THE ROLE OF DYNAMIC ICE-BREAKUP ON BANK EROSION AND LATERAL MIGRATION OF THE MIDDLE SUSITNA RIVER, ALASKA

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Abstract

Rivers in northern, boreal regions experience winter ice formation that influences several geomorphic processes including bank erosion and lateral channel migration. Not only are the ice-driven processes complex and highly variable in time and space, but they are difficult to observe due to the logistical challenges of conducting fieldwork when the rivers are frozen in the winter and during ice breakup in the spring. Characterizing and quantifying the processes that drive bank erosion, whether during the summer open-water period or when ice is in the channel, is important for predicting channel dynamics in boreal rivers where there is a mixed ice-fluvial regime that is sensitive to on-going climate change. Of particular importance is understanding the erosional processes that form or maintain complex channel and riparian systems which in turn provide diverse aquatic habitat for a range of salmonid species. This study utilized an extensive set of field data and observations, to quantify the extent to which channel change is driven by ice and fluvial processes on the Susitna River, a large gravel-cobble bed river in south-central Alaska. Surprisingly, given the apparent dynamic nature of the river, longer-term rates of bank erosion (evaluated over 61 years) along the Middle Susitna River determined by aerial photo analysis (1951 – 2012) are relatively low in comparison to bank erosion rates reported along gravel-bed rivers, in general.

Aerial photography and videography over two one-year periods, 2011 to 2012 (included a thermal ice-breakup) and 2012 to 2013 (included a dynamic ice-breakup), were used to identify short-term erosion rates for distinct geomorphic reaches (single channel and multi-channel), determine the amount of erosion by the type of geomorphic surface and quantify when most bank erosion occurred annually; whether during the open-water season or when ice was in the channel, particularly during ice-breakup. The aerial imagery was supplemented by field observations and data collected along the Middle Susitna River over two field seasons and output from a 2-D (SRH-2D) depth-averaged hydraulic model.

The majority of bank erosion (measured as conversion of vegetated floodplain to unvegetated channel), 54 to 61 percent in single channel and multi-channel subreaches, respectively, occurs or is initiated over a short period of time during dynamic breakup of the river's ice cover in the Spring. The erosion is attributable to the combined effects of relatively high-water discharge and the presence of ice floes and ice rubble. Lower elevation vegetated bars as well as higher elevation fluvial terrace margins were the most susceptible to bank erosion, notably by impacting ice floes. Mid-elevation, active, densely vegetated floodplain surfaces, with margins partly protected by cantilevered vegetated rootmats, were much less susceptible to erosion.

The relatively low long-term erosion rates for the Middle Susitna River may partly be explained by the low frequency of dynamic, ice-breakup events that initiate large-scale bank erosion. Additionally, the longer term impacts of ice processes that result in the formation of gravel-cobble pavements at bank toes that reduce the potential for toe scour, and the extensive presence of cantilevered vegetation root mats that protect the vulnerable sand and silt

layers that overlie the lower bank gravels from fluvial erosion, limit the potential for bank erosion and lateral channel migration during the open-water period of the year.

Introduction

Understanding the processes that drive geomorphic changes is important for predicting future channel changes, especially for rivers in boreal regions that are particularly sensitive to a warming climate. The amount of erosion that is driven by the presence of an ice-regime has been quantified for some boreal rivers such as the Colville River, Alaska (Walker, 1973; Walker and Hudson, 2002) and Mackenzie River, Northwest Territories, Canada (Outhet, 1974), both rivers inset within permafrost terrain, where the majority of erosion occurs during or shortly after the ice-breakup period. The importance of the ice-regime and erosion on other boreal rivers such as rivers on Banks Island, Canadian Arctic (Miles, 1976), seems to be of less importance, where the majority of the erosion occurs during the open-water runoff period due to summer rain storms. Permafrost and drainage size may be indicators of the importance of an ice-regime on bank erosion processes (Scott, 1978) yet the importance of the ice-regime remains unknown for many rivers in boreal regions. Reported observations of the effects of ice on bank erosion on northern rivers (Marusenko, 1956; Smith, 1980; Beltaos, 1995; Zabilanksy et al., 2002; Prowse and Culp, 2003) include increased erosion during the ice-breakup period from ice run gouging, abrasion (Ettema and Kempema, 2012), and ice-jam release waves (Beltaos, 2018).

This investigation of erosional processes was conducted as part of a proposed hydroelectric project (Alaska Power Authority [APA] 1984, Alaska Energy Authority [AEA] 2012) on the Susitna River, Alaska. The objective of the investigation, using a synthesis of current and historical data and short-term erosion analysis over two one-year periods with distinctly different ice breakup regimes and open-water flows, was to characterize the extent channel change and lateral migration are driven by ice and fluvial processes.

Study Area and Background

The Susitna River is a predominantly gravel- and cobble-bed river, subject to long, frigid winter weather conditions. As shown in Figure 1 the river originates in the Alaskan Range and has been sub-divided into four large-scale geomorphic segments referred to as, Above Maclaren, Upper River, Middle River and Lower River, as it flows approximately 580 km to Cook Inlet near Anchorage, Alaska (Tetra Tech, 2015a). The most downstream, southerly geomorphic segments, including the Lower and Middle Susitna Rivers, do not flow through permafrost terrain.

The geomorphic segment analyzed for this study of bank erosion is referred to as the Middle River and extends 135 km downstream from the proposed dam site (RK 301) to the Susitna River confluence with its next two major tributaries, the Chulitna and Talkeetna Rivers, referred to as the Three Rivers Confluence (RK 165). Through this segment, the river alternates between primarily confined single channel reaches and multi-channel reaches in valley floor expansions zones. The active channel is between 260 m and 300 m wide, while the valley bottom width ranges from 625 m to about 720 m. A railroad on the east side of the river provides some, though limited, lateral constraint through a portion of the reach. The surface bed material, sampled at the heads of mid-channel bars and islands, is composed of gravel and cobbles with a median grain size (D_{50}) of 60-65 mm. Sampling of the bed material beneath the ice cover along the thalweg of the channel during winter, , yielded somewhat higher D_{50} values of 65 mm to 94 mm (Tetra Tech, 2014a).

