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Aufeis as a Major Forcing Mechanism for Channel Avulsion and Implications of Warming Climate

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Key Points:

- Aufeis that persists into summer on rivers of the Alaskan Arctic coastal plain can force channel avulsion
- Sites with repeated aufeis in successive years have wider channel migration zones
- Loss of aufeis as climate warms may result in narrower and less diverse river corridors

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Prompted by field observation of an aufeis-induced channel avulsion along the Hula Hula River in June 2021, we use measurements of channel migration zone width along 15 rivers flowing north across the Arctic coastal plain in Alaska, USA. We differentiated sites with aufeis that covered $\geq$1 km^2 in early summer during the period 2017–2021 from sites without such aufeis formation. All but four of the 28 sites with aufeis have widths greater than the 95% confidence interval and 20 sites fall outside of the 95% prediction interval for channel width based on drainage area. Pairwise comparison indicates that the population of aufeis sites have significantly wider channel migration zones ($p < 0.0001$) than non-aufeis sites after accounting for drainage area. Seasonal aufeis facilitates lateral channel migration and associated heterogeneity. Loss of aufeis under warming climate may reduce habitat diversity in these river corridors.

Plain Language Summary

Aufeis forms in Arctic river corridors when groundwater springs continue to provide water to the surface after the river is covered by ice. The resulting shelves of ice can be up to 3 m thick and extend across the channel and floodplain. As this ice slowly melts in early summer, it can divert river flow from the active channel onto the floodplain, creating new channels. This paper examines the resulting width of the floodplain across which active channel migration occurs. Comparing sites with and without aufeis, we find that sites with aufeis are significantly wider. Loss of aufeis with warming climate will reduce the habitat diversity of Arctic rivers.

1. Introduction

High-latitude and high-altitude rivers can have numerous hydrological and geomorphological effects from the seasonal formation of ice (Best et al., 2005; Ettema & Kempema, 2012; Prowse & Beltaos, 2002), as exemplified by the formation of aufeis (Åkerman, 1982; Alekseyev, 2015; Toniolo et al., 2017). Aufeis derives from a German word for "ice on top" and is now commonly used to refer to all forms of frozen overflow (Ensom et al., 2020). Icing is sometimes used to describe the process in which water emerges from the subsurface and freezes, whereas aufeis or the Russian term naled refer to the resulting bodies of ice (Ensom et al., 2020). Aquitards such as permafrost can promote movement of water toward the surface and conduits for flow occur in fractured bedrock, carbonate lithologies with karst weathering, and zones of high effective porosity in alluvium (Ensom et al., 2020). Typical aufeis locations include valleys in proximity to mountains with high elevations; limestone areas with springs; glacial morphology such as terminal moraines and glacial deposits that create strong spatial heterogeneity in hydraulic conductivity; and fault systems (Ensom et al., 2020). Aufeis commonly re-forms each winter in the same locations (Morse & Wolfe, 2015; Yoshikawa et al., 2007), can extend for greater than 4 km^2 (Morse & Wolfe, 2015), and averages 1–2 m thick (Alekseyev, 2015) but can exceed 3 m in thickness (Li et al., 1997).

The water source for aufeis can be a spring, river, or active-layer water expelled to the surface during seasonal freezing (K. L. Carey, 1973). Writing of aufeis in the braided channel of Jarvis Creek, Alaska, Daly et al. (2011) describe how individual channels accumulate frazil ice at the surface and anchor ice over the channel substrate during initial freezeup. As water level in each channel rises in response to the formation of ice cover, channels with higher water-surface elevations spill across gravel bars into lower channels and the spillover freezes. Pressurized conduit-type flow can occur between channels, as evidenced by upwelling of water through openings in the ice cover at the downstream ends of conduits. This movement of water across the river corridor promotes the progressive formation of aufeis via spatially extensive but shallow sheet flow that may be fed by tiny fractures in the ice, and via narrower active channels atop the ice that are fed by visible openings with upwelling water (Daly et al., 2011).

Hydrologic effects of aufeis include enhanced overbank flooding because of ice blocking the channel during the start of the melt season (Daly et al., 2011; Toniolo et al., 2017; Zufelt et al., 2006). Aufeis can also stabilize discharge by providing melt water during warm, dry periods (Li et al., 1997). Geomorphic effects include the formation and development of river networks on and within the aufeis (Alekseyev, 2015). Aufeis channel networks can also create esker- and kame-like ridges and mounds as the ice melts and sediment frozen into the ice or carried in meltwater channels is deposited (Bennett et al., 1998). Åkerman (1982) describes formation of a pavement beneath aufeis, formation of nivation-type hollows, and the formation of steps in a stream's longitudinal profile where the location of aufeis sheets limits streambed erosion by channeling flow toward the margins of the aufeis. Åkerman also describes aufeis creating a braided reach along a stream that otherwise follows "a more or less straight course" (Åkerman, 1982, p. 197).

