.* 2005). This measure of surface water balance (P – ET) has declined significantly in the Alaska Arctic between 1960 and 2001, resulting in a decrease in water availability with time (Hinzman *et al.* 2005). A change in water availability could impact the fitness of fish and wildlife species directly and/or through modifications to critical habitat. Although precipitation is expected to increase with climate change, this increase is expected to be smallest in the summer (Prowse *et al.* 2006b). When combined with an expected increase in ET, the future surface water balance could see a further decline.

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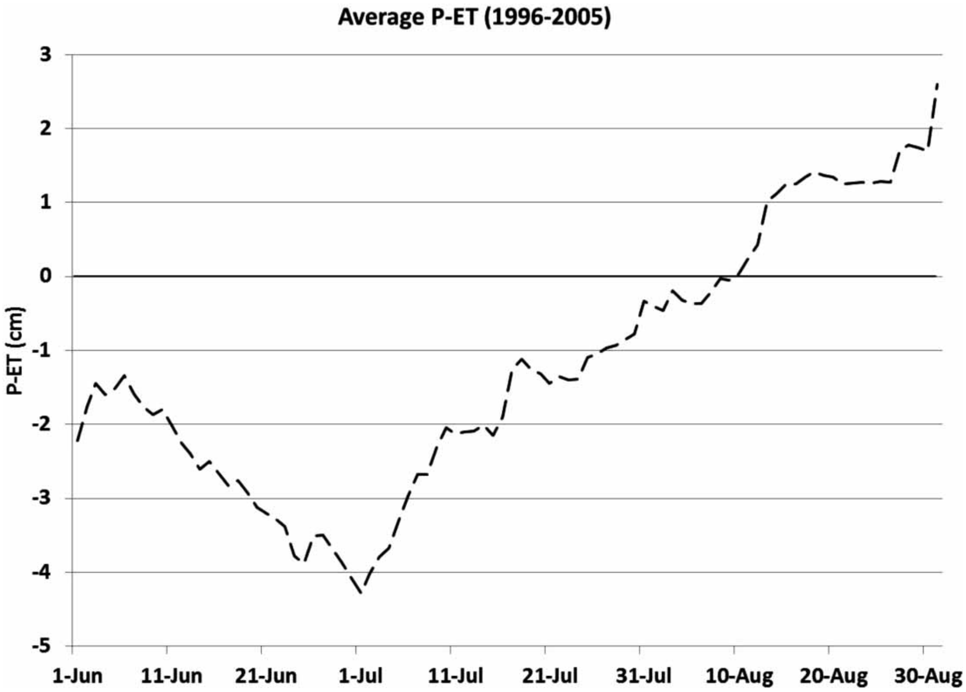

Figure 1 | Average surface water balance (P – ET) values as calculated from data collected at Imnavait Creek meteorological station, after snowmelt runoff (1996–2005). P – ET does not start at zero on 1 June, because P – ET was calculated for each year as soon as warm season measurements began each spring. The date 1 June was chosen as the start date because this is the earliest date that all years have data.

On the Alaska North Slope, hydrologic connectivity can be described seasonally in the following manner. After breakup, water levels are high, as an entire winter's worth of snow melts and flows across frozen surfaces in a period of 1–2 weeks, to overflow the banks of streams, lakes, and rivers. With long days and warm temperatures in the summer, ET can exceed P, leading to a general drying of the landscape (Hinzman & Kane 1992; Kane *et al.* 2008a). On the coastal plain, this drying leads to fragmentation of the drainage network (Bowling *et al.* 2003; Kane *et al.* 2008a) and results in a loss of hydrologic connectivity between smaller ponds, lakes, and streams and larger lakes and rivers. Connectivity may be re-established after strong enough rainfall events. In the fall, daylight hours decrease as do temperatures and ET rates. This typically results in a slight increase in water levels and brief re-establishment of connectivity before freeze-up.

The spatial extent of any barriers to connectivity that form on the landscape during the summer is not well understood. Bowling *et al.* (2003) show as much as a 73% reduction in inundated area over the course of a summer on the coastal plain of Alaska, with a minimum level of connectivity occurring in July and a slight increase in September. Many researchers have documented the occurrence of barriers to connectivity as a result of low or no flow in streams and rivers (Kane *et al.* 2008b), even documenting stranded fish due to such barriers (Morris 2003; Martin *et al.* 2009).

It is believed that flow occurs below the surface of the river through these critical sections during periods of low flow in the system. In areas underlain by continuous permafrost, there exists an area of unfrozen soil below the river. This thaw bulb varies in thickness depending on the time of the year, water temperature and type of substrate. Water can flow within a stream channel or beneath the channel within the thaw bulb. This subsurface flow does not generally penetrate into deep groundwater because of the permafrost layer below (Kane *et al.* 2013). The ground below streambeds also continually thaws during the summer, allowing additional water to flow below the surface in this thawed region. This subsurface flow, referred to as hyporheic flow, is not unique to the Arctic. Typically less than 100% of the surface water passes through the hyporheic zone (Boulton *et al.* 1998), but in these critical reaches, flow becomes 100% hyporheic. In these cases, the river bed appears dry, but upstream and downstream the river is flowing (Kane *et al.* 2008b). Because of the remote landscape of the Arctic and the ephemeral nature of this phenomenon, instances are not well documented in terms of spatial and temporal extent. This type of event may not typically be modeled in a routine hydrologic model, but for the purposes of fish migration, such an event is critical. Eyewitness accounts have placed these events as occurring when stream flows were at very low levels due to lack of precipitation (Kane *et al.* 2008b). Some research has been done on hyporheic flow in the Upper Kuparuk (Zarnetske *et al.* 2007, 2008), but the research sites studied did not include those sections that lose surface water flow.

