Climatic Change (2020) 162:385–404
https://doi.org/10.1007/s10584-020-02748-9

Implications of climate variability and changing seasonal hydrology for subarctic riverbank erosion

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Received: 8 April 2019 / Accepted: 20 May 2020 / Published online: 4 June 2020

Abstract
Warmer climatic conditions have been associated with numerous hydrologic changes that may impact riverbank erosion in cold regions, but the net effect is not well understood. We used regression and correlation analyses to examine the relationships among subarctic riverbank erosion and seasonal hydrology, the impact of climate change and variability, and the societal implications. Geomorphic change (loss and gain of vegetated land) was mapped along several river reaches in the Yukon River Basin, Alaska, throughout 1984 and 2017 using Landsat satellite imagery. Annual erosion rates were estimated from these spatial data. At most study sites, erosion rates (km^2/year) were either positively correlated ($r = 0.68$–0.84, $p = 0.0085$–0.061) with monthly mean discharge within the cold season or inversely correlated ($r = -0.74 - -0.62$, $p < 0.10$) with river ice breakup date in the spring. These proximate controls on erosion, in turn, were influenced both by climate variability and long-term climatic change. We conclude that increased cold season discharge and earlier freshet that occurs under warmer conditions enhance riverbank erosion in most areas. Climate-related changes to fluvial dynamics may impact communities through effects on infrastructure, travel safety, channel navigability, fish and wildlife habitat, and access to subsistence resources.

Keywords Climate change · Subsistence · Riverbank erosion · Fluvial geomorphology · Hydrology · River ice

1 Introduction

Most rural communities in the Arctic are mixed cash-subsistence economies where people depend on hunting, trapping, and gathering as an important source of subsistence (Brinkman

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s10584-020-02748-9) contains supplementary material, which is available to authorized users.

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et al. 2016). Many communities are located off of the road system, but adjacent to waterways. People rely on rivers for travel, subsistence fishing, and access to subsistence resources (Brabets et al. 2000; Johnson et al. 2016). River channels change over time due to continual erosion and fluvial deposition. However, studies with rural communities across the region reveal a widespread perception that riverbank erosion, bar deposition, and channel change have increased in recent decades (Alaska Native Tribal Health Consortium 2016; Carothers et al. 2014; Herman-Mercer et al. 2011; Wilson et al. 2015). In addition to the direct impacts of erosion on infrastructure and land (Larsen et al. 2008), the addition of debris to channels and the shifting of bars can affect boat navigation, making some routes hazardous or inaccessible (Alaska Native Tribal Health Consortium 2016; Cold et al. 2020), and disrupt subsistence activities (Carothers et al. 2014; Payne et al. 2018). Therefore, understanding the controls over channel dynamics, quantifying how rates of erosion have changed, and predicting the direction of future change are important to the livelihoods of the people who depend on waterways for access to subsistence resources (Brinkman et al. 2016).

Riverbank erosion is influenced by numerous controls—the relative importance of which is not well understood for high-latitude rivers (Lawson 1983; Scott 1978). Hydrological regimes of subarctic rivers are distinct from those of temperate regions because of the strong influence of river ice, snowmelt runoff, glacial runoff, permafrost, and seasonally frozen ground, factors which also affect riverbank erosional processes. Flow velocity impacts riverbank erosion rate in both frozen and unfrozen sediments (Larsen et al. 2006; Scott 1978). The thaw and erosion of permafrost-affected banks occurs most rapidly through exposure to water, but also occurs above water level through solar radiation (Eardley 1938; Kanevskiy et al. 2016; Lawson 1983; Williams 1952). An extended period of low flow occurs throughout winter, though fluvial erosion beneath river ice has been documented (Ettema 2002; Schneider et al. 2013). In catchments with snowmelt-dominated runoff regimes, river discharge usually peaks during the spring freshet (Brabets et al. 2000). Freshet discharge can be amplified by the effects of river ice breakup, with backwater from ice jams causing flooding (Lesack et al. 2013; Prowse 2001). Freshet discharge, ice jam flooding, and ice scour have all been cited as important agents of river channel change in high-latitude rivers (Clement 1999; Ettema 2002; Prowse 2001; Scott 1978).

Each of these potential hydroclimatic drivers of riverbank erosion may be influenced by climatic change and variability. Statewide annual air temperatures have exhibited a warming trend of ~1 °C from 1920 to 2012 (Bieniek et al. 2014), and both air temperatures and precipitation are expected to increase (IPCC 2013). The IPCC Fourth Assessment Report predicts a ~4.5 °C increase in average air temperature and a ~21% increase in precipitation for the North American subarctic and arctic region by the end of the twenty-first century under an intermediate greenhouse gas emissions scenario (scenario A1B, Climate Model Intercomparison Project, version 3) (Christensen et al. 2007). Superimposed on the warming trend are significant multidecadal and interannual fluctuations in air temperature that are influenced by atmospheric teleconnections, in particular, the Pacific Decadal Oscillation (PDO) and El Niño-Southern Oscillation (ENSO) (Bieniek et al. 2014; Hartmann and Wendler 2005; Mantua et al. 1997; Papineau 2001). Mean annual air temperatures in Alaska were 0.9–1.5 °C higher during a warm phase of the PDO (1977–2001) relative to the previous cool phase (1951–1975) (Hartmann and Wendler 2005). Warmer conditions are associated with numerous changes that may impact erosion: reduced duration of river ice cover (Brown et al. 2018), thinner ice, reduced breakup severity (fewer mechanical breakups, ice jams, spring floods) (Prowse et al. 2012), enhanced permafrost thaw (Osterkamp 2007), increased glacial melt (Folland et al.

2001), increased winter streamflow (Rennermalm et al. 2010), and changing seasonality of streamflow (Brabets and Walvoord 2009). These hydrologic shifts may have opposing effects on riverbank erosion, but the net effect is unclear.

The primary objectives of this research were to identify important hydroclimatic drivers of riverbank erosion in subarctic Alaska and assess the impacts of climate change and variability. Motivated by concerns expressed by rural communities about the impacts of erosion on subsistence practices (Cold et al. 2020), we investigated patterns and controls of riverbank erosion in reaches of the Yukon, Tanana, and Chandalar rivers in interior Alaska. First, we mapped and quantified areas of geomorphic change (loss and gain of vegetated land) over multiyear time intervals between 1984 and 2017 using Landsat satellite imagery. We examined relationships between riverbank erosion rates, river discharge, and river ice breakup date. Then, we assessed temporal patterns of these hydroclimatic variables to infer the impact of climate variability and change on riverbank erosion. Finally, we explored the societal consequences of the erosion patterns identified.

2 Methods

2.1 Study area

Our study area is within the Alaskan portion of the Yukon River Basin (Fig. 1). The descriptions of the study area were derived from the overview by Brabets et al. (2000) unless noted otherwise. The majority of the basin has a continental subarctic climate. Climate normals (1981–2010) averaged among the first-order weather stations (i.e., stations maintained by the National Weather Service) within the interior Alaskan climate division show a mean annual air temperature of − 3.1 °C and annual precipitation of 348 mm (Arguez et al. 2010). The region is typically composed of boreal forest vegetation and is predominantly underlain by discontinuous permafrost, but also includes areas of sporadic and continuous permafrost.