This paper was inspired by an observation during a float trip down Alaska's Hula Hula River in June 2021. While floating northward across the coastal plain toward the Arctic Ocean, we unexpectedly came across an abrupt vertical drop just over a meter high in tundra along what was elsewhere (i.e., up- and downstream) a cobble-bedded braided channel with an average gradient of ~0.006 m/m. A large accumulation of aufeis was diverting surface flow laterally across the coastal plain and the flow extended into unchannelized tundra, where the diverted flow had created multiple headcuts. Based on this field observation that aufeis could force channel avulsion, we use remote imagery to systematically examine the active channel migration zone of several rivers flowing northward to the Arctic Ocean in the context of locations of repeated annual formation of aufeis. We hypothesize that the presence of aufeis correlates with portions of the river corridor that are significantly wider than portions without aufeis. Because lateral channel migration can result in greater geomorphic and habitat heterogeneity within the river corridor, loss of aufeis under warming climate may reduce habitat diversity in these river corridors. We test our hypothesis by analyzing the width of channel migration zones along rivers across the coastal plain of Alaska in portions of the rivers with and without aufeis.

2. Materials and Methods

2.1. Study Area

A series of rivers flow north from the Brooks Range in Alaska, USA across the Arctic coastal plain to the Arctic Ocean. Although the portions of these rivers within the mountain range commonly have large accumulations of aufeis that persist into early July (Figure S1 in Supporting Information S1), we focus on the portion of each river downstream from the mountains (Figure 1). Table 1 summarizes characteristics of the rivers. Thirteen of these rivers included annually recurrent aufeis patches of at least 1 km^2 surface area. We included two additional rivers, the Jago and the Colville Rivers, to evaluate downstream trends in channel migration zone width in the absence of such recurrent aufeis patches.

Rivers of the Arctic coastal plain have spatially and temporally limited gauge records, but hydrologic reconnaissance studies indicate that the rivers cease to flow during the late winter except in local zones of groundwater discharge that form aufeis downstream (Childers et al., 1977). Flow originates from snowmelt, groundwater springs and, in some of the rivers, glacial melt. Childers et al. (1977) estimate average maximum peak discharge for these rivers at 0.4 m^3/s/km^2. This low value reflects the small value of average annual precipitation (330 mm) across Alaska's North Slope. Peak flow typically (but not always) occurs during the spring breakup, when the stage can be significantly increased by the presence of ice jams (Sloan, 1983).

The Arctic coastal plain is underlain by continuous permafrost. The rivers are predominantly braided, with channel gradients in the range of 0.001 on the largest rivers to 0.008 on the smallest. Limited portions of the Kuparuk River have a single, sinuous channel. As on braided rivers in other regions, lateral channel migration and avulsion result in highly heterogeneous river corridors (Figure S2 in Supporting Information S1), with multiple channels, including some fed by hyporheic return flow; spatial diversity of flow depth, velocity, and substrate; and diverse species and age of riparian vegetation. Springs that feed aufeis accumulations tend to be sites of particularly dense aquatic and riparian vegetation and provide overwintering sites for fish including Arctic char (*Salvelinus alpinus*) (Childers et al., 1977). Huryn et al. (2021) found that aufeis facilitates the existence of rich and spatially extensive groundwater-dependent invertebrate communities with significantly different community structure than those present in surface habitats. River corridors in this tundra environment attract migratory songbirds (Winner, 2003), shorebirds (Johnson et al., 2007), waterfowl (Larned et al., 2012), and willow ptarmigan