The North Slope of Alaska encompasses the Alaska Arctic and stays below freezing for 8–9 months of the year, with temperatures as low as −60 °F, and up to 24 hours of darkness each day. Fish that live in this region have developed life-history strategies that allow them to either avoid these harsh winters by migrating elsewhere or find suitable refuge within the region (Wrona *et al.* 2014). A major limiting factor for fish species on the North Slope is the ability to find adequate overwintering habitat (Craig 1989). Overwintering sites consist of those waterways or bodies that do not freeze solid in winter and that have an adequate dissolved oxygen supply throughout the cold period. Craig (1989) concluded that fish lose 95% of their available habitat over the winter.

Arctic grayling (*Thymallus arcticus*) are a resident salmonid species found throughout the Arctic (Tack 1980). Resident species do not migrate out of the region during any portion of their life cycle. Arctic grayling is a subsistence species on the North Slope (Morris 2003) and has been the subject of long-term study in the Kuparuk River to assess the impact of increased nutrient availability on growth (Deegan & Peterson 1992; Golden & Deegan 1998; Deegan *et al.* 1999, 2011; Buzby & Deegan 2000, 2004). Breakup signals a major migration for grayling from their overwintering location to their spawning grounds (Bishop 1971; Morris 2003). Arctic grayling in the Upper Kuparuk leave their upstream overwintering site, Green Cabin Lake, when river flow resumes in the spring, and travel to spawning sites, which may be as far as 50 km downstream (Buzby & Deegan 2004). The spring migration involves a prespawning migration to the spawning area and includes both juvenile and adult grayling (Tack 1980). This migration occurs when rivers and streams are at or near flood stage. Once spring melt occurs, Arctic fish species must find suitable spawning and feeding grounds in order to reproduce and find enough food during the brief open-water season to sustain them through the next long winter. Arctic grayling in particular migrate to selected locations for spawning and then a different location for feeding, and then finally migrate back to an overwintering site for a total of three separate migrations during the warm season. Previous studies have shown that grayling may migrate up to 100 km from their overwintering site to their feeding grounds, even utilizing marine environments to migrate to adjacent freshwater systems (West *et al.* 1992; Morris 2003).

The research presented here examines how future changes in the climatic and hydrologic regimes of the Arctic may impact fish movement. Specifically, this research will assess the occurrence of barriers to fish migrating to overwintering sites.

STUDY AREA

The Upper Kuparuk is a 142 km^2 watershed located in the foothills of the Brooks Range on the North Slope of Alaska. This watershed has a stream length of 25 km and a basin length of 16 km (Kane *et al.* 2004); it is a headwater basin of the Kuparuk River, which drains directly to the Arctic Ocean 200 km to the north. Figure 2 shows the location of the watershed. It is situated in a region of continuous permafrost that is nearly 300 m thick (Osterkamp & Payne 1981). Subsurface flow is limited to the active layer, which is a shallow zone that undergoes seasonal freezing and thawing each year. Typical active layer thaw depths range from 25 to 50 cm, but can reach up to 100 cm depending on soil type, slope, aspect, and soil moisture (Hinzman *et al.* 1991). Stream gauging on the Upper Kuparuk began in 1993, with several weather stations added in 1996. Breakup or spring melt usually occurs in mid to late May in the Upper Kuparuk.

Thirty to forty percent of the annual precipitation in the Alaska Arctic occurs as snow in the winter and melts over a relatively short period in the spring (Kane *et al.* 2008b), thus ensuring the availability of considerable liquid water at the onset of the warm season. Data collected in the Upper Kuparuk River basin on the North Slope of Alaska between 1996 and 2011 showed an average summer precipitation of