The rivers of focus in this study include the Yukon River and two of its tributaries, the Tanana and Chandalar rivers. The Yukon River flows from northwestern Canada through interior Alaska into the Bering Sea, draining an area of ~ 855,000 km^2. The Tanana River drains the north side of the glaciated Alaska Range, with ~ 115,000 km^2 basin underlain by discontinuous permafrost. The Chandalar River drains the south side of the Brooks Range. The Chandalar River basin is ~ 35,000 km^2 and is underlain by continuous permafrost.

The seasonal hydrologic regimes of these rivers are shown in Fig. 2. Extended subfreezing temperatures reduce discharge in winter. In the Chandalar River, winter streamflow is negligible, whereas groundwater discharge maintains wintertime low flow under ice cover in the Yukon and Tanana Rivers. The period of winter low flow generally lasts from January through March. In April or May, river ice cover diminishes (breakup) and streamflow rises (the spring freshet) as air temperatures increase and snow melts. The Yukon and Chandalar rivers both exhibit a snowmelt-dominated runoff pattern, where streamflow peaks with spring freshet and declines throughout the summer and fall, with secondary peaks occurring as a result of precipitation events. The hydrologic regime of the Tanana River is influenced by glacial meltwater, which causes a sustained increase in discharge throughout the summer before receding in the fall, and is also influenced by precipitation events. The fall recession typically occurs from October through December as freezing air temperatures gradually reduce flow and ice cover forms.

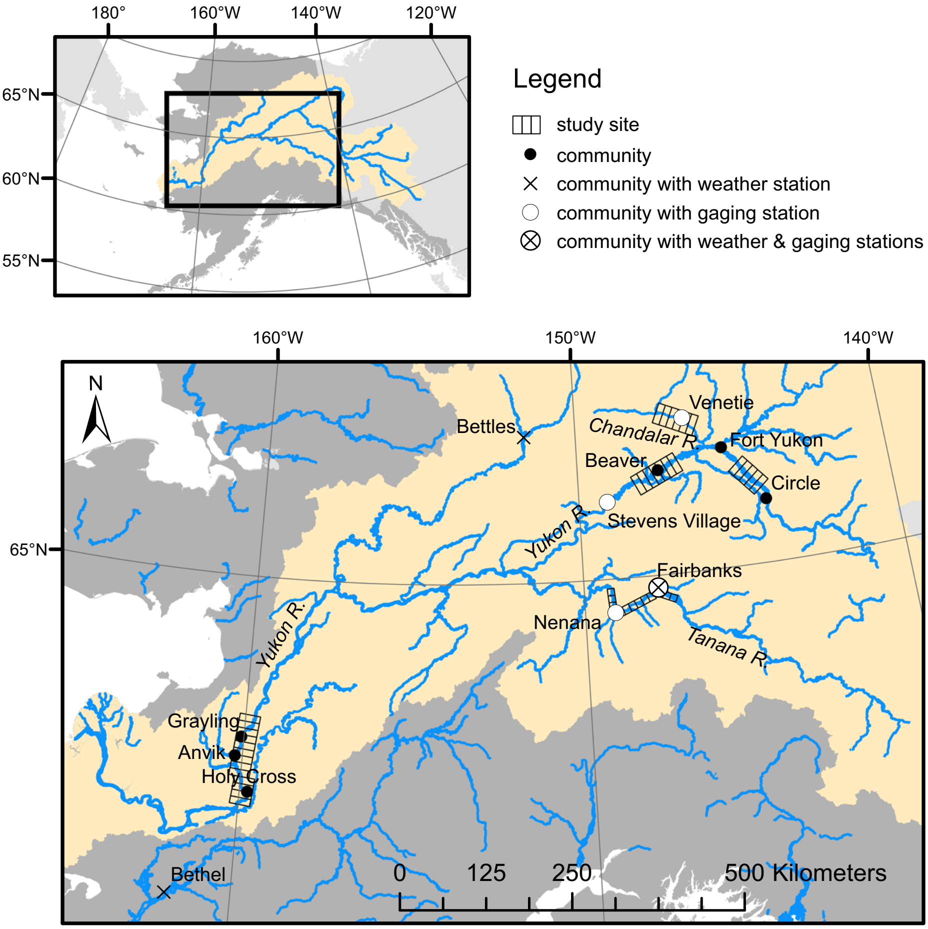

Fig. 1 Study area maps showing locations of study area within the Yukon River Basin (tan) in Alaska, USA (dark gray), major rivers, study sites, nearby communities, and weather and gaging stations

2.2 Site selection

Six study sites near communities were chosen along the Yukon, Tanana, and Chandalar rivers (Fig. 1, Table 1). The sites on the Yukon and Chandalar rivers were selected because community members have reported that channel change has affected access to subsistence resources, traveler safety, and local economies (Brinkman et al. 2016; Cold et al. 2020). Rural communities in the region are heavily reliant on river travel for subsistence, travel to adjacent communities and traditional camps, and for barge delivery of commercial goods. Additional sites on the Tanana River were included to expand the diversity of river reaches in terms of hydrologic regimes (snowmelt runoff and glacier runoff) and channel morphology (braided, wandering, and meandering). Braided reaches have numerous interlaced channels divided by unstable bars and islands and exhibit abundant lateral shifting, whereas meandering reaches have one or few sinuous channels with more stable islands and less lateral activity (Buffington and Montgomery 2013). Wandering reaches are transitional between braided and meandering morphologies, with multiple channels and moderate lateral activity and bar/island stability (Buffington and Montgomery 2013).

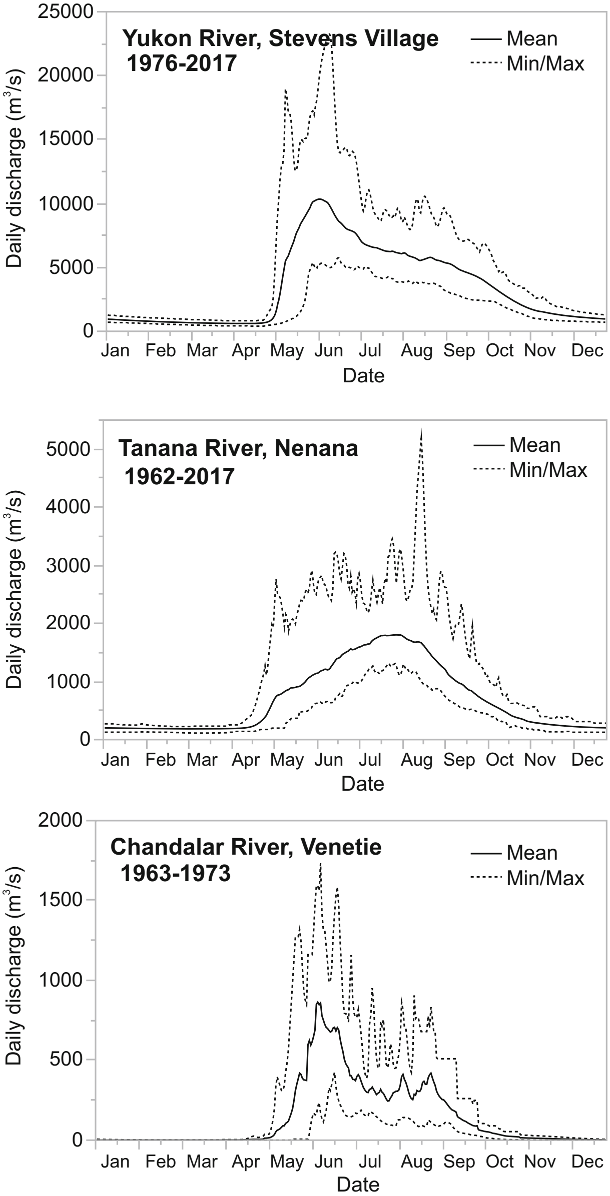

Fig. 2 Annual hydrographs of the Yukon, Tanana, and Chandalar rivers showing mean, minimum, and maximum daily discharge. Data obtained from USGS gaging stations (https://waterdata.usgs.gov/ak/nwis/sw)