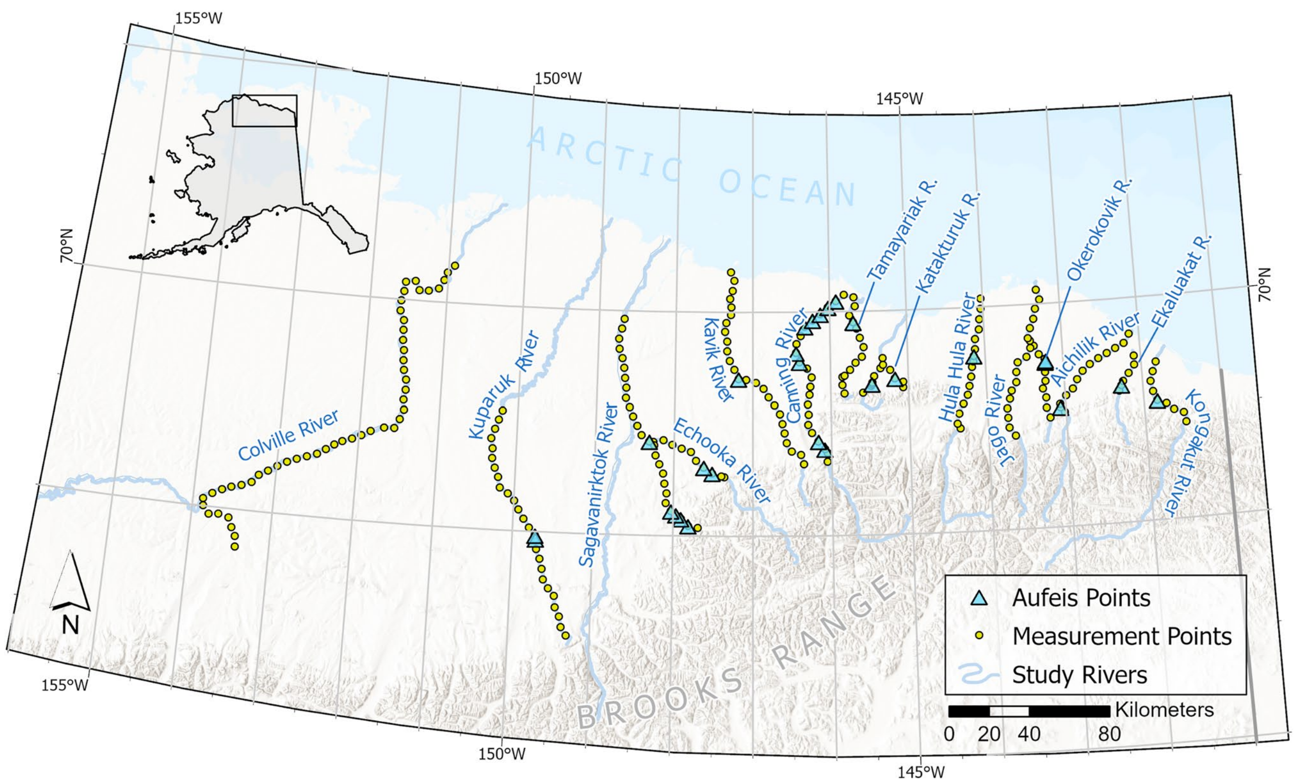

Figure 1. Location map of the study area, showing measurement points with and without persistent aufeis accumulations during the period 2017–2021. Inset map shows the location within the State of Alaska, USA.

(*Lagopus lagopus*) (Christie et al., 2014), as well as moose (*Alces alces*) (Zhou et al., 2020) and other wildlife. The distribution of individual fish species varies among rivers, but Dolly Varden (*Salvelinus malma*), Arctic cisco (*Coregonus autumnalis*) (M. P. Carey et al., 2021), broad whitefish (Leppi et al., 2022), chum salmon (*Oncorhynchus keta*) (Craig & Haldorson, 1986), Arctic grayling (*Thymallus arcticus*) (West et al., 1992), and other fish species (P. C. Craig, 1989) use the active channels in most coastal plain rivers.

2.2. Methods

We used monthly satellite imagery accessed using Planet Explorer (Planet Team, 2017) to search for persistent aufeis patches ≥1 km^2 in areal extent along rivers draining the study area. Monthly images from June and July during the period 2017–2021 were used to identify annually recurrent and spatially extensive aufeis patches: the entire area is usually snow-covered during May and much of the aufeis has melted by August. Areal extent of individual aufeis patches identified in this manner varied from just over 1 km^2 to more than 20 km^2. (Several of the aufeis sites identified in this way are also mentioned as persistent aufeis accumulation zones in Childers et al., 1977 and Harden et al., 1977). We then measured active channel migration zone, starting at the point where each river leaves the Brooks Range and flows north across the Arctic coastal plain and ending at the delta with the Arctic Ocean. We measured channel migration zone at 5 km intervals downstream based on the valley trend (i.e., not along the sinuosity of any single channel). Where necessary, we added more measurement transects to capture the substantial increase in channel migration zone width associated with recurrent aufeis patches. We defined channel migration zone based primarily on color of the ground surface, which reflects the presence of vegetation, and evidence of surface hydrologic connectivity in the form of secondary channels that branch from and then rejoin the main channel downstream (Figure 2).