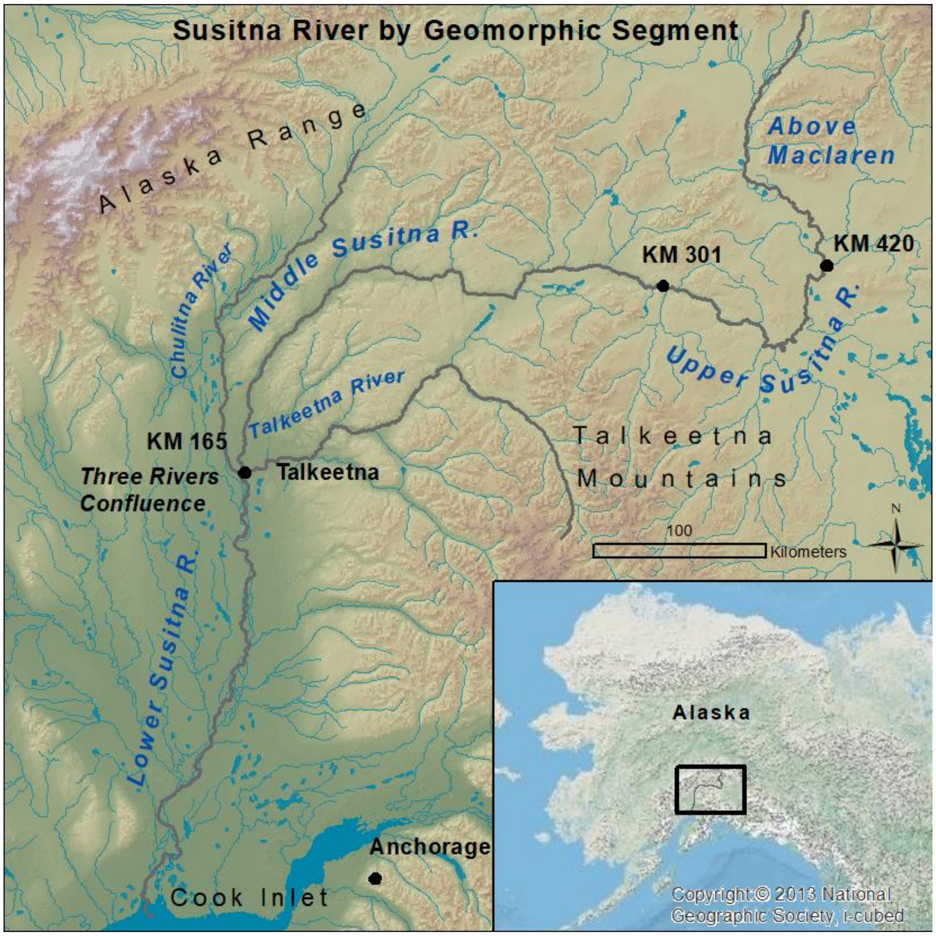

Figure 1. Geomorphic Segments along the Susitna River, Alaska (Vandermause, 2018).

Two reaches with different morphologies were selected for analysis within the Middle River. River kilometer (RK) 225.4 to RK 197.5 (Reach 6), and RK 197.5 to RK 173.6 (Reach 7). Reach 6 is a multiple channel reach with sediment storage in mid-channel bars, vegetated islands, and continuous floodplain segments. Reach 7 is a primarily single channel reach with limited sediment storage in mid-channel bars, vegetated islands, and non-continuous bank-attached floodplain segments. Wider valley bottom reaches with multiple channels and a suite of depositional lower-, mid-, and higher elevation surfaces are located upstream of valley floor constrictions. Multi-channel reaches are areas of higher ice activity which include larger sizes and numbers of ice-jams and ice runs, compared to single channel reaches (Beltaos, 1995).

The latest geomorphically-significant event in the Susitna River Basin was during the Little Ice Age, a Holocene-age glacial event that peaked in 1750 and begin to recede sometime between 1800 to 1850 (Luckman, 2000; Calkin et al., 2001; Reyes et al., 2006). Dendrochronology of present-day terrace surfaces along the Middle River is consistent with the timeline of glacial retreat. Terrace surfaces were defined as surfaces above the 100-yr open water elevation (Tetra Tech, 2015b). Channel degradation since glacial retreat has resulted in the development of terrace surfaces which occupy more than one-half of the non-channel valley bottom area. Meadows, open spruce-poplar forests and open spruce-paper birch woodlands are common vegetation types on terrace features. Less than one-half of the valley bottom area is composed of surfaces linked to the active hydrologic regime. The geomorphically-active river corridor is characterized by depositional surfaces categorized by elevation and top-of-bank vegetation

(Figure 2). As shown in Figure 2, there is a vertically-differentiated continuum that is dependent primarily on vertical accretion of the geomorphic surfaces over time (Leopold and Wolman, 1957). Vegetated bars at lower, more frequently inundated locations (overtopped between the 2-yr to 5-yr open water flows and comparable to the bank-full event) are colonized by willow-alder shrub vegetation which develop into poplar forests on low-to mid- elevation young floodplain surfaces (overtopped at approximately the 5-yr open water flow). With time and continued deposition, low elevation surfaces shift into mid-elevation mature floodplain surfaces (overtopped between the 20-yr to 50-yr open water flows) and slightly higher-elevation old floodplain surfaces (overtopped around the 50-yr open water flow) that are colonized by spruce-poplar forests and spruce-paper birch forests with increasing age.

Comparison of channel survey data since the 1980s along the active river corridor indicates no reach-wide degradation or aggradation trends (Tetra Tech, 2014e). Since the first period of aerial photography record, starting in 1951, the Middle Susitna River has experienced rather modest, reach-scale bank erosion and lateral migration. The channel has essentially maintained its planform, and only rarely have entire islands been completely eroded. Long-term rates of channel change over two 30-year periods (1951-1983 and 1983-2012), determined from aerial photography overlays (Tetra Tech, 2014b), are relatively low compared to the size of the river (approximately 5 percent of the total reach area or less). Long-term rates of lateral bank retreat are also low, averaging approximately 10 percent or less of the channel width over two 30-year periods. Long-term erosion rates compared to a compilation of channel migration rates for a number of similar sized gravel-bed rivers (Lagasse et al. 2004) indicate that bank erosion along the Middle Susitna is a factor of 10 less than for comparable channel systems (Vandermause, 2018). For contrast, vegetated islands on the unregulated, gravel-bed Fiume Tagliamento River (Italy), with a pluvio-nival snow regime, are typically eroded in 20 years or less (Gurnell et al., 2001).

The contributing drainage area of the Middle Susitna River at the closest gaging station (Gold Creek Station; USGS Gage No. 15292000) is approximately 16,000 km^2. The average annual flow of the Susitna River at Gold Creek is 277 m^3/s with high seasonal variability (Tetra Tech, 2013a). Flows decrease with receding temperatures through the late fall. Flows remain low through the ice-covered period when temperatures fluctuate between -4^{0}C and -12^{0}C, with an average monthly low in March of approximately 40 m^3/s. As temperatures rise and ice begins to melt within the basin, the ice breakup period typically occurs between late April and late May and consists of either thermal ice-breakups, dynamic ice-breakups, or a combination of the two (HDR Alaska, Inc. 2015). Peak flows correspond with the rise in temperature and melting of snow through the basin, with an average monthly flow of 745 m^3/s in June.