2.3 Remote sensing and image classification

2.3.1 Scene and site selection

Areas of geomorphic change within channels, indicated by shifts between vegetated and non-vegetated classes, were mapped and quantified over multiyear time intervals between 1984 and

Table 1 Study site descriptions

Study site	Nearby communities	Channel morphology	Hydrologic regime	Longitude, Latitude	Study area length
Yukon R., Holy Cross	Holy Cross, Anvik, Grayling	Meandering	Snowmelt	− 160.166, 62.620	130 km
Yukon R., Beaver	Beaver	Wandering	Snowmelt	− 147.464, 66.341	70 km
Yukon R., Fort Yukon	Fort Yukon, Circle	Braided	Snowmelt	− 144.531, 66.162	50 km
Tanana R., W Fairbanks	Fairbanks, Nenana	Wandering	Glacial	− 148.807, 64.576	90 km
Tanana R., E Fairbanks	Fairbanks	Braided	Glacial	− 147.467, 64.752	30 km
Chandalar R., Venetie	Venetie	Braided	Snowmelt	− 146.608, 67.038	60 km

2017. Landsat satellite imagery from Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Operational Land Imager (OLI) sensors were acquired from the United States Geological Survey (USGS) (http://earthexplorer.usgs.gov). Multiple criteria were used for compiling imagery. Scenes with significant cloud cover, haze, or smoke were excluded, as were scenes with missing data due to scan-line corrector failure. Additionally, we considered timing within the hydrologic year (October 1–September 30), water levels, plant phenology, and snow cover. Ideally, images would be acquired towards the end of the hydrologic year in order to capture the majority of changes that occurred within that year; however, the scenes must be acquired before plant senescence or snowfall for accurate image classification. We excluded scenes with high water levels, where flooding of vegetated areas was observed. From the compilation of all imagery meeting these criteria from 1984 to 2017, 8–9 mosaics per site were selected for change detection over multiple time periods. We maximized the number of time periods considered while keeping the length of the periods as consistent as possible. The magnitude of change over time also needed to appropriately match the spatial resolution of the imagery. Because the pixel size of 30 m is typically larger than the scale of most riverbank erosion within a year, intervals including multiple years were needed for change detection. Areas with cumulative erosion less than the pixel size might not be detected, though they may be significant. The number and length of intervals selected were constrained by the availability of suitable imagery. Table S1 summarizes the imagery used in analysis.

The exact location and area of each study site was determined by the overlap of the imagery selected (Table 1). Study sites were subdivided into multiple 10-km-wide rectangular segments oriented along the main axis of the river for the purpose of calculating mean rates of erosion and colonization. The channel areas were defined by including contiguous pixels that were classified as non-vegetated in any of the years considered, including the main channel, side channels, and barren land. Narrow channels (< 60-m wide) and any areas affected by cloud cover were manually excluded.

2.3.2 Image classification and change detection

Image classification was conducted using thresholds of the Normalized Differenced Vegetation Index (NDVI). We utilized NDVI products derived from atmospherically corrected surface reflectance products processed by the U.S. Geological Survey (USGS 2017). Pixels with NDVI ≥ 0.2 were classified as vegetated, and pixels with NDVI < 0.2 were classified as non-vegetated (Carlson and Ripley 1997). Areas of riverbank erosion were defined by all pixel-based changes from vegetated to non-vegetated classes within the channel area, including banks, islands, and bars. Conversely, areas of vegetation colonization were defined by pixel-based changes from non-vegetated to vegetated classes. The total areas of erosion and colonization were extracted for each 10-km segment for each time interval, and mean annual rates of change per study site were calculated. Though vegetation colonization is indicative of previous deposition, we did not compare it quantitatively with erosion since there is unknown variability in the length of time for deposits to become colonized. We present the colonization data primarily to show the spatial patterns of geomorphic change. The spatial data products created through this study, showing riverbank erosion and vegetation colonization over time, are accessible via the NASA Oak Ridge National Laboratory Distributed Active Archive Center (https://doi.org/10.3334/ORNLDAAC/1616) (Brown 2019).

2.4 Data analysis

We used simple linear regression and correlation analysis to identify relationships between site-level erosion rate and hydroclimatic variables, examine relationships among hydroclimatic variables, and assess temporal trends. The hydroclimatic variables we considered in various analyses included monthly mean discharge, peak freshet discharge (maximum daily discharge from April–June), river ice breakup date, monthly mean air temperature, total annual snowfall, and the monthly PDO index. Erosion rate is often sensitive to stream power, a function of river discharge and slope (Larsen et al. 2006; Nanson and Hicken 1986). In the absence of local topographic data, river discharge is used as a proxy for stream power. Normality of all data was assessed using the Shapiro-Wilk test ($p > 0.05$) (Shapiro and Wilk 1965). Some data had lognormal distributions: erosion rate for the Yukon River at Fort Yukon, monthly mean precipitation, total snowfall, and individual monthly discharge. These data were log-transformed prior to parametric analysis. We report the full range of alpha values to allow the reader to determine significance, though we interpret statistical significance at an alpha level of 0.10. This interpretation is consistent with previous hydrological studies in the region and allows for direct comparisons (Brabets and Walvoord 2009; Ge et al. 2013; Walvoord and Striegl 2007).

When establishing relationships with erosion rate, hydroclimatic data were averaged by time interval of the associated imagery. Given the sample size limitations ($n = 7$–8 time intervals) inherent in our remote sensing-derived datasets of erosion, there is uncertainty in these results. In our interpretation, we looked for coherence of relationships among sites and plausible explanations of patterns as indicators that the observed relationships were robust.

Long-term temporal trends in river ice breakup dates were determined for the Yukon River (1896–2017) and Tanana River (1917–2017) using linear regression. Because climate and hydrology in this region are closely linked with the Pacific Decadal Oscillation (Brabets and Walvoord 2009; Hartmann and Wendler 2005), we compared breakup dates across cool and warm phases of the PDO. Multidecadal time periods were defined using the April PDO index value (warm phases: 1922–1944, 1977–2017; cool phase: 1945–1976). The Tukey-Kramer HSD test was used as a conservative comparison of mean breakup date across all pairs of the three PDO phases (Kramer 1956; Tukey 1953). To avoid confounding the trend analysis of the discharge datasets, we included only years within the recent PDO warm phase.