Drainage area was calculated for each channel migration zone measurement point using 1/3 arc-second digital elevation models for northern Alaska (US Geological Survey, 2019). Flow direction and accumulation were determined from elevation models and watershed boundaries were estimated for each measured point along the river network using the Hydrology toolset in ArcGIS Pro 2.8.0.

Table 1
Characteristics of Rivers, Listed From East to West, With Drainage Area at the Downstream Transect

River	Drainage area (km^2)	Survey coordinates	
		Start (upstream)	End (downstream)
Kongakut (9 transects)	3,775	69.42879	69.70399
		−141.48723	−141.50869
Ekaluakat (6 transects)	301	69.58882	69.73935
		−142.30434	−142.08742
Aichilik (13 transects)	1903	69.51218	69.83793
		−143.02083	−142.13046
Okerokovik (12 transects)	534	69.49206	69.83732
		−143.20675	−143.41403
Jago (17 transects)	2410	69.41935	70.06313
		−143.65699	−143.29597
Hula Hula (16 transects)	1901	69.46330	70.03712
		−144.35874	−144.02255
Katakturuk 2 (5 transects)	110	69.65620	69.75817
		−145.07156	−145.32398
Katakturuk 1 (7 transects)	489	69.63619	69.78765
		−145.58412	−145.32712
Tamaryaiak (13 transects)	837	69.63338	70.02317
		−145.82374	−145.67174
Canning (23 transects)	5082	69.33240	70.06298
		−146.05239	−145.68245
Kavik (25 transects)	4182	69.32205	70.17962
		−146.35177	−147.29086
Echooka (10 transects)	1195	69.26420	69.41792
		−147.36331	−148.26513
Sagavanirktok (26 transects)	12,140	69.03681	69.96426
		−147.68864	−148.67332
Kuparuk (26 transects)	1323	68.54134	69.53415
		−149.28536	−150.19577
Colville (50 transects)	58,474	68.83326	70.16655
		−153.41937	−150.92496

Simple linear regressions were fit for channel migration zone width as a function of drainage area for reaches not affected by aufeis within each basin. Both the 95% confidence interval for mean width and the 95% prediction interval for width at each drainage area were calculated based on the linear models. Reaches with aufeis were then compared to non-aufeis reaches to visually determine whether there are significant differences in width for a given drainage area. To confirm width patterns associated with aufeis, a second linear model was developed for channel migration zone width with drainage area and the categorical presence of aufeis (yes or no) as predictor variables. We used Tukey-adjusted pairwise comparisons to consider the statistical differences in widths between points influenced by aufeis and not influenced by aufeis, accounting for variation with drainage area. The hypothesis will be supported if the confidence and prediction intervals of channel migration width, and the pairwise comparisons, differ significantly for sites with and without aufeis. All statistical analyses were performed using R and the emmeans package (Lenth, 2022).

3. Results

Figure 3 shows trends in channel width versus drainage area at the study sites. The 95% confidence and 95% prediction intervals are given for each linear regression to show both the bounds of the expected mean channel width (i.e., confidence interval) as well as bounds of all expected widths (i.e., prediction interval). Channel width measurements at aufeis sites that fall outside of the 95% prediction interval are unpredictably high for that drainage area on that watershed.

The range of values for drainage area and channel width vary over more than an order of magnitude between watersheds. All but 4 of the aufeis sites (2 on the Canning, 1 each on the Okerokovik and Sagavanirktok) have channel widths greater than the 95% confidence interval. Of the 28 sites with aufeis, 20 sites also fall outside of the 95% prediction interval. In addition, the pairwise comparison indicates that the population of aufeis sites is statistically different ($p < 0.0001$) than non-aufeis sites after accounting for drainage area. In other words, at the majority of sites analyzed, channel widths affected by aufeis are significantly wider than reaches not affected by aufeis. The analyses thus support the hypothesis.