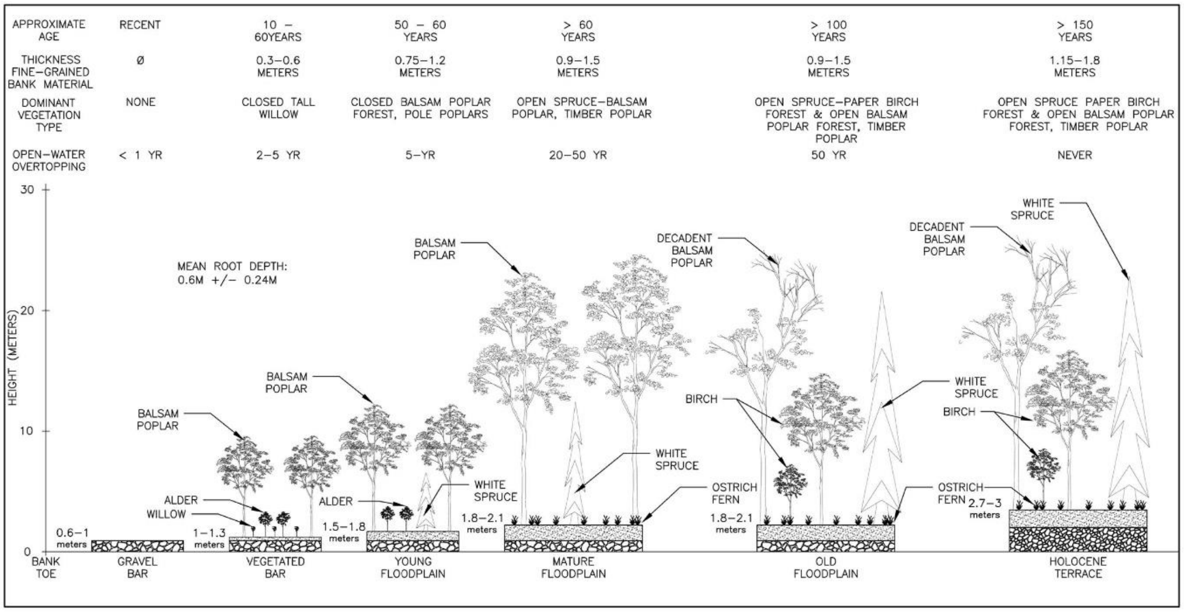

Figure 2. Geomorphic and vegetative succession of typical geomorphic surfaces in the Middle Susitna River (Vandermause, 2018).

Methods

Geomorphic mapping, field measurements, material sampling and observations were used to characterize geomorphic surfaces, bank height and morphology and stratigraphy (Figure 1) as well as the presence/absence of erosion and the primary modes of bank failure. Average open-water inundation frequency for each of the identified geomorphic surfaces was determined from a 2-D hydrodynamic model (SRH-2D) using the flow record from the USGS Gold Creek gage (No. 15292000).

Analysis of time-sequential aerial photographs and aerial videography was used to identify and measure short-term erosion, by geomorphic surface. The short-term erosion analysis was performed over two, one-year periods with distinctly different hydrologic regimes including varying open-water peak flow events and types of ice-breakup. The first period of analyses, shown in Figure 3, was between May 2011 through September 2012 and included two approximately 2-year flows, one flow between the 2-yr to 5-yr recurrence interval and a thermal ice-breakup. The second period of analysis, shown in Figure 4, was between September 2012 to September 2013 and included one 2-yr flow, one approximately 20-yr flow, one near 50-yr flow, and a dynamic ice-breakup.

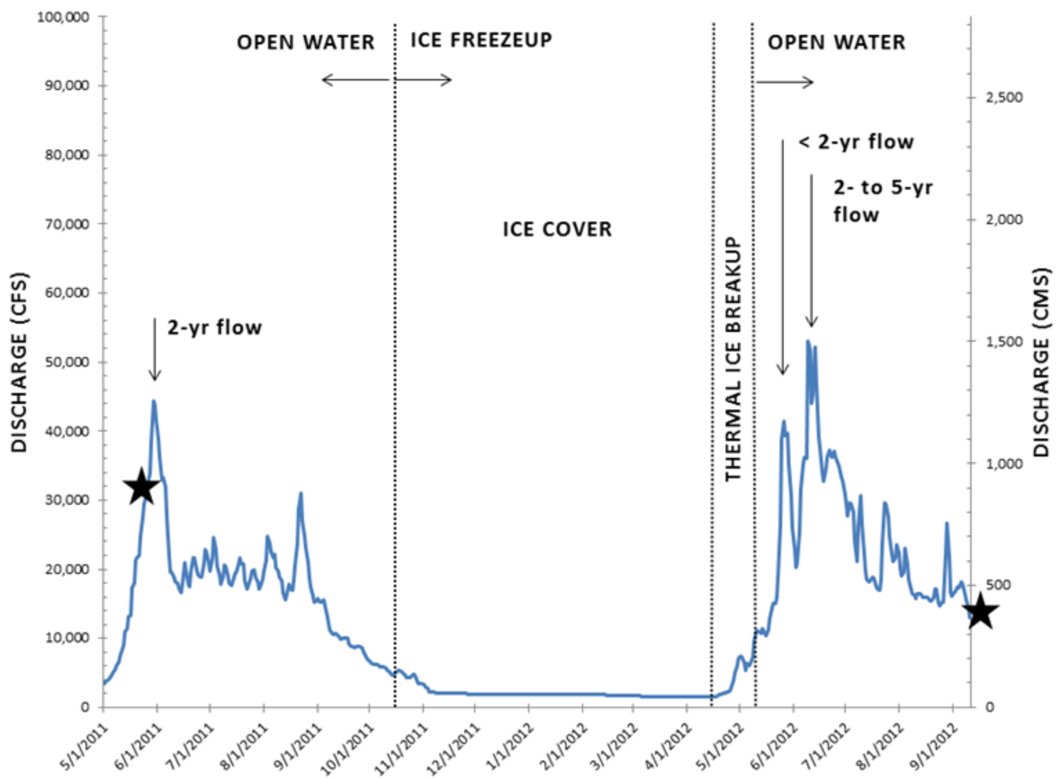

Figure 3. Mean daily discharge between 2011 and 2012 aerial imagery flights at Gold Creek gage. The black stars represent date of aerial photography flight.