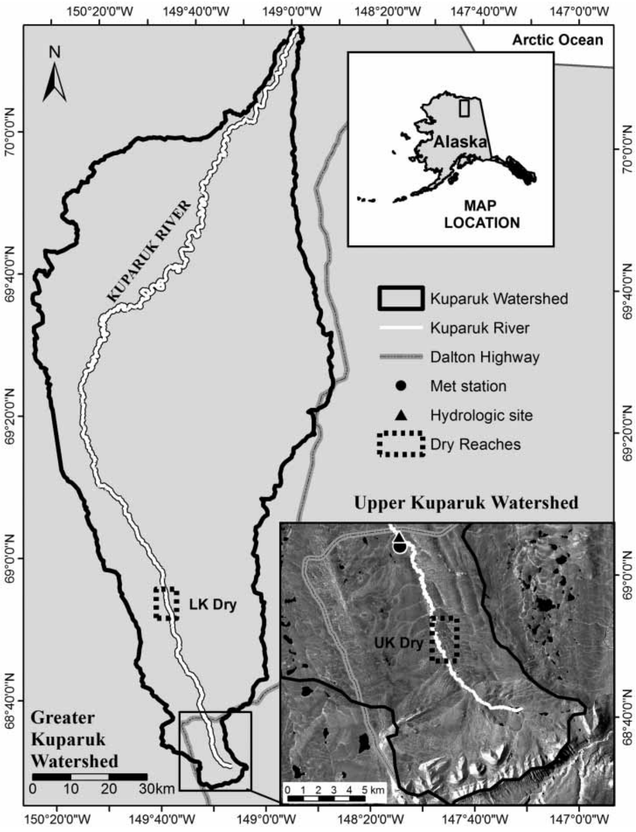

Figure 2 | Map showing the location of the Kuparuk watershed, North Slope of Alaska. Image shows the location of the Lower Kuparuk dry reach site (LK Dry), the Upper Kuparuk dry reach site (UK Dry), as well as the Upper Kuparuk meteorological station and stream gauging site.

approximately 214 mm and an average end-of-winter snow water equivalent value of near 107 mm (Kane *et al.* 2012). A study of two neighboring watersheds on the North Slope of Alaska estimated that 36–50% of the precipitation falling in the summer leaves through ET with variations attributed to differences in slope and vegetation between the watersheds studied (Kane *et al.* 2004).

The summer moisture regime of the active layer is closely tied to precipitation because the active layer has limited storage capacity (Hinzman & Kane 1992; McNamara *et al.* 1998) and potential for significant ET. Dry conditions during the summer require a certain amount of water to satisfy soil storage potential before runoff is generated (Hinzman & Kane 1992). Kane *et al.* (2004) determined that only 15 mm of summer precipitation was needed to initiate an increase in runoff rates in three arctic streams. Arctic watersheds typically have significant runoff response to snowmelt (Kane *et al.* 2008b), but the foothills location of the Upper Kuparuk combined with limited storage reservoirs leads to a high summer rainfall runoff response as well (Kane *et al.* 2004). A summer runoff event may exceed the peak flow of breakup. Kane *et al.* (2004) reported that over a 10-year period, the peak flood event was snowmelt-generated for five of those years, with rainfall-generated events responsible for the other half.

The Upper Kuparuk represents a simplified case for studying hydrologic connectivity in that connectivity is analyzed along the river itself as opposed to looking at the complex hydraulic linkages between a river and connecting ponds, lakes, and wetlands. Flow has not been recorded to cease completely at the Upper Kuparuk stream gauging site located 15 km downstream of the headwater lake, nor at the US Geological Survey gauging site near the mouth of the Kuparuk River.

METHODS

The first step in this research was to identify locations that may present barriers to fish migration. Critical reaches were identified as those sections of the Kuparuk River between the headwater lake and the main spawning ground 50 km downstream that run dry during periods of low flow in the summer. Interviews with researchers on the North Slope identified two locations along the Kuparuk. The two locations on the Kuparuk are referred to as the Lower Kuparuk and the Upper Kuparuk due to their relative upstream and downstream spatial positions. These critical reaches are identified in Figure 2. Figure 3 shows the Upper and Lower Kuparuk dry reaches during periods with surface flow and during dry periods. Once the general location of the critical reaches was established, pressure transducers were installed each spring from 2010 to 2012 and removed the following fall. Discharge measurements were taken periodically within these reaches, typically three times during the summer, as often as logistical restraints allowed. Aerial photography was obtained in 2010 using low-flying aircraft during a dry spell, which allowed for further identification of the exact location and length of these dry reaches. The Upper Kuparuk dry reach

Figure 3 | The upper left photograph shows the Lower Kuparuk site, looking downstream, during a dry spell and the upper right photograph shows the Lower Kuparuk site, looking across the channel, during high flows in the fall. The bottom left photograph shows the Upper Kuparuk site, looking upstream, during a dry spell and the bottom right photograph shows the Upper Kuparuk site, looking upstream, with surface flow in the fall.

measured 2 km in length, while the Lower Kuparuk dry reach measured over 8 km in length.

A stream gauging site with a stilling well is located on the Upper Kuparuk River just above the Dalton Highway bridge. Although stage data have been collected at this site since 1993, the stilling well was moved in 1996; thus, data collected before 1996 were not used in this analysis. Stage data are recorded from breakup in the spring until instrumentation is taken out before freezeup each fall. The exact dates vary slightly each year but typically run from 1 June to 10 September each year. The reference to summer values in the following section refers to this measurement period.

RESULTS

Stage data collected at critical reaches were compared with stage data collected at the long-term gauging site. A linear relationship was established between stage at each critical dry reach and stage at the gauging site on the Upper Kuparuk. The Upper Kuparuk dry reach site is 10 km upstream of the Upper Kuparuk stream gauging site. Daily stage data at the Upper Kuparuk stream gauging site significantly predicted Upper Kuparuk dry reach stage values collected in 2011 and 2012 with the null hypotheses failing at $p < 0.001$ (Figure 4). The Upper Kuparuk gauging site stage also explained a significant proportion of variance in the Upper Kuparuk dry reach stage, $R^2 = 0.86$. Data from 2010 were not used because placement of the pressure transducer was located just outside of the dry reach. This placement was corrected based on the aerial photography collected in 2010.