Discharge data were retrieved from USGS gaging stations on the Yukon River at Stevens Village (ID 1543500), the Tanana River at Fairbanks (ID 15485500) and Nenana (ID 15515500), and the Chandalar River at Venetie (ID 15389500)(https://waterdata.usgs.gov/ak/nwis/sw). Most analysis for Tanana River discharge used the Fairbanks gaging station data, except when longer time series of the Nenana station were used to develop relationships with meteorological variables. River ice breakup dates from the Yukon River (Dawson, Yukon Territories, Canada) and the Tanana River (Nenana, AK, USA) were acquired through the U.S. Environmental Protection Agency (https://www.epa.gov/climate-indicators/alaskan-rivers). Meteorological data from Bettles, Alaska, were used with Yukon and Chandalar River gaging station data, and meteorological data from Fairbanks, Alaska, were used with Tanana River gaging station data. These data were provided by the Alaska Climate Research Center (http://climate.gi.alaska.edu/acis_data). Monthly PDO index values maintained by Washington University were used (http://research.jisao.washington.edu/pdo/) (Mantua and Hare 2002).

3 Results

3.1 Spatiotemporal patterns of erosion and colonization

Maps of the spatiotemporal progression of channel change are shown in Figs. 3 and 4. Mean erosion rates ranged from 0.08–0.13 km^2/year per 10-km reach, and were generally highest with braided geomorphologies, with the exception of Yukon R./Beaver (wandering) reach which had a mean erosion rate similar to braided reaches (Fig. 5). Mean colonization rates ranged from 0.07–0.30 km^2/year and were also highest in the braided reaches (Fig. 5). Erosion and colonization rates varied temporally but with no clear trend (Fig. 6).

3.2 Relationships between erosion rates and hydroclimatic variables

Erosion rates in reaches of the larger rivers (Yukon and Tanana) showed several patterns regarding relationships with hydrological variables (Fig. 7). Beaver, E. Fairbanks, and Ft. Yukon reaches were similar in that erosion rates had statistically significant positive correlations with monthly mean river discharge within the cold season months ($r = 0.68$–0.84, $p = 0.0085$–0.061). Erosion rates at Holy Cross and W. Fairbanks had mostly negative correlations with cold season discharge, though only statistically significant at Holy Cross ($r = -0.73$, $p < 0.10$). Holy Cross, W. Fairbanks, and Ft. Yukon reaches were similar in that erosion rates were most strongly correlated with variables related to the timing of breakup and the spring freshet (see "Relationships among hydroclimatic variables" section). Erosion rate was inversely correlated with breakup date at each of these reaches, but the relationships were statistically significant only in Holy Cross ($r = -0.74$, $p < 0.10$) and W. Fairbanks ($r = -0.62$, $p < 0.10$). Erosion rates at these sites were positively related to spring discharge (April for the Tanana R. and May for the Yukon R.), but significant only in Holy Cross ($r = 0.85$, $p < 0.05$), and were inversely correlated with mean discharge for subsequent summer month(s), significant only in Holy Cross ($r = -0.78$– -0.72, $p = 0.039$–0.070) and Ft. Yukon ($r = -0.79$, $p < 0.05$).

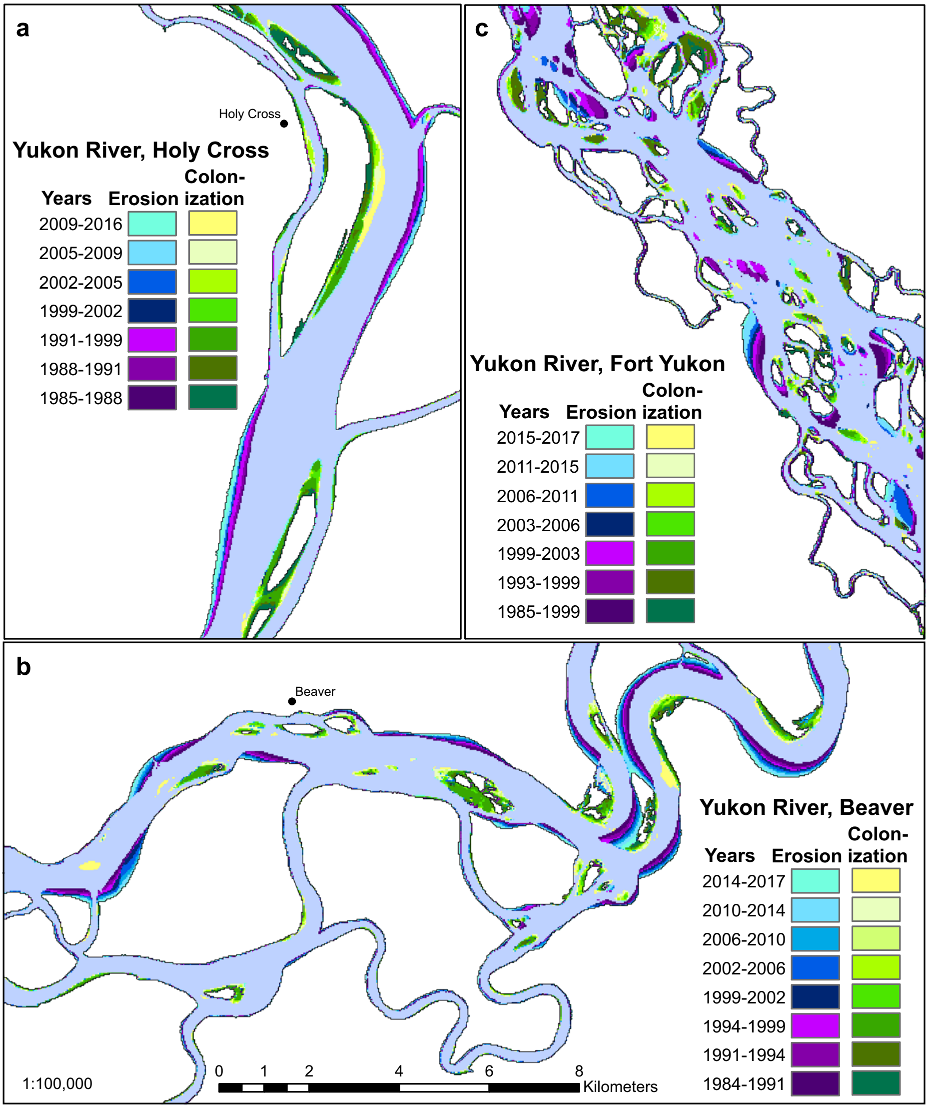

Fig. 3 Spatiotemporal patterns of riverbank erosion and vegetation colonization along the Yukon River near Holy Cross (**a**), Beaver (**b**), and Fort Yukon (**c**). The scale is the same for all panels. Subsets of study sites are pictured. Full spatial datasets can be accessed at https://doi.org/10.3334/ORNLDAAC/1616

No recent discharge or breakup records were available for the smaller braided Chandalar River, but erosion rate had inverse relationships with monthly mean air temperature in April ($r = -0.78$, $p < 0.05$) and May ($r = -0.97$, $p < 0.001$), and a positive relationship with Yukon River breakup date ($r = 0.81$, $p < 0.05$). The direction of the relationship between breakup date and erosion rate on the Chandalar River was opposite of most found on the Yukon and Tanana Rivers. One exception is E. Fairbanks, where erosion rate had a weak positive correlation with breakup date ($r = 0.40$, $p > 0.10$).