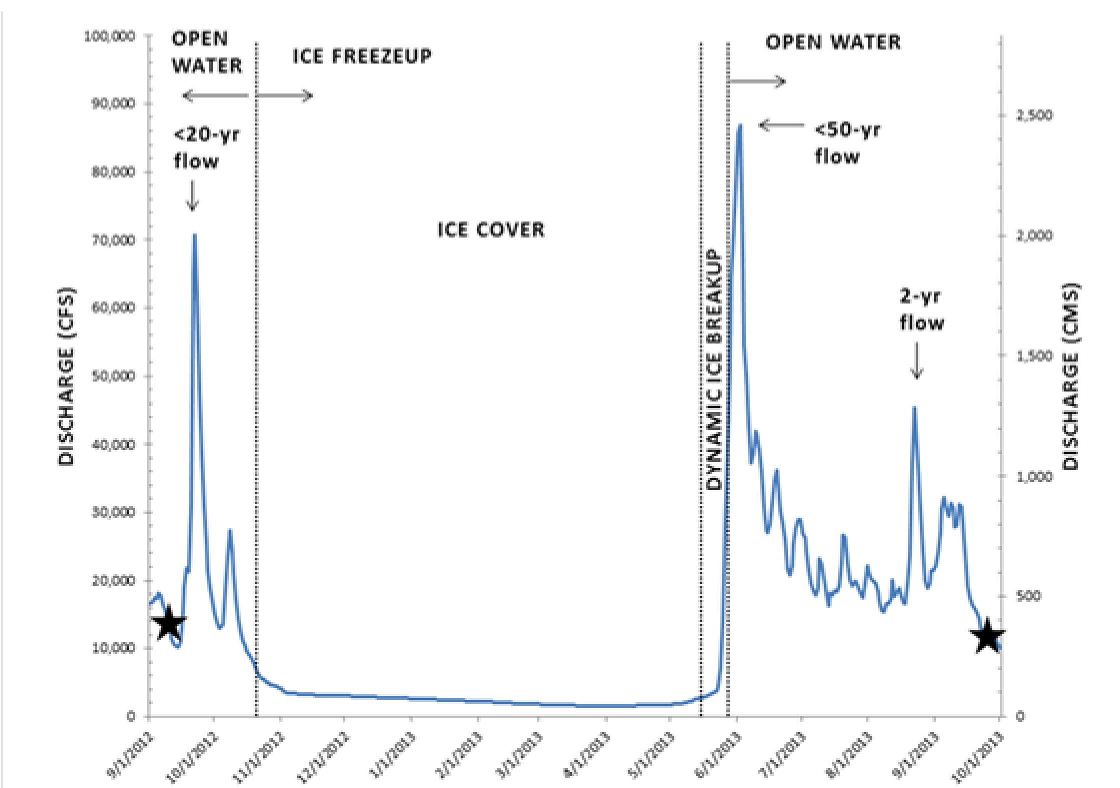

Figure 4. Mean daily discharge between 2012 and 2013 aerial imagery flights at Gold Creek gage. The black stars represent date of aerial photography flight.

Channel changes between the aerial photographs were categorized into approximate time period “bins” within the year: ice freeze-up, ice breakup, and the open-water period. Aerial reconnaissance videos flown periodically between the aerial photography flights, collected during ice-freeze up, ice-cover, ice-breakup, and post ice-breakup, were reviewed to attribute channel change to a specific time period within the year. Changes within the channel over each one-year period for both the geomorphic reaches (Reach 6, Reach 7) were categorized into two types of change: (1) Erosion: i.e., conversion from vegetated bar or floodplain to un-vegetated channel; and (2) Vegetation reset: the area of mature vegetation on a vegetated bar or floodplain that is converted to low-lying vegetation. Channel change was also linked to the identified geomorphic surfaces (Figure 2) in order to relate erosion to varying degrees of bank-resistance; where bank resistance is based on bank height, sediment composition and top-of-bank vegetation type.

Finally, short-term erosion rates and erosion by geomorphic surface over the two, one-year periods were compared to long-term erosion rates and erosion by geomorphic surface over two 30-year periods from 1951-1983 and 1983 to 2012.

Results and Discussion

Part 1 Bank Observations by Geomorphic Surface

The tops of all banks through Reaches 6 and 7 were vegetated with trees and shrubs, with the exception of very old floodplain surfaces or terraces where the tree vegetation succession has reached a point where trees are sparse and have been replaced by low-lying shrubs, grasses, and ostrich ferns. The absence of hydro-geomorphic conditions required for recolonization by the tree-dominated vegetation community precludes re-establishment of forest species.

The vegetated bars are composed of an approximately 1 m thick basal gravel unit overlain with about 30 cm of primarily sand. The bank toe is frequently paved or armored with gravels and cobbles, the bank profile is gradually sloping, and bank-top vegetation is composed of alders and willows. The vegetation is often disturbed by ice-push, but is resilient and able to regrow from an established root network.

The floodplain surfaces are composed of an approximately 1 m thick basal gravel unit overlain by about 80cm (young floodplain surface) to 1.2 m (mature floodplain surface) of interbedded sand and silt units that form a vertically-fining stratigraphic sequence that is typical of fluvial systems. The bank-top vegetation, composed primarily of dense poplars and spruces, develops extensive root mats that tend to provide effective cohesion to the low-cohesion sands and silts. The extensive root mats stabilize the upper bank (Simon and Collison 2002; Pollen and Simon, 2005) and buffer the abrasive effects of ice rubble moving along banks.

Erosion of the underlying, non-root reinforced sand and silts, causes the root mats to hang down over the bank faces forming what has been termed vegetation rip rap (Church and Miles, 1982) (Figure 5).

The extensive presence of overhanging vegetated rootmats along the Middle Susitna River indicates that these features persist for some time in stabilizing the bank, and thereby preventing significant lateral retreat during the open-water season. This reinforcing effect is, however, time-limited. In the short-term, protective rootmats can be removed by mechanical shearing of ice. However, the main time-limiting factor is the vegetation succession (Figure 2) where the trees reach the end of their life cycle and die off, that then leads to a lack of root reinforcement for the upper bank. Accordingly, the bank profile for the old floodplain and terrace surfaces will again be partially or completely exposed, and therefore becomes more susceptible to the erosive effects of ice and water flow.

Almost all banks showed some sign of ice disturbance. Ice effects, as expected, were more common and often more damaging to the overbank vegetation on lower geomorphic surfaces including vegetated bars and young floodplains. These lower geomorphic surfaces were often characterized by large swaths of ice-bulldozed vegetation or leaning pole poplars. While the effects of ice were present on higher surfaces including mature floodplains, old floodplains, and terraces, the effects were less pervasive than on the lower geomorphic surfaces and included tree ice-scars, ice-deposited cobbles or gravels on top of the bank, or pockets of bent and leaning trees.

The cantilevered bank is one of the most common bank forms along the Middle Susitna River. Erosional processes that contribute to this feature can be caused by water flow, ice-processes, or a combination of the two. Bank retreat occurs when the stress on the river's banks from applied external forces exceeds the bank's resistive properties. The location, magnitude and duration of applied external force are functions of a suite of variables: regional and local climate, water level, water depths, velocity, shear stress, presence of in-channel ice, and strength of in-channel ice. The effect of each variable changes throughout the year, but can generally be categorized based on the primary hydrologic regime. A schematic of erosional processes observed to occur along the Susitna River during each of the primary hydrologic regimes and associated values for discharge, velocity, bank condition, and ice-breakup type is presented in Figure 6. Ice-breakup type (i.e. thermal versus dynamic) is used as a proxy term indicating the strength condition of river ice.

