CGU HS Committee on River Ice Processes and the Environment
19th Workshop on the Hydraulics of Ice Covered Rivers
Whitehorse, Yukon, Canada, July 9-12, 2017.

Aerial Monitoring of Vegetation to Identify Ice-related Bank Erosion Along the Middle Reach of the Susitna River, Alaska

Renee Vandermause[1] and Robert Ettema[2]
[1] *TetraTech Inc., Fort Collins, CO, 80523*
renee.vandermause@tetratech.com

[2] *Civil and Environ. Eng., Colorado State University, Fort Collins, CO 80523*
Robert.Ettema@colostate.edu

Whereas many studies have been performed regarding variables that affect bank erosion along rivers that do not experience ice formation, far less studied is bank erosion along rivers that experience ice formation. Quantifying the erosive effects of ice along a large river reach is a complex and difficult undertaking; collecting data on a remote, sizeable river during the winter ice-period can be logistically difficult, costly and even dangerous. This study used extensive aerial imagery, and associated data, previously collected on the Susitna River, Alaska, to identify the extent ice-processes may lead to or possibly amplify bank erosion along a 50-kilometer stretch of the Middle River portion of the Susitna River. The analysis focused on changes in river-bank vegetation over two one-year periods (one with a thermal ice break-up and one with a dynamic ice break-up). It used reconnaissance videos and photographs at three time periods within the year, to identify ice-related erosion. Vegetated features from aerial photography images were digitized and overlain to identify bank erosion and channel changes. The images were then analyzed at ice freeze-up, ice-break up, and post high-summer flows to identify the timing and likely causation of erosion. The analysis found an extensive amount of vegetation retreat and removal to be driven by ice-related processes during high-flow, break-up events. The delineation of vegetation change, coupled with reconnaissance videos at key time periods, was found to be an effective method for delineating ice effects on the banks of the Middle Susitna River. A further finding is that ice effects were more pronounced for multi-channel reaches than single-channel reaches, because multi-channel reaches enable ice blockages to divert water and ice laterally into alternate channels or over low islands and bars.

1. Introduction

The present study was motivated by a proposed hydroelectric project involving a relatively high (221m) dam and large reservoir for the Susitna River, Alaska. The project prompted many studies to improve understanding of the river and identify the project's potential impacts. In the course of this effort the project generated an extensive archive of information regarding bank and channel conditions along the Susitna River, especially the reach that extends from the proposed dam site downstream about 100km to Susitna's confluence with the Chulitna and Talkeetna Rivers, and is the reach thought likely to be most affected by the hydroelectric project (Tetra Tech 2014a).

A unique aspect of this study was its access to a large archive of publically available aerial videos and photographs recording bank and channel conditions along the Susitna River. This video archive and an associated data archive were assembled during 2011 through 2015, and present an opportunity to evaluate the extent to which ice affects the banks of a major, permafrost-free Northern River over a reach-scale; i.e., a relatively large river subject to long, frigid winter weather conditions.

This paper presents aerial monitoring as a method to identify large-scale channel change (i.e., greater than 30 m x 30 m) owing to water flow and ice-related processes. Through the use of consecutive aerial imagery datasets and aerial reconnaissance videos and photographs taken at key time periods within the year (freeze-up, break-up, and open-water flow), the magnitude, location and timing of large-scale channel change was determined. The method, augmented by on-the-ground observations was used to address three questions:

1. To what extent do ice-related processes influence lateral bank retreat and vegetation removal along the Middle Susitna River?
2. What ice-related processes caused the changes?
3. What factors mitigated the ice-related processes?

Illustrative insights were obtained for the Middle Susitna River regarding each of these questions. The insights likely pertain generally to all rivers subject to frigid winter conditions. Note that this paper retains the designation of Project River Mile (Mile) developed as part of the Susitna-Watana project in terms of mile units; for simplification herein they are referred to as "Mile."

2. Background on the Middle Susitna River

By way of context to the extents of channel and bank erosion along the Middle River it is useful to consider briefly the overall geomorphology, air temperatures, magnitudes of water flow, and character of ice formation and break-up.

2.1 Geomorphology

The Susitna River (Figure 1) downstream of the proposed dam is conventionally described in terms of two segments: the Middle Susitna River (Middle River) from the proposed dam site at Mile 187.1 downstream to the Susitna's confluence with the Chulitna and Talkeetna Rivers at the Three Rivers Confluence (Mile 102.4); and, the Lower Susitna River (Lower River) from the Three Rivers Confluence downstream to Cook Inlet at Mile 3.3 (Tetra Tech, 2015a). Due to the possible mitigating effects of the large inflows of water and sediment from the two major tributaries, it is thought that the Lower Susitna River Segment would be far less affected by the proposed dam than would the Middle Susitna River (Tetra Tech, 2014a). Additionally, the dynamic nature of the Lower River appears to be driven more by its open-water hydrologic and sediment regimes than an ice regime (Tetra Tech, 2015a). This could, in part, be due to the shallow aspect and wide lateral extent of the Lower River (up to 1.6km wide) that can diffuse the erosive effect of an ice event.