A similar process was used for the Lower Kuparuk dry reach site, which is 30 km downstream of the Upper Kuparuk stream gauging site. Although the relationship becomes less reliable as the distance between stations becomes greater, these sites are on the same stream and, therefore, are still likely to be closely related (Searcy 1960). The Upper Kuparuk gauging site stage significantly predicted the Lower Kuparuk dry reach stage values with the null hypothesis failing at $p < 0.001$ (Figure 5). The Upper

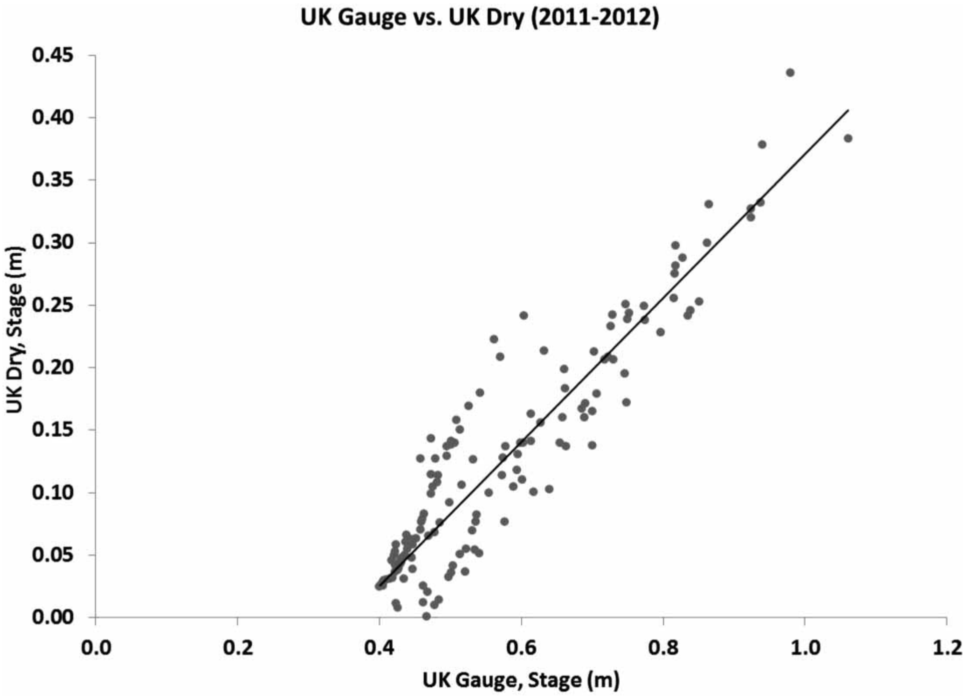

Figure 4 | Relationship between daily stage height data at the Upper Kuparuk dry reach site (UK Dry) and the Upper Kuparuk stream gauging site (UK Gauge).

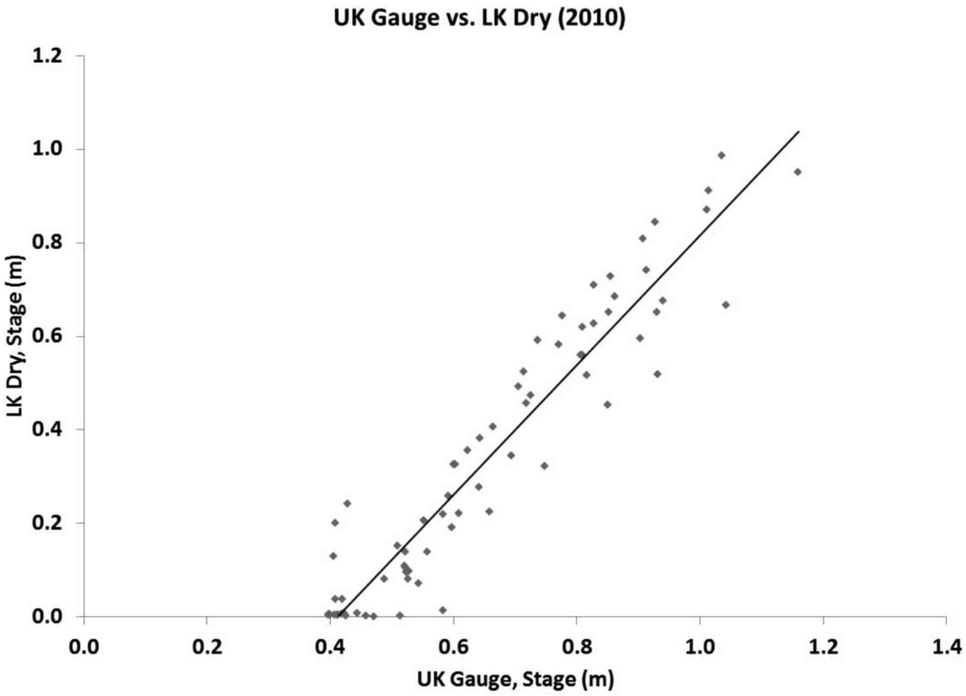

Figure 5 | Relationship between daily stage height data at the Lower Kuparuk dry reach site (LK Dry) and the Upper Kuparuk stream gauging site (UK Gauge).