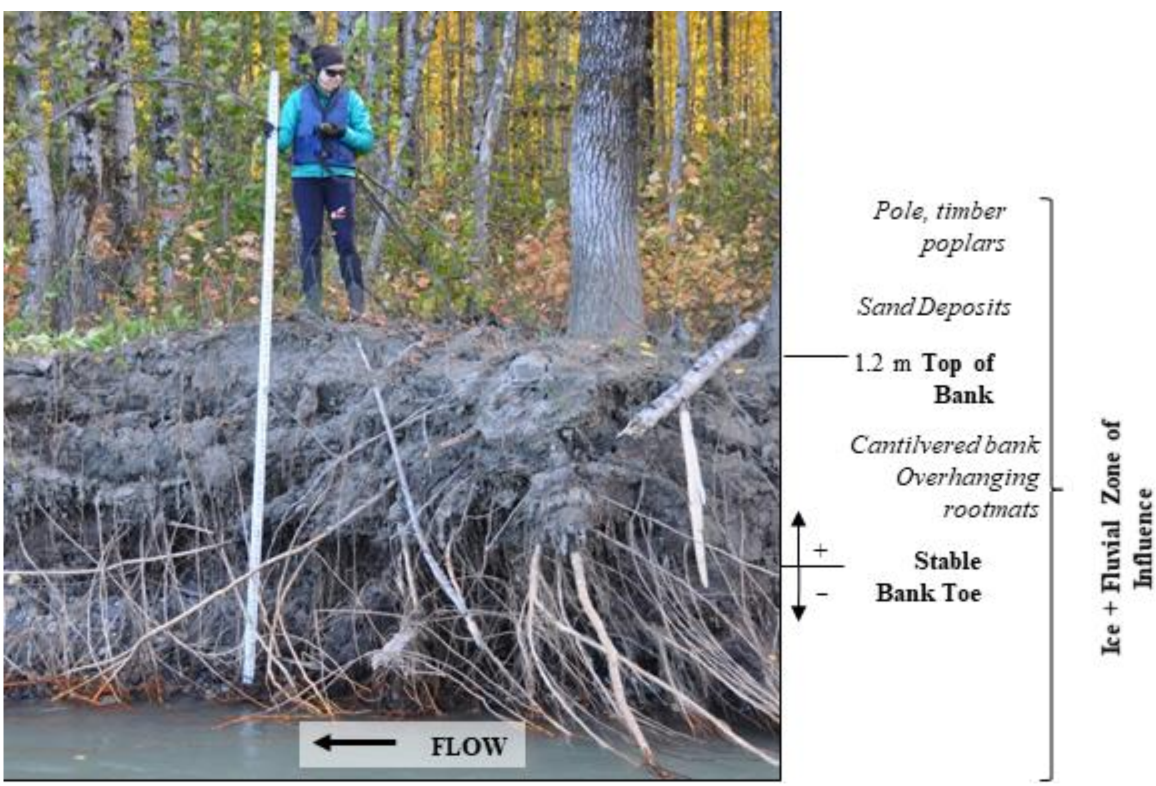

Figure 5. Photograph and schematic of cantilevered bank on active floodplain surfaces.

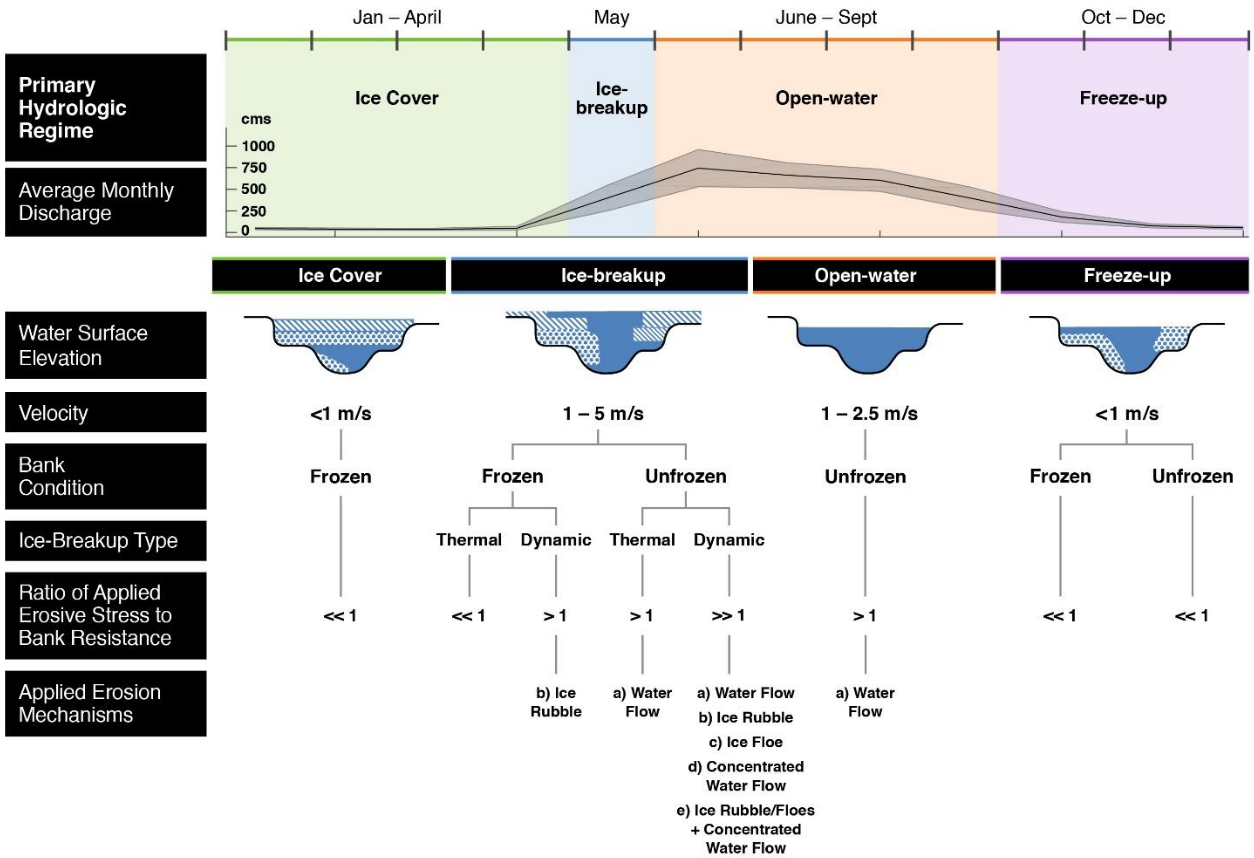

Figure 6. Schematic of hydrologic, hydraulic, bank conditions, and applied erosion mechanisms throughout the year (Vandermause, 2018)

Incipient motion calculations derived from the 2-D model results, indicate that fluvial shear stresses (even at the 100-yr recurrence interval) are unable to mobilize the bank toe sediments at many locations along the Middle Susitna River that have historically eroded (Tetra Tech, 2015c). Therefore, fluvial erosion can only occur when the shear stresses are sufficiently high to erode the sands and silts that are located above the basal gravel toe. This leads to cantilever failure of the upper bank materials (Thorne and Tovey, 1981; Church and Miles 1982; Collins, 1990).