4. Discussion and Conclusions

The braided channels of the Alaskan Arctic coastal plain are mostly shallowly incised into the active layer above the permafrost. The typical bank morphology is an upper layer of sand-to clay-sized sediment in which cohesion is increased by a dense root network from the overlying tundra vegetation (Figure S3 in Supporting Information S1). Bank erosion occurs as the cobble-to boulder-sized sediment of the lower bank is removed, undercutting the cohesive upper layer, which then collapses into the channel and can continue to form cohesive blocks for periods of at least a few weeks.

Although peak unit discharge on these rivers is relatively low, it creates sufficient hydraulic force relative to bank erosional resistance to foster active braiding on most of the studied rivers. The presence of seasonal ice-jam floods likely enhances this process. Best et al. (2005), for example, found a step change in downstream channel cross-sectional area along the Kuparuk River, which they attributed to enhanced bank erosion associated with floating ice. (We have a measurement site at this location, but we identified it as a non-aufeis site and the channel migration width falls within the 95% confidence interval.) The presence of seasonal aufeis likely also enhances braiding and avulsion along the coastal plain rivers. As mentioned previously, the observation of an

Figure 2. Example of measuring channel migration zone width, here on the Echooka River at 69.41683, −148.08508. The yellow line is 520 m long. White arrow indicates flow direction.

aufeis-initiated knickpoint along the Hula Hula River during June 2021 was the impetus for the analysis summarized in this paper. An extensive accumulation of aufeis around 69.8276, −144.1283 had diverted flow from the channel across the tundra, initiating multiple arcuate knickpoints within individual braid channels and across the unchannelized tundra (Figure 4). We presume that the greater potential for ice jams to form around ledges of aufeis projecting across the active channel in late spring-early summer, along with the potential for aufeis to laterally displace stream flow across the tundra, create the mechanisms that lead to greater channel migration zone width at sites of persistent aufeis formation.

The channel-widening associated with aufeis may also occur where we did not detect persistent aufeis accumulations during the 2017–2021 study period. An aufeis-associated flood occurred in spring 2015 on the 35 km of the Sagavanirktok River upstream from Deadhorse, Alaska (Toniolo et al., 2017). Our two downstream-most sites on the Sagavanirktok River fall within this area. One of these, which we identified as non-aufeis-influenced based on the 2017–2021 imagery, lies on the 95% prediction interval line in Figure 3. This suggests that aufeis-influenced flooding that occurs during a single year, rather than repetitively over successive years, may also be able to increase the width of the channel migration zone. In this context it is important to note that our analysis of channel migration width and persistent aufeis sites is not meant to imply that persistent aufeis is the only mechanism promoting channel migration on the coastal plain.

Given the association of persistent aufeis accumulations with wider portions of the river corridor on the Arctic coastal plain, it is worth considering the potential effects of warming climate on these river corridors. Permafrost across the North American Arctic is retreating northward, thinning, and becoming less spatially continuous (Jorgenson et al., 2006). At least some Alaskan rivers historically characterized by ice breakup and ice-jam floods are now increasingly losing ice in a more gradual process sometimes referred to as meltout or mush out. This represents a historical shift from mechanical to thermal spring breakup of ice cover (Beck et al., 2013) and the seasonal loss of ice cover is occurring progressively earlier each year. The combined degradation of permafrost and the loss of ice-jam floods may lead to less thick and spatially extensive aufeis (Pavelsky & Zarnestke, 2017)