Kuparuk gauging site stage also explained a significant proportion of the variance in the Lower Kuparuk dry reach stage, $R^2 = 0.90$. Data used for this relationship are from 2010. The pressure transducer installed at the Lower Kuparuk dry reach site was washed away by extremely large flows during spring breakup in 2011, and pressure transducer placement in 2012 occurred later in the season, so data do not represent the full open-water season. These relationships were then used to derive stage values at the critical reaches extending back to 1996. The results of this recreated historical data set are discussed below.

Stage duration curves were generated from daily stage values at the Upper Kuparuk stream gauging site and the Upper and Lower Kuparuk dry reach sites for the years 1996–2012 (Figure 6). The curves were generated using the total-period method described by Searcy (1959) for the creation of flow duration curves. Using this method, all stage values for the total period are sorted and ranked from largest to smallest value and exceedance probability is determined based on this ranked position. The stage duration curve represents the likelihood that a given water surface elevation will be exceeded over a pre-specified period (Vogel & Fennessey 1995). The 'Loss of Connectivity' line indicates the stage height of 0.06 m. Data collected from tagged Arctic grayling in the Upper Kuparuk during the 2010–2012 field seasons indicate that migration stops when stage values measured in the Upper Kuparuk dry reach fell below 0.06 m (Deegan *et al.* 2011; L. Deegan, personal communication, 23 March 2012). This finding was used to determine that hydrologic connectivity becomes severed at this stage height. As water levels fall in the system, dry patches do not occur uniformly throughout the dry reaches, so one point measurement is used to approximate flow throughout these reaches, which vary in length from 2 to 8 km. A stage height of 0.06 m in the Upper Kuparuk dry reach has an exceedence probability of 74%. If we assume that the years 1996–2012 represent the full range of flows typical in this system, then there is a 26% chance of flows falling below 0.06 m on any day in the summer.

The timing and duration of dry spells at the Upper Kuparuk and Lower Kupuark sites as identified by the recreated data set show little differentiation (Figure 7). Although located 40 km apart, the occurrence of dry spells is nearly identical at both locations. The shaded area indicates the

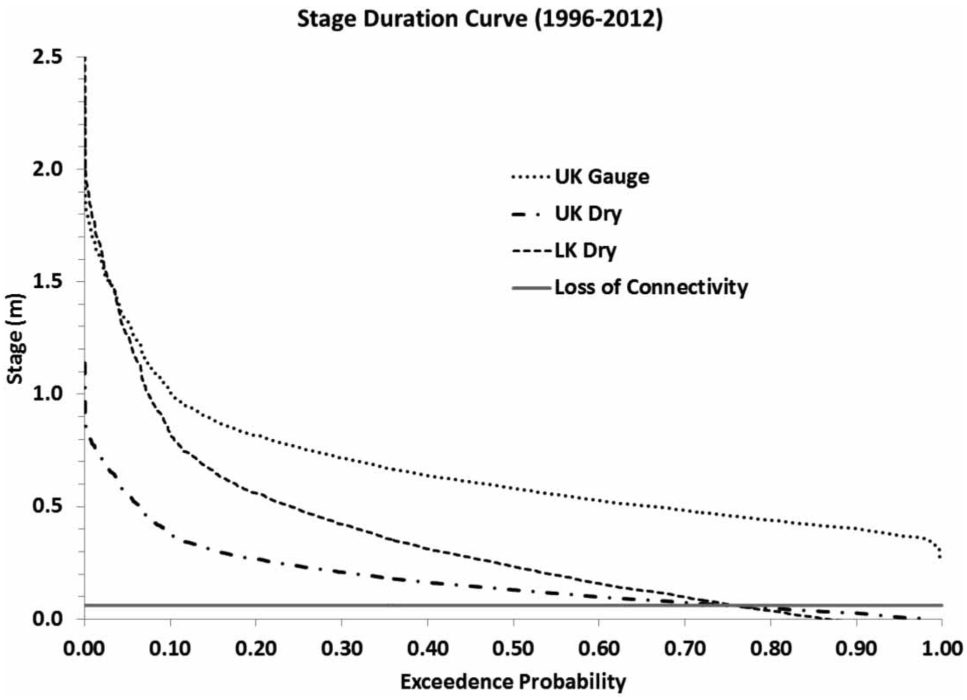

Figure 6 | Stage duration curve based on daily stage values measured at the Upper Kuparuk stream gauging site (UK Gauge) and calculated for the Upper Kuparuk (UK Dry) and Lower Kuparuk (LK Dry) dry reach sites for the years 1996–2012.