The manner whereby river ice forms and moves along the river creates additional processes that may cause bank erosion. As erosional processes involving ice act in conjunction with water flow, making it difficult to differentiate effects due solely to ice or water flow, the combined effects are referred to as the "ice-driven regime." As summarized in Vandermause (2018), when ice blocks accumulate or are shoved along a bank, and are directly in contact with a bank, several factors may cause large-scale bank erosion along a root-reinforced cantilevered bank. From a synthesis of historical ice observations (during the 1980s), current ice observations (2012-2015), review of reconnaissance videos during the 2013 dynamic ice-breakup, results of 2D hydrodynamic modeling, and results from a numerical analysis of possible impact stresses exerted by ice, four ice-driven erosion processes were identified along the Middle Susitna River.

Erosion Process 1: Ice rubble (i.e., small ice blocks typically 10m or less wide and approximately 1m thick) abrasion and gouging. Ice rubble is conveyed downstream, largely parallel to banks, and shearing along bank faces. As most banks are protected with an upper layer of rootmats, this process was observed to scar, break, or remove some rootmats completely. Rubble impact appears to be more severe for banks at the head (i.e. upstream end) of the island or bar where ice rubble is conveyed directly into the bank. Removal of vegetation rootmats, exposes the unconsolidated fine-grained material above the gravel core to further entrainment by fluvial erosion. Overall this process was found to locally scar vegetation but results in limited lateral bank retreat.

Erosion Process 2: Ice floe (i.e., large blocks of ice ranging from greater than 10m to over 100m in width and approximately 1m thick) allision with banks and ride up onto low islands. Ice floes are capable of greater impact stresses than ice rubble, and were observed to bulldoze and completely removing top-of bank vegetation, in particular on low-elevation vegetated bars. While this process was found to significantly modify vegetation succession regimes (i.e. reset the vegetation succession), it had a more limited effect on bankline migration.

Erosion Process 3: Increased bed shear stresses due to flow constrictions or diversions from in-channel ice. While 1-D modeling of flow under an ice-cover on the Susitna River identified increased velocities (HDR Alaska, Inc., 2014b), shear stress values still did not exceed values required for bank toe mobilization. Observations during the 2013 ice-breakup revealed large main channel jams diverting all upstream flow into secondary channels, causing the banks to overtop and overbank flow on geomorphic surfaces that are not inundated during the same discharge under open-water conditions. While this process may cause entrainment of the surficial non-consolidated fine-grain material above the basal core, fluvial modeling of the diversion of water flow into secondary channels at a range of flows common during the ice-breakup period, did not produce shear stresses capable of exceeding critical shear at the bank toe (Vandermause, 2018). It is possible that flow surges from ice-jam breaks may cause sufficient bed shear stresses to mobilize the bed and bank (HDR Alaska, 2014d). Observations and modeling on other boreal rivers indicate surges released from ice-jam breaks have reached velocities not observed in open-water conditions (Beltaos and Burrell, 2005; Beltaos et al., 2018; Beltaos, 2018).

Erosion Process 4: Process 4 is a combination of ice rubble (Process 1), ice floes (Processes 2), and increased or diverted water flow (Process 3). While fluvial bed-shear stresses at unconstricted and constricted/diverted flows do not exceed critical shear values for bank toe mobilization, increased fluvial stresses coupled with ice-induced shear stresses are likely to cause bank erosion and consequent lateral retreat, as was observed during the 2013 ice-breakup.

Part 2 Erosion Analysis

Between 2011 and 2012 (thermal ice-breakup year) only 4 locations had identifiable lateral retreat. The locations of bank retreat were along the sides of mid-channel islands or bank-attached floodplain units and the distances did not exceed 10 m. Between 2012 and 2013 (dynamic ice-break up year), 63 locations had identifiable lateral retreat. The locations of bank retreat were along the sides of mid-channel islands, and bank-attached floodplain or terrace units and ranged from 10m to nearly 100m in distance (Table 1).

Overall, a majority of erosion in the two geomorphic reaches (61 percent of erosion in Reach 6 and 53 percent of erosion in Reach 7), and all vegetation scour, occurred predominantly during ice breakup or during both ice breakup and the open-water regime immediately after ice breakup. In Reach 6, only 3 percent of the eroded area (corresponding to one location) could be attributed solely to fluvial processes (i.e., occurring pre-freeze up during the open-water season). Given the hydrologic record during the fall of 2012 prior to freeze-up, it is likely that this bank eroded during the nearly 20-year flow event in late September. In Reach 7, no areas of erosion could be attributed solely to fluvial processes.

For both reaches, erosion during 2012-2013 was nearly 4 to 8 times the historical erosion rates, while erosion during 2011-2012 was minimal. Total erosion during 2012-2013 ranged from 10 to 30 percent of the total amount of historical erosion from 1951-2012. Between 2011-2012 erosion rates and total erosion were small fractions of historic rates of erosion. These rates indicate that large-scale erosion is episodic.

Table 2 summarizes the timing and likely erosion regime (i.e., fluvial or ice-related) for erosion occurring between 2012 and 2013. In Reach 6, about 40 percent of the erosion occurred in the ice-breakup window (May 25, 2013 – May 29, 2013). Another 20 percent, categorized as "Ice-breakup through fall", occurred sometime between the onset of ice-break up (May 25, 2013) and when the next imagery set was flown (September 2013). These locations were categorized within this larger time frame because the reconnaissance videos and photographs did not provide sufficient evidence that the location eroded during a specific event (i.e., only during breakup). Some of the videos taken during ice breakup viewed the locations via oblique angles of observation, thus hampering definitive categorization of erosion during ice breakup. Additionally, erosion at these locations was likely exacerbated by the subsequent high-flow event (nearly 50-year event) following breakup. However, review of the videos and photographs indicated that, for many of the locations that eroded during the ice-breakup to fall period, erosion was likely initiated during ice-breakup. This conclusion was determined based on the aerial flight images and on-the-ground photographs where trees were significantly ice-scarred and leaning over and lateral bank retreat was significant, ranging from 10 to 30 m. It is likely that open-water erosional processes also contributed to the prevalence of cantilevered banks along the Middle River; however, it is unlikely that open-water erosional processes contribute to large-scale bank retreat. This conjecture is based on an analysis of bank retreat at surveyed cross-sections. From a comparison of 60 cross-sections surveyed in 2012 and 2013 with 2014 LiDAR-based topography, only one location had identifiable, substantial erosion. During this time period, all cross-sections were subjected to a 2-year peak flow where the water-surface elevation was above the basal gravel core and adjacent to the non-cohesive sand and silt bank sediments and 60 percent of the cross-sections were subjected to a nearly 50-year peak flow that inundated the entire bank face.