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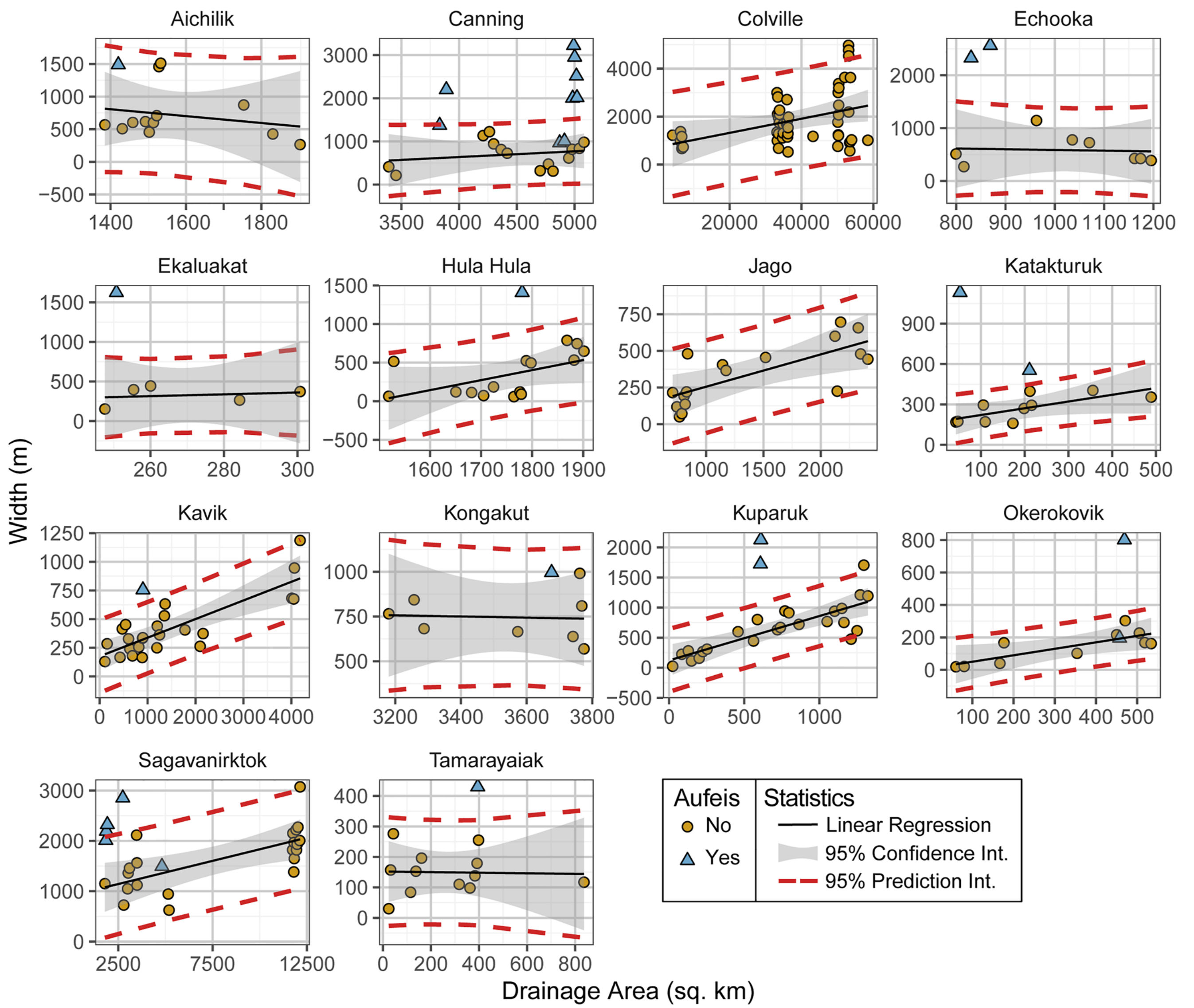

Figure 3. Channel width versus drainage area for each of the 14 watersheds. Sites at which aufeis was present are distinguished from those without substantial early summer aufeis accumulations. The 95% confidence and prediction intervals are also indicated. The Colville and the Jago do not include any aufeis sites.

and lower erosive forces exerted against the channel banks of rivers on the coastal plain. Permafrost degradation and warming air temperatures will also foster changes in vegetation (Epstein et al., 2012) that may effectively strengthen the erosional resistance of stream banks via greater rooting depths and denser above-ground vegetation that helps to dissipate flow energy along the channel margins and in overbank areas. A thicker active layer may increase infiltration and subsurface storage and reduce surface runoff to rivers (Woo et al., 2008). On the other hand, annual precipitation is likely to increase at 60 to 90°N as climate warms (Rawlins et al., 2010). Although it is challenging to predict the detailed responses of the river corridors to warming climate (Lininger & Wohl, 2019), a likely scenario for portions of the coastal plain rivers is that they will become less laterally mobile, resulting in a gradual decline in the spatial heterogeneity and habitat diversity of river corridors and associated reduction in important habitat for species such as Arctic grayling that use secondary channels in braided river systems (Yuan et al., 2022). This represents one of many implications of a contracting cryosphere as global climate warms.

Figure 4. Knickpoint in unchannelized tundra immediately east of the channel migration zone of the Hula Hula River on the Arctic coastal plain, June 2021. The white line at the right rear (below the mountains) is a portion of the aufeis. Knickpoint here is about 1 m tall; knickpoints in some of the braid channels were 1.5–2 m tall. Vegetation in the foreground has recently emerged from seasonal ice and snow cover.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Basic data used in analysis are also archived in the Mountain Scholar open access repository at http://dx.doi.org/10.25675/10217/235524.

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