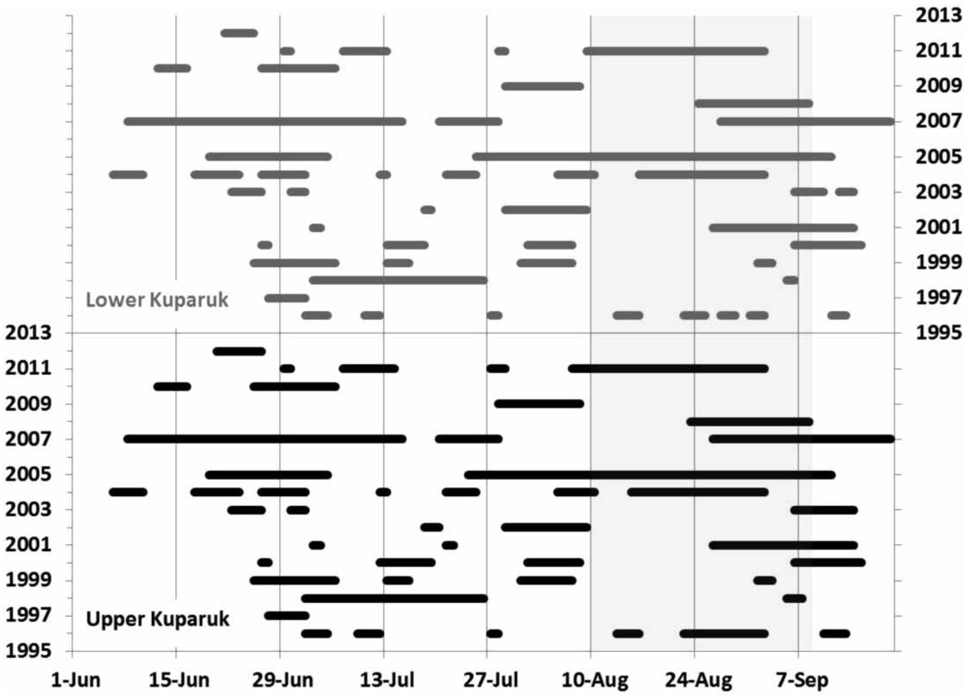

Figure 7 | The recreated dataset showing the seasonal distribution of dry spells at the Lower and Upper Kuparuk dry reach sites for the period 1996–2012. The shaded region indicates the time period during which Arctic grayling migrate to their overwintering site.

critical fall migration period when Arctic grayling in the Upper Kuparuk travel to their overwintering sites. The summer of 2011 provided a good opportunity for studying dry spells, as over 30 days were recorded as no-flow events at both the Upper and Lower Kuparuk sites. Of particular importance was the occurrence of nearly 2 weeks of no flow during the fall grayling migration. Researchers were able to measure the impact of this barrier on tagged grayling in the Upper Kuparuk. Results showed that nearly 75% of the biomass accumulated during the previous 2 months was lost during this 2-week period (L. Deegan, personal communication, 23 March 2012).

To get a picture of how often such events occur on average in any given year, the total number of days per year with no flow was plotted for each site (Figure 8). The overall average was 27 days for the Upper Kuparuk dry reach site and 26 days for the Lower Kuparuk dry reach site. Only 1 year in 17 had no dry spells.

There is a slight increase in the timing of dry events as the summer progresses (Figure 9). Results for September do not represent a full month, as the data recording instrumentation are removed from the river each fall just prior to freezeup, which can occur from early to late September. A one-way analysis of variance (ANOVA) showed that the difference between monthly means was not significant with a value of $p = 0.66$ for the Upper Kuparuk and $p = 0.53$ for the Lower Kuparuk.

DISCUSSION

The occurrence of dry spells in the Kuparuk River system has been documented by other researchers (Kane *et al.* 2008b), but their frequency has not been previously quantified. The results presented here document the timing and duration of such flows as well as highlight the impact on migrating fish species such as Arctic grayling. The similarity in the timing and duration of dry spells at both the Lower and Upper Kuparuk dry reach sites reinforces the concept put forth by Kane *et al.* (2008b) that in Arctic settings with continuous permafrost, floods mainly impact the stream channel and adjacent floodplain, while drought is pervasive throughout the watershed.