Table 1. Total area of valley bottom-land, total eroded area, and erosion rates for Reaches 6 and 7 over four time periods.

Time Period	Valley Bottom Land Area (m^2)	Total Eroded Area (m^2)	Eroded Percent of Total Valley Bottom Land Area	Erosion (m^2/km)	Erosion Rate (m^2/km/yr)	Erosion (m/y)	Eroded percent of 1951-1983 Erosion	Eroded percent of 1983-2012 Erosion
Reach 6								
1951-1983	13,306,400	1,192,800	9.0%	42,800	1,300	1.3		
1983-2012	13,844,000	538,700	3.9%	19,300	700	0.7		
2011-2012	14,694,600	6,500	0.04%	200	200	0.2	0.5%	1.2%
2012-2013	14,694,600	158,100	1.1%	5,700	5,700	5.7	13.3%	29.3%
Reach 7								
1951-1983	9,471,200	318,200	3.4%	13,300	400	0.4		
1983-2012	9,418,000	151,100	1.6%	6,300	200	0.2		
2011-2012	9,978,800	0	0.0%	0	0	0.0	0.0%	0.0%
2012-2013	9,978,800	33,900	0.3%	1,400	1,400	1.4	10.7%	22.4%

Note:

1. All values are rounded to the nearest hundred
2. Valley Bottom Land Area is determined from the land area from 1951 for 1951-1983, from 1983 for 1983-2012, and from 2012 for both 2011-2012 and 2012-2013
3. Data sources for valley bottom land area and historical erosion rates can be found within Tetra Tech (2014c)

Table 2. Total Erosion from 2012-2013 (dynamic ice breakup year) categorized by time period of erosion.

Time, Regime (Duration of Period)	Reach 6	Reach 7
	Percent of Total Erosion from 2012-2013	
Fall through Pre-freeze-up, (~30 days)	3%	0%
Ice Breakup, Ice/Fluvial, (~5 days)	41%	7%
Ice Breakup Through Fall, Ice/Fluvial (~150 days)	20%	46%
Unclear	36%	46%

The magnitude of erosion by geomorphic surface is summarized in Table 3. Generally, there are similar trends in the magnitude of erosion for the three categories of geomorphic surfaces over the various time periods for each geomorphic reach. In Reach 6, excluding erosion that occurred between 2011 to 2012, the erosion of terrace surfaces (i.e., high banks with minimal upper bank root-reinforcement) was 40 to 50 percent of the total erosion during each time period. In Reach 7, 40 to 50 percent of the historical erosion also occurred on terrace surfaces. Between the time periods that vegetated bar surfaces were linked to erosion data (i.e., 1983-2012 and 2012-2013), erosion of vegetated bars composed nearly 25 percent of the total erosion while the active floodplain surfaces composed 25 to 33 percent of total erosion. The anomaly to this trend was in Reach 7; between 2012 to 2013, only 4 percent of the total eroded area occurred on terrace surfaces and 76 percent occurred on vegetated bars. Notably, for both reaches, excluding the period 2011 to 2012, approximately 75 percent of the total erosion was either on higher geomorphic surfaces or on vegetated bars, while approximately 25 percent of total erosion was on active floodplain surfaces. These findings indicate that most erosion occur on surfaces with less relative root reinforcement than the more active floodplains surfaces; for the terrace surfaces, root reinforcement, if present, is higher on the bank and less able to form "vegetation rip-rap" while vegetated bars are typically low enough in the channel to be overridden by ice, thereby negating protective qualities provided by root reinforcement.

The overall magnitude of bank erosion and erosion as percentage of valley bottom area by reach, was greater in the multi-channel reach (Reach 6) compared to the single channel reach (Reach 7). This is likely the result of more geomorphic surfaces susceptible to erosion including low-elevation vegetated bars and older, high-elevation old floodplains that are less protected by root-reinforced upper banks. Additionally, it is a result of the higher ice activity in multi-channel reaches upstream of constrictions that are more prone to ice-jam formation and consequently ice-induced diversion of flow and ice rubble, and ice jam breaks.

Table 3. Percent short-term and long-term erosion that eroded from terrace surfaces, active floodplain surfaces, and low-lying vegetation.

Time Period	Total Eroded Area (m^2)	Percent Erosion of Terrace Surfaces[1]	Percent Erosion of Active Floodplain Surfaces[2]	Percent Erosion of Low-lying vegetation[3]
		Reach 6		
1951-1983	1,192,200	45%	55%	n/a
1983-2012	538,400	53%	26%	22%
2011-2012	6,500	31%	69%	0%
2012-2013	158,000	39%	35%	25%
		Reach 7		
1951-1983	318,000	41%	59%	n/a
1983-2012	151,000	53%	20%	27%
2011-2012	0	0%	0%	0%
2012-2013	33,900	4%	20%	76%

Note:

1 Terrace surfaces were defined as land units within the valley bottom that were 1.5m higher than the 100-year water-surface elevation (Tetra Tech, 2015b).

2 Active floodplain surfaces were defined as land units within the valley bottom that were vegetated with mature tree-stands. For the 2011-2012 and 2012-2013 periods this was determined during the sequential aerial photography analysis. This constituted all of the area that was not terrace surfaces between 1951-1983 as there was no reliable method to determine what were mature tree stands or low-lying vegetation. For the 1983-2012 period this was determined by subtracting the total area of low-lying vegetation from the total area that eroded that was not a terrace surface.

3 For the periods 2011-2012 and 2012-2013, low-lying vegetation was determined during the sequential aerial photography analysis. For the period 1983-2012, low lying vegetation that eroded was determined as the amount of vegetation that established between 1951-1983 and subsequently eroded during 1983-2012.

Conclusions

Short-term erosion over a one-year period with a dynamic ice-breakup comprised 10 to 30 percent of long-term erosion (over two 30-year periods). Minimal lateral bank retreat occurred during a one-year period with a thermal ice-breakup. While both one-year periods of short-term erosion analysis experienced several flows above the 2-year recurrence interval and flows near the 20-year and 50-year recurrence interval, 2D depth-averaged fluvial modeling indicated shear stress at the bank toe often does not exceed the shear stress required for sediment mobilization even at the 100-year recurrence interval. Thus, a major driver for fluvial erosion is generally absent, most likely the result of long-term ice armoring and compaction of the bed material. A majority of erosion from 2012 to 2013 (53% to 61% for Reaches 7 and 6, respectively) was attributed to the ice-breakup regime. High short-term erosion rates during a dynamic ice-breakup year, minimal erosion during a thermal ice-breakup year, insufficient fluvial shear stresses even at high flows, and observation of erosion during the ice-breakup regime indicates that erosion, when it occurs, is episodic and driven by dynamic ice-breakups.