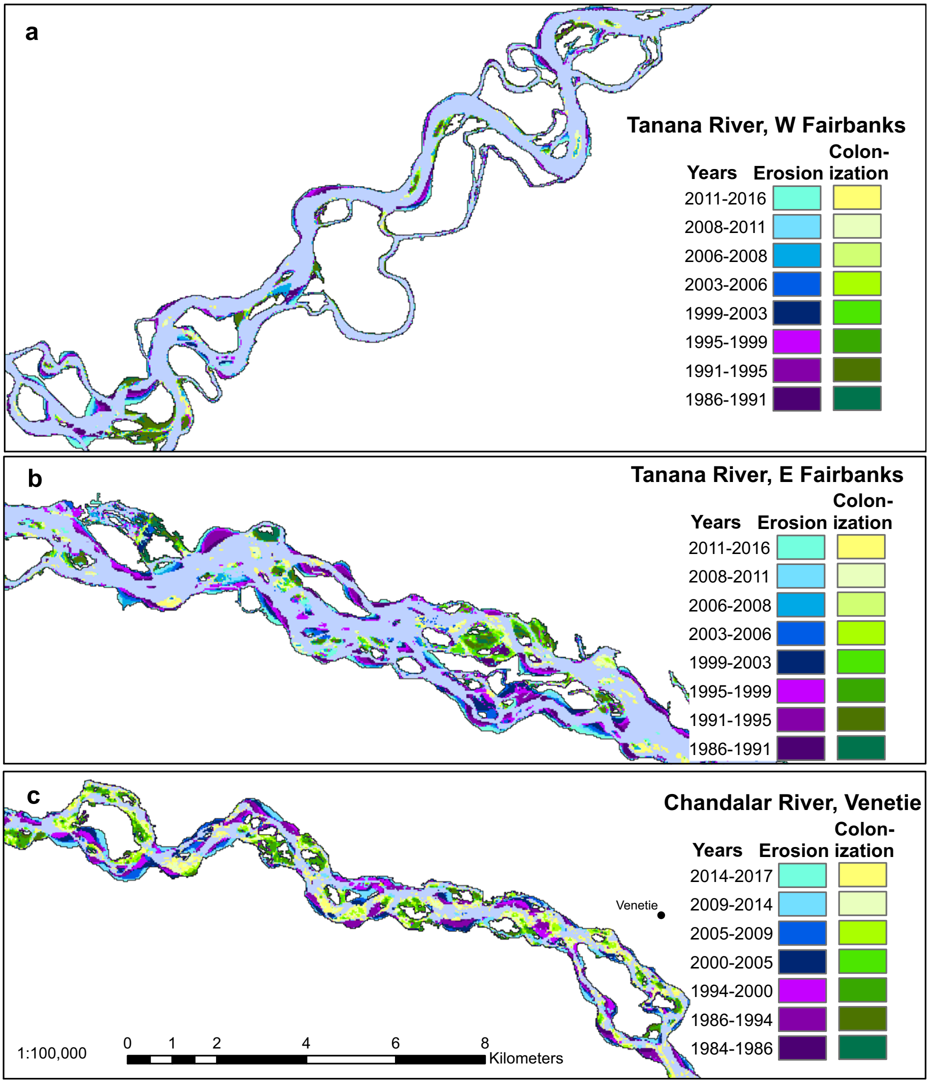

Fig. 4 Spatiotemporal patterns of riverbank erosion and vegetation colonization along the Tanana River west of Fairbanks (**a**), east of Fairbanks (**b**), and the Chandalar River near Venetie (**c**). The scale is the same for all panels. Subsets of study sites are pictured. Full spatial datasets can be accessed at https://doi.org/10.3334/ORNLDAAC/1616

3.3 Relationships among hydroclimatic variables

Relationships among hydroclimatic variables are presented in Table S2. Similar relationships were found for the Yukon and Tanana Rivers. Mean April–May air temperature was negatively associated with breakup date ($p < 0.0001$). Breakup date was inversely related to monthly mean discharge in spring (May for Yukon, April for Tanana) ($p < 0.001$, $p < 0.0001$), but was positively correlated with monthly mean discharge in early summer (June) ($p = 0.0002$–0.007). Monthly mean discharge in May (and June for the Tanana) was

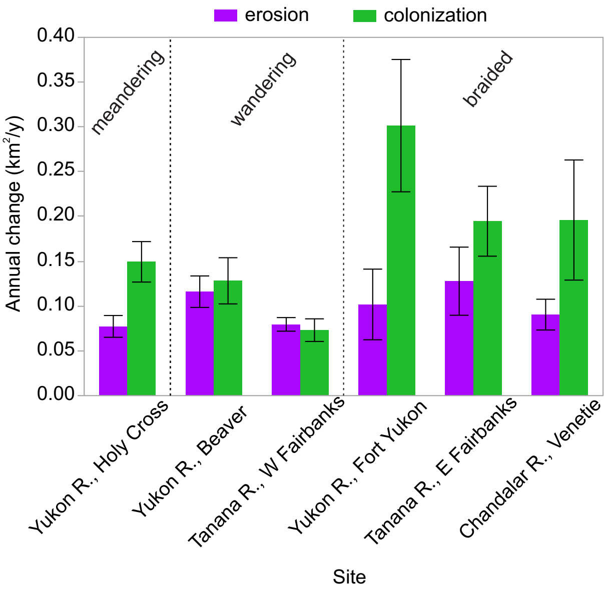

Fig. 5 Mean riverbank erosion rates and vegetation colonization rates by site. Error bars represent the 95% confidence interval

also related to total winter snowfall ($p < 0.0001$–0.0002). Breakup date had a positive relationship with peak flow during freshet, but was only statistically significant for the Tanana ($p < 0.01$).

Only a decade of streamflow data were available for the Chandalar River. The relationships between monthly mean air temperature and monthly mean/maximum discharge for April/May were all positive, though these relationships varied in statistical significance ($p = 0.05$–0.2). Total annual snowfall was related to maximum discharge in June ($p < 0.05$), peak annual discharge ($p < 0.01$), and mean annual discharge ($p < 0.05$).

3.4 Streamflow and breakup trends

From 1977 to 2017 (hydrologic years), the Yukon River at Stevens Village had increases in monthly mean discharge for September–November (+ 22 to + 33%, $p =$ 0.0043–0.061) and May (+ 37%, $p < 0.05$), and a decrease for June (− 20%, $p < 0.10$) (Fig. 8). Over the same time period, the glacially fed Tanana River (Fairbanks) showed increases in monthly mean discharge for October–April (except for December) (15–30%, $p = 0.0042$–0.079) (Fig. 8). There were no significant trends in annual discharge at either site.

Over the long-term, Yukon River breakup date decreased by 0.06 days/year (1896–2017) ($p < 0.0001$), and Tanana River breakup date decreased by 0.08 days/year (1917–2017) ($p < 0.001$)(Fig. 9). Among the three PDO phases considered, the largest differences in mean breakup date occurred between cool phase (1945–1976) and warm phase (1977–2017): In the warm phase, mean breakup date was 5.6 days earlier on the Yukon ($p < 0.0001$), and 5.4 days earlier on the Tanana ($p < 0.001$) (Fig. 9). Relative to the historic warm phase (1922–1944), the recent warm phase (1977–2017) had mean breakup dates that were 2.6 days earlier for the Yukon ($p < 0.10$) and 3.8 days earlier for the Tanana ($p < 0.05$) (Fig. 9).