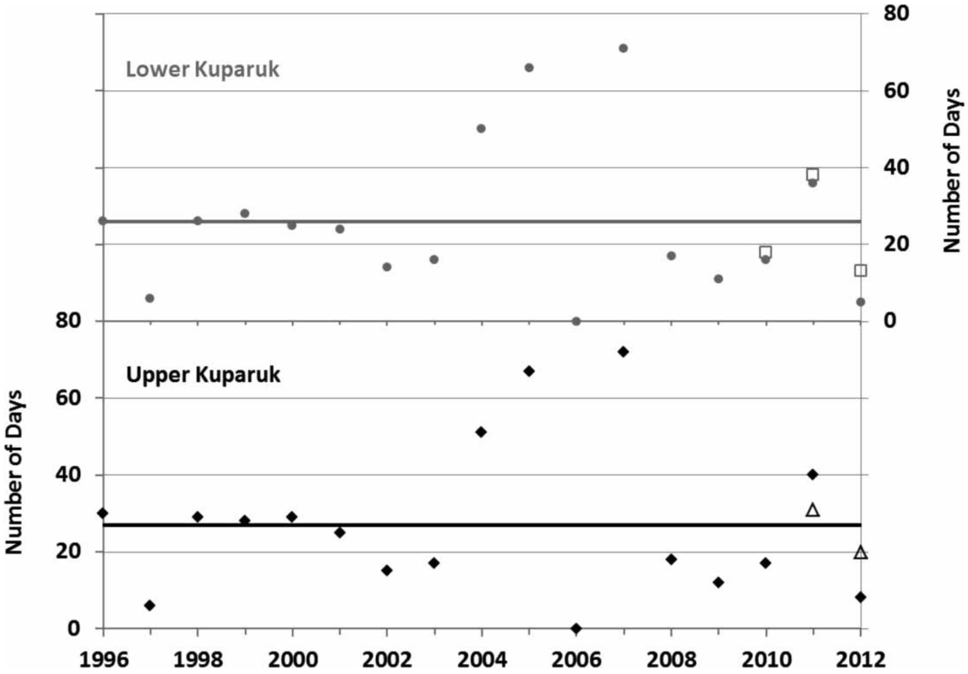

Figure 8 | Estimated number of days per summer with no above surface stream flow at the Lower and Upper Kuparuk dry reach sites based on 17 years of data. Solid symbols show calculated values and observed values are hollow symbols. The straight line represents the average annual value for the period of record.

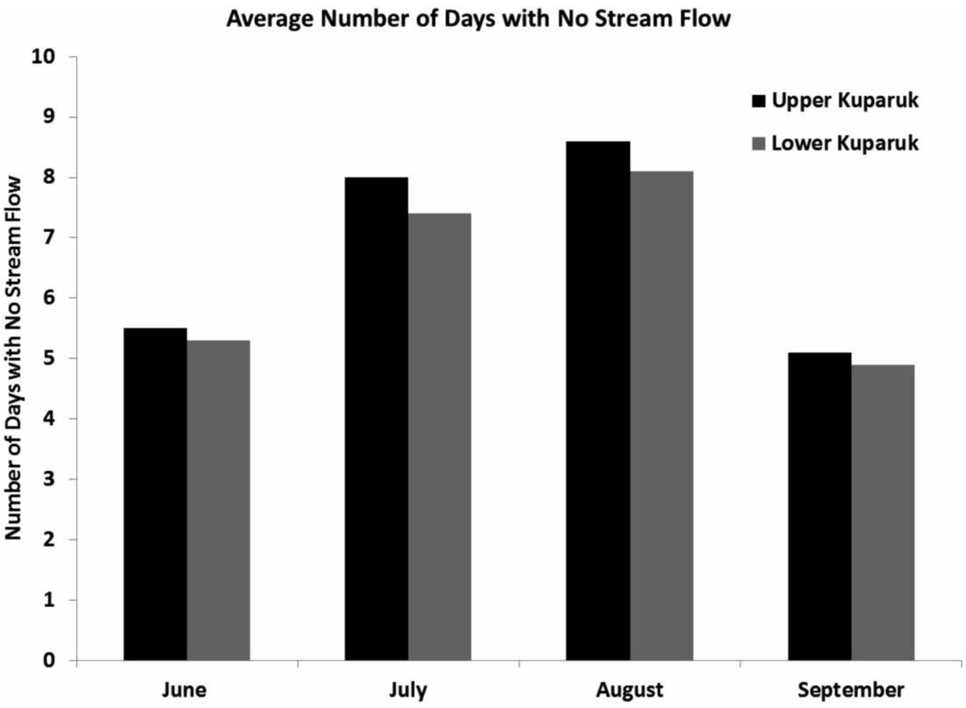

Figure 9 | Average number of days per month with no flow at the Upper and Lower Kuparuk dry reach sites.

The dry reaches identified as part of this research occur along cobble and gravel-lined riffle sections, with some pools maintaining water even amid dry spells. These pools, however, become hydrologically disconnected from each other as well as the upstream and downstream reaches with flowing surface water. Previous work on hyporheic flow in this region showed greater thaw depths beneath riffle and gravel bar features in alluvial-lined streams than in neighboring pool features (Brosten *et al.* 2009). The dry reaches identified in this research also occur just upstream of aufeis features. It is hypothesized that there are large thaw bulbs beneath these dry reaches which create preferential subsurface flow paths for water and provide additional subsurface storage reservoirs for the aufeis fields that form downstream later in the next winter (Kane *et al.* 2013). The physical explanation for the large thaw bulbs at these locations is the occurrence of unfrozen glacial moraines along the stream channel (Kane *et al.* 2013).