Low rates of channel change have been observed on other boreal rivers (Brice, 1971; Lewis and McDonald, 1973; Scott, 1978). Scott (1978) suggests that overall low long-term rates of erosion may be due to the timing of erosion where most erosion occurs in small increments during the annual spring breakup flooding. In contrast, this investigation of erosion on the Middle Susitna River indicates that the majority of erosion is episodic (at least 53 to 61 percent in both reaches), and occurs infrequently, the result of dynamic ice-break up. This finding has important implications for the maintenance of geomorphic complexity as a changing climate may affect the intensity and frequency of dynamic break up events.

References

Alaska Energy Authority (AEA), 2012. Revised Study Plan. Susitna-Watana Hydroelectric Project, FERC Project No. 14241 Submittal: December 14, 2012.

Alaska Power Authority, (APA) 1984. Draft Environmental Impact Statement. Susitna Hydroelectric Project, FERC Project No. 7114 – Alaska. Volume 1 – Volume 7. May 1984. ARLIS document number "APA 1653" at http://www.arlis.org/susitnadocfinder/.

Beltaos, S., 1995. *River ice jams*, Water Resources Publications, Highlands Ranch, Co., U.S.A.

Beltaos, S., 2018. Erosion potential of dynamic ice breakup in Lower Athabasca River. Part II: Field data analysis and interpretation. *Cold Regions Science and T echnology*, 148, pp.77–87.

Calkin, P.E., Wiles, G.C., Barclay, D.J., 2001. Holocene coastal glaciation of Alaska. *Quaternary Science Reviews*, 20(1), pp.449-461.

Church, M., Miles, M.J., 1982. Discussion on Processes and mechanisms of bank erosion. In: Hey, R.D, Bathurst, J.C., Thorne, C.R. (Eds), *Gravel-bed Rivers: fluvial processes, engineering, and management,* John Wiley & Sons.

Gurnell A.M., Petts, G.E., Hannah, D.M., Smith, B.P.G., Edwards, P.J., Kollmann, J., Ward, J.V. and Tockner, K., 2001. Riparian vegetation and island formation along the gravel-bed Fiume Tagliamento, Italy. Earth Surface Processes and Landforms, 26, 31-62.

HDR Alaska, Inc., 2015. 2014-2015 Study Implementation Report, Ice Processes in the Susitna River, Study 7.6. Susitna-Watana Hydroelectric Project, FERC No. P-14241 Filing: November 9, 2015. Prepared for Alaska Energy Authority, Anchorage, Alaska.

Leopold, L.B., and Wolman, M.G., 1957. River Channel Patterns: Braided, Meandering and Straight. U.S. Geol. Surv. Paper. 282-B.

Luckman, B.H., 2000. The Little Ice Age in the Canadian Rockies. *Geomorphology*, 32(3), pp.357-384.

Marusenko, Y. I., 1956. The Action of Ice on River Banks. *Priroda*, 12, pp.91-93. *In Russian*.

Outhet, D.N. 1974. Progress Report on Bank Erosion Studies in the Mackenzie River Delta, N.W.T. In: Hydrological Aspects of Northern Pipeline Development. Environmental Social Committee, Northern Pipelines, Task Force on Northern Oil Development, Report No. 74-12.Pollen, N., Simon, A., 2005. Estimating the mechanical effects of riparian vegetation on stream bank stability using a fiber bundle model. *Water Resources Research*, 41(7).

Prowse, T.D. Culp, J.M., 2003. Ice breakup: a neglected factor in river ecology. *Canadian Journal of Civil Engineering*, 30(1), pp.128–144.

Scott, K.M. 1978. Effects of Permafrost on Stream Channel Behavior in Arctic Alaska. Geological Survey Professional Paper 1068.

Simon A, Collison A.J.C, 2002. Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. *Earth Surface Processes and Landforms*, 27(5), pp.527-546.

Smith, D.G., 1980. River ice processes: thresholds and geomorphic effects in northern and mountain rivers. In: Coates, D.R., Vitek, J.D. (Eds), *Thresholds in Geomorphology*, George Alleen and Unwin, London, pp.323-345.

Tetra Tech, 2015a. Geomorphic Reach Delineation and Characterization, Upper, Middle, and Lower Susitna River Segments – 2015 Update Technical Memorandum. Attachment 1 to 06.05 Geomorphology Study 2014-2015 Study Implementation Report. Susitna-Watana Hydroelectric Project, FERC No. P-14241 Filing: November 2015. Prepared for Alaska Energy Authority, Anchorage, Alaska. 37 p.

Tetra Tech, 2015b. 2014-2015 Study Implementation Report, Geomorphology Study, Study Plan Section 6.5. Susitna-Watana Hydroelectric Project, FERC No. P-14241 Filing November 9, 2015. Prepared for Alaska Energy Authority, Anchorage, Alaska.

Tetra Tech. 2015c. 2014 Fluvial Geomorphology Model Development. Susitna-Watana Hydroelectric Project, FERC No. P-14241 Filing: November 2015; Study Completion and 2014/2015 Implementation Reports. Attachment 1 to 06.06 Fluvial Geomorphology Modeling below Watana dam 2014-2015 Study Implementation Report. Prepared for Alaska Energy Authority, Anchorage, Alaska. 100 p.

Tetra Tech. 2014a. Winter Sampling of Main Channel Bed Material. Susitna-Watana Hydroelectric Project, FERC No. P-14241 Filing: September 26, 2014; Technical Memorandum. Prepared for Alaska Energy Authority, Anchorage, Alaska. 68 p.

Tetra Tech, 2014b. Susitna River Historical Cross Section Comparison. Susitna-Watana Hydroelectric Project, FERC No. P-14241 Filing: September 17, 2014; Technical

Tetra Tech, 2014c. Mapping of Geomorphic Features and Turnover within the Middle and Lower Susitna River Segments from 1950s, 1980s, and Current Aerials. Susitna-Watana Hydrolectric Project, FERC No. P-14241 Filing: September 26, 2014; Technical Memorandum. Prepared for Alaska Energy Authority, Anchorage, Alaska.

Tetra Tech. 2013. Stream Flow Assessment. Susitna-Watana Hydrolectric Project, FERC No. P-14241. Prepared for Alaska Energy Authority, Anchorage, Alaska. 103 p.

Vandermause, R. 2018. The Role of Dynamic Ice-Breakup On Bank Erosion And Lateral Migration Of The Middle Susitna River, Alaska. Master's thesis. Colorado State University, Fort Collins, CO

Walker, J.H., Hudson, P.F., 2003. Hydrologic and geomorphic processes in the Colville River delta, Alaska. *Geomorphology*, 56(3), pp.291–303.Zabilanksy, L.J., Ettema, R.J. Wuebben, J. and Yankielun, N.E., 2002. Survey of River-ice Influences on Channel Bathymetry along the Fort Peck Reach of the Missouri River, Winter 1998-1999. United States Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover NH, Contract Report.