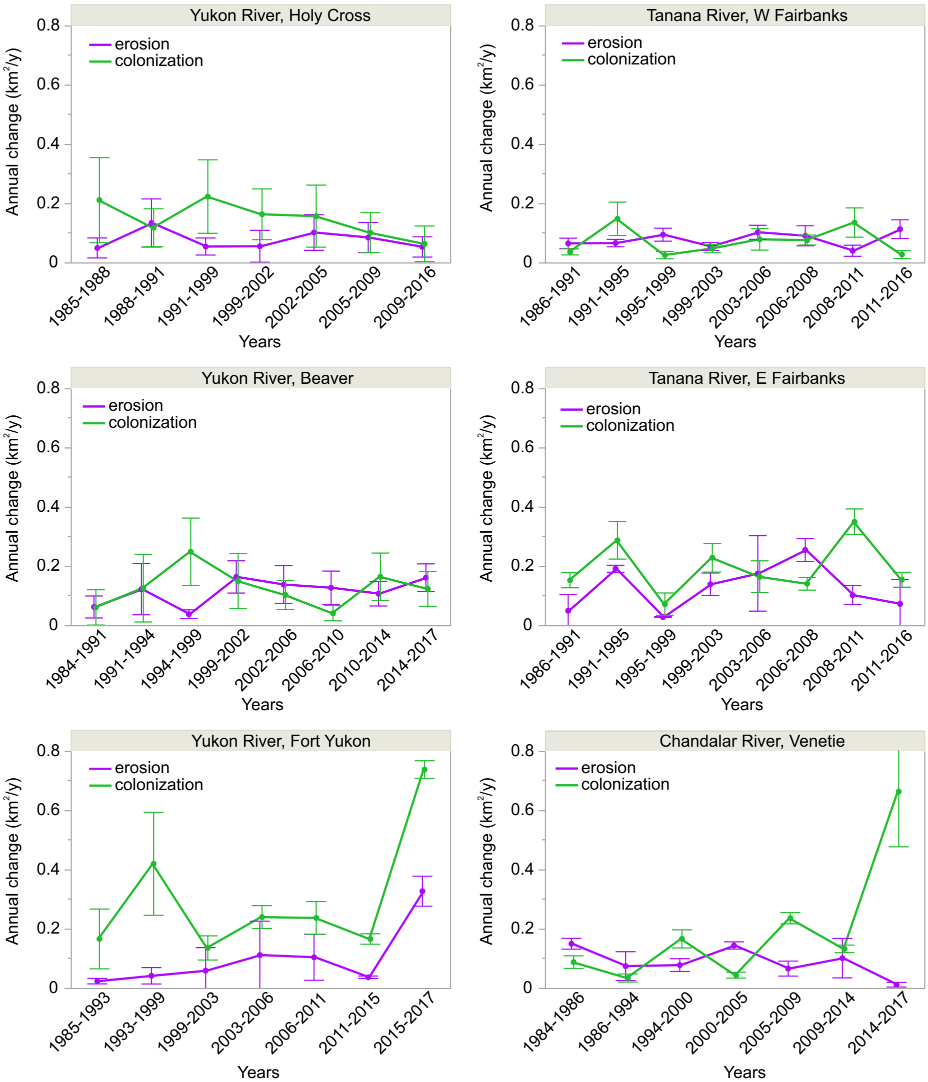

Fig. 6 Temporal variation in mean annual rates of riverbank erosion and vegetation colonization (per 10-km reach) ± SD

4 Discussion

By mapping riverbank erosion and vegetation colonization, we documented the recent evolution of subarctic riverine landscapes. Over time, meander cut banks of outer bends eroded while nearby point bars aggraded and were colonized (Figs. 3 and 4). The dynamic nature of channel change tended to increase along the gradient from meandering to braided morphology (Figs. 3, 4, and 5). The temporal variation in rates of riverbank erosion yielded important insight into potential hydroclimatic controls over erosion, and ultimately to how the riverine landscape may be influenced by climate change and

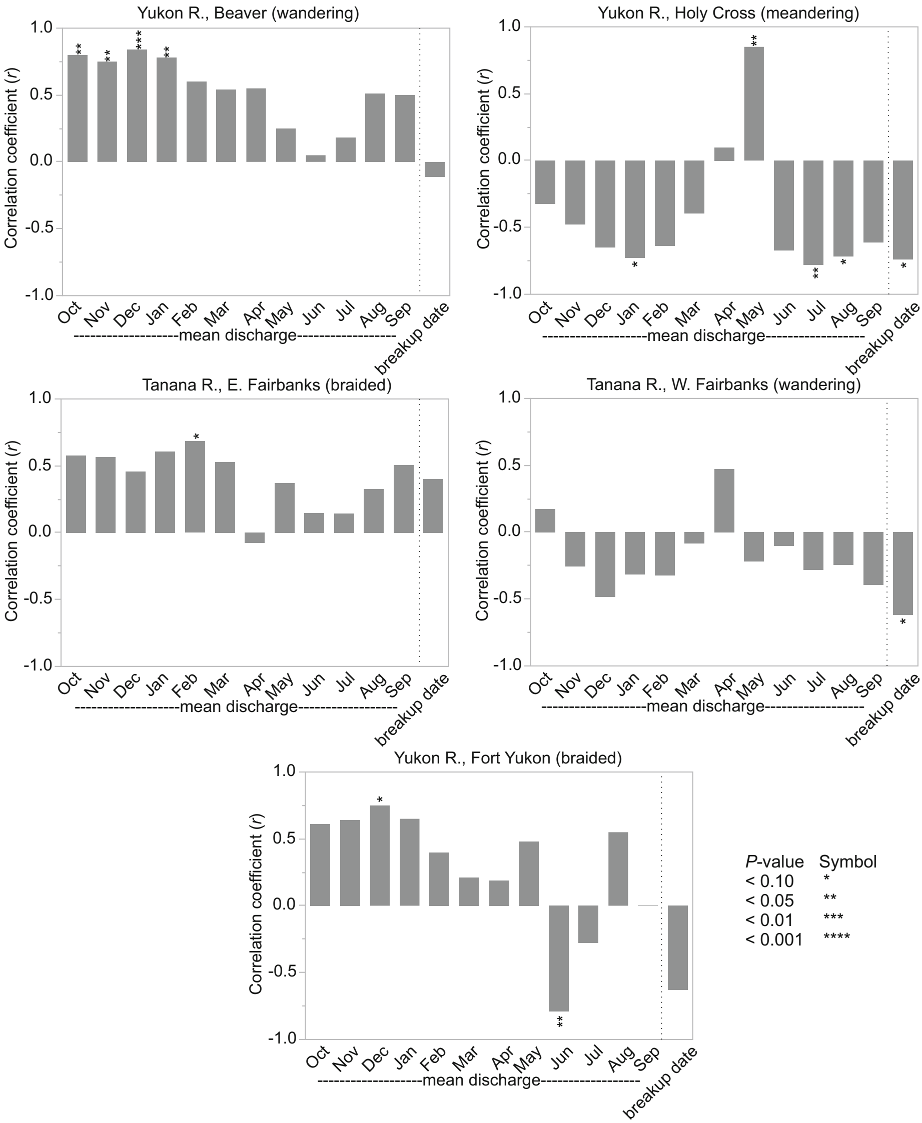

Fig. 7 Correlations of riverbank erosion rates with monthly mean discharge and river ice breakup date of the Yukon and Tanana Rivers

variability. Bank erosion was influenced by multiple factors, and the relative effect of each varied among river reaches, in some cases apparently impacted by geomorphology. Several patterns emerged regarding the dominant hydroclimatic drivers of bank erosion. Among the study sites in the larger Yukon and Tanana Rivers, erosion rates at half significantly increased with greater cold season discharge, and at half significantly increased with earlier breakup or freshet. Below we discuss the key hydroclimatic associations with erosion rates, potential mechanisms, hydrologic trends, and societal implications.