Mid-August has been identified as the start of the fall migration period for Arctic grayling (L. Deegan, personal communication, 23 March 2012). Interestingly, this time period corresponds to the average date at which the surface water balance becomes positive, as shown in Figure 1. Salmonid life histories are intimately connected to discharge, timing, and stage in streams and rivers (Reist *et al.* 2006; Bryant 2009). It makes sense, therefore, that Arctic grayling have adapted to begin migration to overwintering sites when on average the system reaches a positive surface water balance, ensuring a greater likelihood that the grayling migration path will be free of barriers. Figure 10 highlights the relationship between Arctic grayling migration and the typical hydrologic regime found in the Upper Kuparuk River basin. Grayling leave overwintering sites quickly after breakup in the spring and migrate to spawning sites. After spawning they migrate to feeding sites, where they spend the rest of the summer adding important biomass. The short summers provide a small window during which fish must find adequate food to grow, put on mass for winter survival, and reproduce successfully. Late summer rain, along with lower ET rates, typically allow for increased connectivity in late summer/early fall when grayling migrate back to their overwintering sites. Fish stranded in water bodies that are good for feeding, spawning, or rearing during summer but not good for overwintering must now move to overwintering sites (Morris 2003).

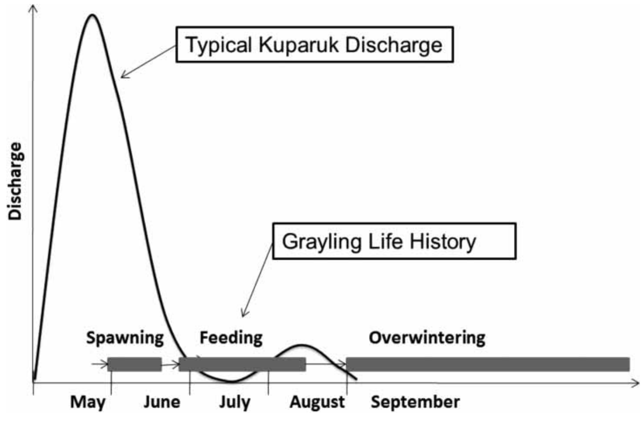

Figure 10 | Relationship between timing of Arctic grayling migrations and typical hydrologic flow regime in non-glacial fed Arctic rivers.

Because climate change alters temperature and precipitation patterns, it has implications for the timing and magnitude of this typical hydrologic regime. In arctic watersheds underlain by continuous permafrost, annual precipitation leaves the watershed primarily as either ET or runoff (Kane *et al.* 1990; Hinzman & Kane 1992; McNamara *et al.* 1998). Large, concentrated rain events would favor increased runoff as the primary mechanism by which water leaves the catchment, while smaller, more frequent rain events favor ET (Hinzman & Kane 1992). Increases in ET may result from increases in air/water temperature, longer ice-free seasons, less moisture in the atmosphere, an increase in transpiring vegetation, and finally increased active layer depth, which decreases surface water levels (Prowse *et al.* 2006b) and allows for additional storage.

The same drivers of these dry events such as a deeper active layer depth and longer ice-free season may lead to increases in nutrient flows which could lead to increased productivity in these systems (Reist *et al.* 2006; Wrona *et al.* 2006). This would have a positive effect on fish populations. Changes in hydrologic regimes such as changes in low flows can in turn affect nutrient and sediment fluxes and ecosystem productivity (Prowse *et al.* 2011). The difficulty in determining the effects of climate variability and change on hydrologic regimes and the resulting impacts to ecosystem structure and function has been well documented (Wrona *et al.* 2006; Prowse *et al.* 2011; Wrona *et al.* 2014). McNamara *et al.* (1998) emphasized the difficulty in separating the influence of the active layer from precipitation patterns on streamflow characteristics in basins underlain by permafrost.

CONCLUSIONS

This research provides a first look at the issue of hydrologic connectivity of river drainages on the North Slope as defined by the needs of a resident fish species. The results of this effort indicate that dry, or disconnection events are a relatively common occurrence in this system. Results of concurrent research also show that dry spells that occur during critical migration periods can have a very negative impact on grayling fitness, particularly entering the overwintering season.

Species develop life-history strategies to cope with the temporal and spatial variability of their present environment (Blanck *et al.* 2007). The life-history strategies adopted by Arctic grayling and other species in the Arctic are the result of adaptation to the physical processes at work in the region (Bryant 2009). Inherent in the adaptation of movement is the idea that no barriers to free movement exist (Fullerton *et al.* 2010). The timing of spring melt, the timing of freeze-up, and the amount and timing of precipitation are all factors to which species have become adapted.

Climate change has the potential to alter natural flow regimes on the North Slope. A change in the dominant flow patterns of arctic streams and rivers could result in a change in the timing and magnitude of high and low flows. The current timing of high and low flows is correlated with migration timing in Arctic grayling. Changes in the timing and magnitude of these flows may lead to fish stranded in their feeding areas unable to reach their overwintering refuge or unable to get to adequate feeding grounds to gain enough energy stores to survive the long winter. The implications of this research in light of climate change are that higher summer temperatures leading to higher rates of ET will lead to a greater occurrence of these dry spells. Precipitation rates are expected to increase with higher temperatures, but the nature of this increase is less clear. Increased active layer thaw depths may also increase the occurrence of dry spells. The Arctic is already witnessing a change in some of these environmental conditions. The rate of this change and the ability of species to adapt will have implications for the numbers and types of species that remain in the region.

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