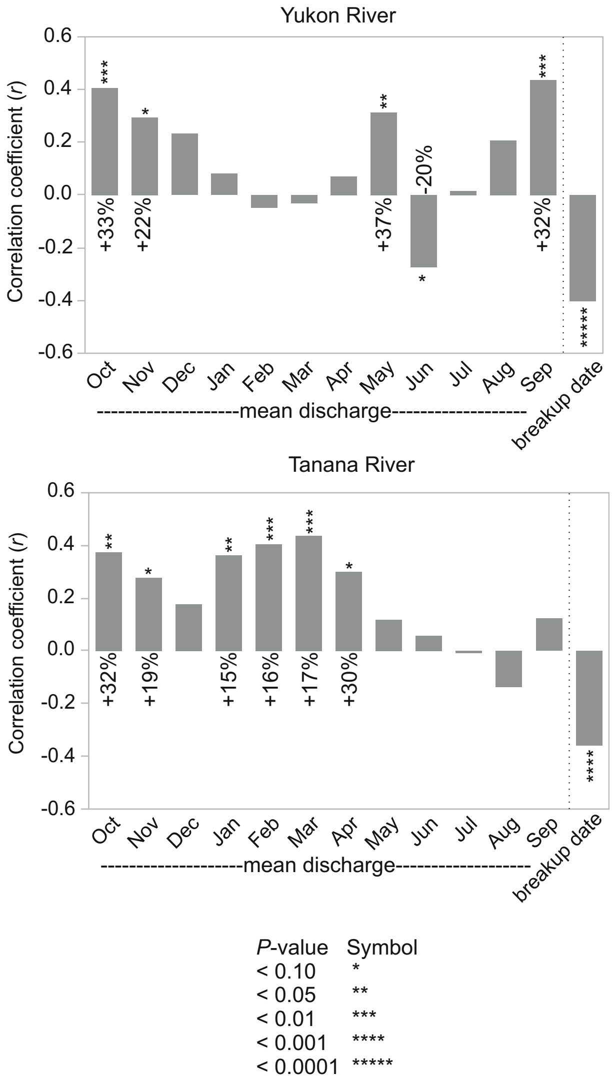

Fig. 8 Trends over time in monthly mean discharge and River ice breakup date of the Yukon and Tanana Rivers. Correlations between hydrological year and monthly mean discharge were for the recent warm phase of the PDO (1977–2017). For monthly mean discharge with significant trends ($p < 0.10$), trend magnitudes (% change) calculated from linear regressions are shown for the 40-year period (1977–2017). Correlations between hydrological year and River ice breakup date were for the long-term period of record for the Yukon (1896–2017) and Tanana Rivers (1917–2017)

4.1 Fall recession and winter discharge

Cold season discharge, spanning the fall recession period through winter low flow, was positively correlated with riverbank erosion rate at multiple study sites on the Yukon and Tanana Rivers (Fig. 7). This is an interesting finding, given that riverbank erosion is typically associated with periods of high flow and extreme hydrologic events (Hooke 2008). Increased cold season discharge could be indicative of a delay in the onset of low flow conditions

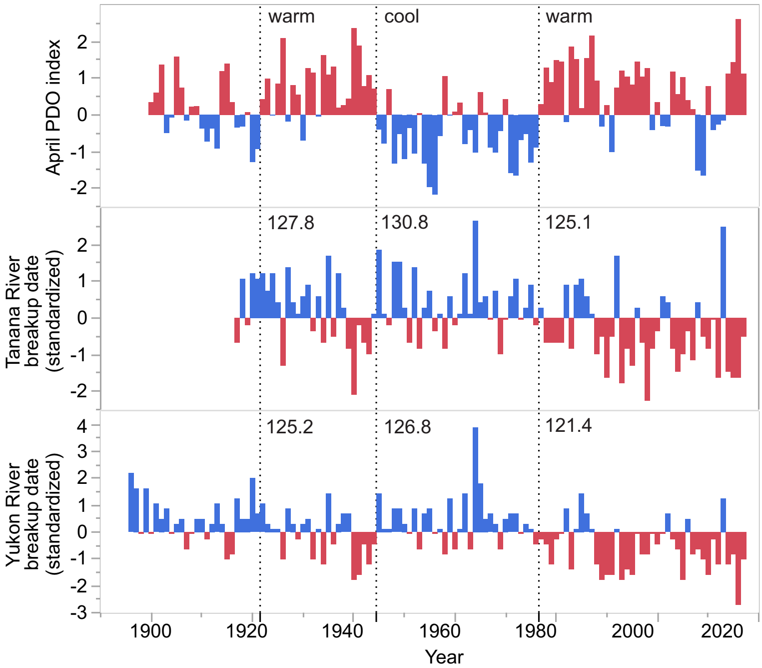

Fig. 9 Variation in standardized Tanana and Yukon river breakup dates over time and in relation to the April PDO index value. Warm and cool PDO phases are delineated with vertical dashed lines. Mean breakup date (Julian day) by PDO phase is indicated. Blue = negative PDO values (cool) or positive standardized breakup dates (late); red = positive PDO values (warm) or negative standardized breakup dates (early)

(Rennermalm et al. 2010). Enhanced erosion could thus be the result of a prolonged season of relatively high flow. It is also plausible that fluvial erosion during low flow is more important than has been recognized and is sensitive to variation in discharge levels. Fluvial erosion beneath ice cover has been shown to cause the collapse of unsupported banks, especially in sinuous or braided rivers where the main channel lies close to the outer banks of bends (Ettema 2002; Schneider et al. 2013; Turcotte et al. 2011). Indeed, the study sites with positive erosion responses to cold season discharge were of wandering and braided morphologies. At a couple study sites, erosion rates were not positively correlated with cold season discharge and were instead more closely related to springtime hydrology. The mechanisms underlying this divergence are unclear, but geomorphology may play a role, given the strongest negative correlation with cold season discharge occurred in the least sinuous study reach (Fig. 7).

There are many conditions that might prolong higher flow, reduce flow recession, and/or increase winter discharge, including increased warm season precipitation (Zhang et al. 2013), delayed soil freeze-up (Yang et al. 2002), delayed river ice freeze-up (Prowse et al. 2007), increased water storage capacity from permafrost thaw (Walvoord and Striegl 2007), and mass loss of glacier ice (Liljedahl et al. 2017). Increased cold season discharge is associated with warm conditions found during positive phases of the PDO and with long-term climatic change (Brabets and Walvoord 2009). Within the recent warm phase of the PDO (1977–2017), we found positive trends in monthly mean discharge in the Yukon River (1977–2017) for September–November (mean = + 29%), which includes the end of the ice-free period through the fall recession of streamflow. Surface runoff dominates streamflow in September, suggesting that increased precipitation may be driving this trend. Tanana River streamflow increased by a similar magnitude for the fall recession (October–November, mean = + 25%), and additionally for the winter period of low flow (January–March, mean = + 16%). Increasing trends in winter low flow have been found throughout the Yukon River Basin, though increases in fall recession flow were found in fewer instances (Brabets and Walvoord 2009). The cold season trends we observed suggest an increase in riverbank erosion for some sinuous reaches of the Yukon and Tanana Rivers.

4.2 Spring breakup and freshet discharge

The characteristics and timing of river ice breakup and freshet discharge are strongly influenced by springtime air temperature (Brown et al. 2018; Prowse et al. 2007). We found interrelationships among warm spring air temperatures, the early timing of river ice breakup and freshet discharge, and the decline in summer discharge (Table S2), consistent with patterns of hydrologic seasonality reported elsewhere (Ge et al. 2013; Yang et al. 2002). The early arrival of above-freezing temperatures causes snow to melt during a time of lower insolation, which often results in a more gradual and extended period of snowmelt accompanied by less intense runoff (Prowse et al. 2006; Woo et al. 2008). We found evidence supporting this pattern on the Tanana River, where early breakup was associated with reduced peak freshet discharge. Early breakup and freshet caused a reduction in monthly mean discharge in early summer, which may explain the inverse relationships between erosion rates and summer discharge found at a couple study sites. The hydrologic conditions related to early spring warming were significantly correlated with increased erosion rates at multiple reaches of the Yukon and Tanana Rivers of all geomorphology types (Fig. 7). The directions of the relationships among spring air temperatures, breakup timing, monthly discharge, and peak flow suggest that increased erosion rates were linked to the earlier timing of breakup and freshet discharge rather than their intensity or magnitude.

By contrast, increased erosion rates on the smaller, braided Chandalar River occurred with cooler springtime air temperatures, despite the associated decrease in peak freshet discharge found in this river. Delayed springtime warming results in snowmelt during a period of high solar insolation, which can cause a rapid rise in river stage (Prowse et al. 2006; Woo et al. 2008), mobilizing large blocks of river ice that have yet to deteriorate thermally (Beltaos 2003). A mechanical breakup like this may precede ice jamming and ice scouring. Ice scour was identified as the cause of historic riverbank erosion events that affected community infrastructure along this river, suggesting that ice-related processes are significant erosive forces at this site (U.S. Army Corps of Engineers 2008). Church (1971) observed the freezing of river ice to the cobble riverbed which caused extensive ice scour, redirected streamflow, and enhanced channel instability (Clement 1999). Increased scouring associated with mechanical breakup may therefore explain the strong inverse relationship between erosion rate and spring air temperature found at this site. Shallow, braided reaches of other rivers may respond similarly to breakup severity. Erosion rate on a braided reach of the Tanana River, for example, showed a weak positive relationship with breakup date, perhaps due to sensitivity to ice-related erosion.

The timing of river ice breakup on the Tanana and Yukon rivers exhibited century-scale change, advancing by an average of 0.7 days/decade, similar to results from previous studies (Bieniek et al. 2011; Brown et al. 2018). As has been found throughout western Canada (Bonsal et al. 2006), breakup timing was also strongly influenced by the PDO, with a pronounced shift to earlier mean breakup date (mean= 5.5 days) when the PDO transitioned from a cool phase to a warm phase in 1976 (Fig. 9). We also found that mean breakup date was earlier (mean = 3.2 days) during the recent warm phase (1977–2017) relative to the historic warm phase (1922–1944), which suggests that the seasonality of springtime hydrology is responding both to multidecadal climate variability and to long-term climatic change.

Within the recent warm PDO phase (1977–2017), positive trends in monthly mean discharge were found in the spring for the Yukon and Tanana Rivers (mean = + 34%), when streamflow typically transitions from groundwater to snowmelt-dominated flow, while a decline in discharge in the summer (June, − 20%) was found for the Yukon River. These streamflow changes reflect a change in seasonality towards earlier snowmelt and freshet discharge. The increase in spring discharge may also be influenced by increased snowfall. Similar changes in seasonal hydrology were found in an earlier study (Brabets and Walvoord 2009). With warmer springtime air temperatures, an increase in the length of the snowmelt period has been detected throughout most sub-basins of the Yukon River since 1988 (Semmens and Ramage 2013). A more gradual snowmelt has likely contributed to calmer breakups and reduced freshet streamflow (Carothers et al. 2014; Herman-Mercer et al. 2011; Wilson et al. 2015; Woo et al. 2008). By extending the high flow season, the trend towards earlier breakup and spring freshet likely increases riverbank erosion in many areas. Yet, the opposing effect of reduced breakup intensity likely reduces erosion in areas highly impacted by ice scour or ice jam flooding.

4.3 Societal implications

These changes may have many different implications for rural communities in the region. Increased erosion rates can threaten infrastructure and property along riverbanks (Larsen et al. 2008), alter access to traditional subsistence resource areas (Brinkman et al. 2016), and impact fish and wildlife habitat (Durand et al. 2011). In some cases, these changes are challenging to subsistence harvesters. Increased erosion adds debris to rivers, which can tangle or destroy nets and fish wheels, and damage boat propellers (Cold et al. 2020). Rapid changes in the position of river eddies have adversely impacted the ability of subsistence fishers to set their nets and fish wheels in optimal locations within fishing seasons that are open for a short period of time (Cold et al. 2020). Increasing the flexibility of hunting and fishing regulations may provide more opportunities to align traditional practices with ideal environmental conditions for local harvest of subsistence resources. Enhanced channel change may also increase subsistence opportunities in some cases, for example, by creating or maintaining fish habitat (Bisson et al. 1987; Durand et al. 2011), or moose habitat through fluvial deposition and the colonization of early-successional vegetation (Chapin III et al. 2006). However, less spring scouring may decrease disturbance to adjacent terrestrial areas, which may reduce the abundance of early-succession vegetation such as willow, a key forage species for moose (Butler et al. 2007).

5 Conclusions

Our work demonstrates the association of subarctic riverbank erosion rates to (1) river discharge during the fall recession and low flow in winter and to (2) the timing of spring breakup and freshet discharge. Our findings suggest that riverbank erosion is generally enhanced along the Yukon and Tanana Rivers by increased fall and winter discharge and by earlier spring freshet, due in part to the longer duration of the ice-free/runoff-dominated high flow season. On the Chandalar River, however, earlier breakup is associated with reduced erosion, which we attribute to reduced breakup intensity in a river strongly influenced by ice scour. The seasonality of streamflow and ice cover of subarctic rivers both fluctuated with climate variability and exhibited long-term change. Overall, the trends towards earlier spring breakup/freshet and increased streamflow in fall/winter indicate increased erosion in the Yukon and Tanana Rivers, but reduced erosion on the Chandalar. Our results provide important information on potential physical processes that warrant more focused attention. With continued improvements in the spatial and temporal resolution of satellite imagery, future research will help clarify patterns and processes of bank erosion occurring at finer scales. Understanding the ways in which climate warming impacts fluvial dynamics will help communities to prepare for change and will help state and federal institutions adapt policies to foster effective local responses.

Acknowledgments We thank the subsistence harvesters who participated in this study and Christopher Arp and anonymous reviewers for their helpful feedback on this manuscript.

Funding information Funding for this study was provided by the NASA Arctic-Boreal Vulnerability Experiment (NNX15AT72A) and the National Science Foundation (1518563).

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