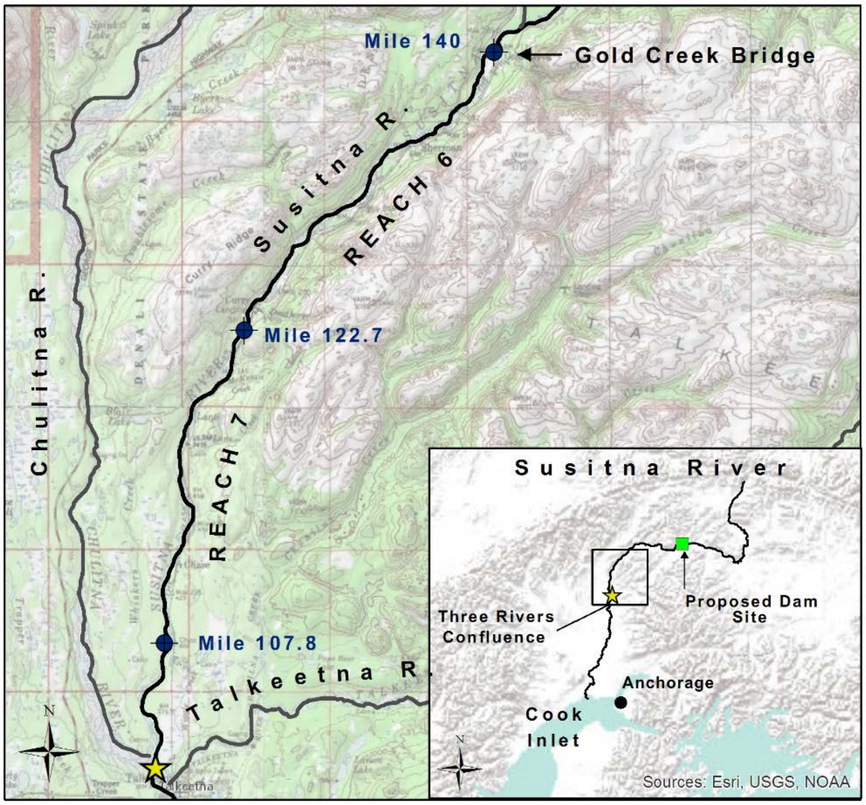

Figure 1. Indicated, is the extent of the Study Area along the Susitna River, Alaska. (Data source: ESRI Basemaps)

The Middle River comprises the portion of the Susitna River downstream of a bedrock canyon and upstream of the Three Rivers Confluence (Tetra Tech, 2015a). This area is confined for the present study (Figure 1) to 53.7km, from Mile 140 at the Gold Creek Bridge to Mile 107.8, and was selected for three reasons: (1) it encompasses multi-channel units, with constrictions, expansion zones, and mid-channel islands that are preferential for ice-jam development (Geomorphic Reach 6, Figure 2b); (2) it encompasses single channel reaches with limited sediment storage (Geomorphic Reach 7, Figure 2a); and, (3), for reasons of time and personnel limits, the entirety of the Middle River study area is reduced from 135km to 50km, while still covering a large enough area to test the methodology on a reach-scale.

The study area is inset from Cretaceous Kahiltna Flysch with undifferentiated Upper Pleistocene moraines, kames, and lacustrine deposits (Tetra Tech 2015a). The sinuosity, ratio of the channel length to valley length, ranges from 1.05 to 1.09. The channel bed is composed of gravel and cobbles with a median grain size of 60-65mm.

Geomorphic reaches have been delineated and described as part of Tetra Tech 2015a; a summary of reach characteristics are presented in Table 1. Geomorphic Reach 6 (Reach 6), from Mile 140.0

to 122.7 Mile, is a laterally confined single channel with sediment storage in mid-channel bars, vegetated islands, and continuous floodplain segments. The reach contains the widest valley bottom area in the Middle Susitna River (aside from just upstream of the Three Rivers Confluence) and is composed of a series of multi-channel units containing a range of channel conditions (fast and deep main channel, shallower side channels, and shallow sloughs) and a range of geomorphic surfaces (gravel bars, vegetated bars, low-lying floodplain units with young vegetation (less than 30 years old), and higher floodplain units with more mature vegetation (greater than 30 years old and up to 150 years old).

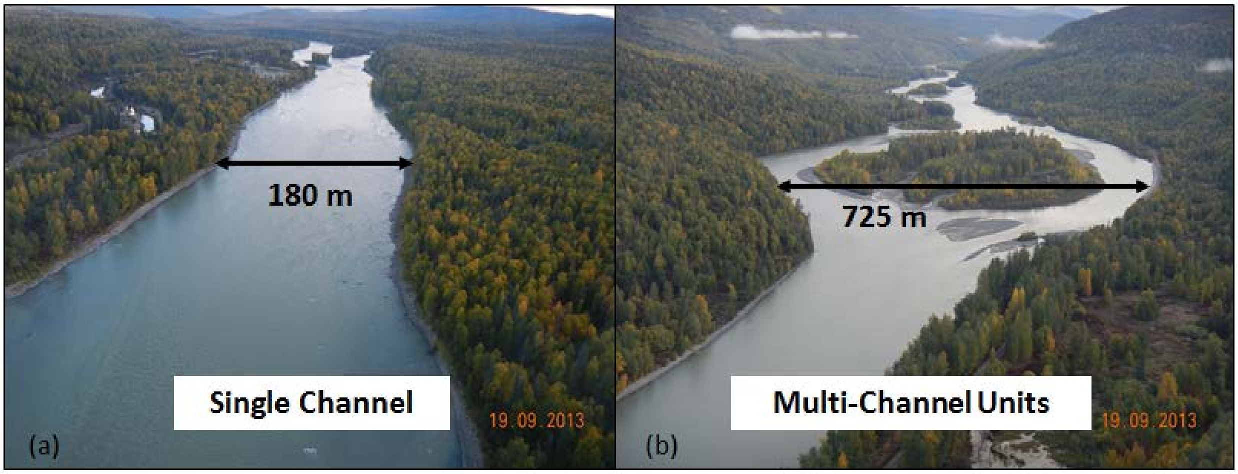

Figure 2. Aerial view upstream in Middle Susitna River: (a) a single channel reach with bank attached floodplain and limited in-channel sediment storage; and, (b) a multi-channel reach with mid-channel bars and island. (Photo Source: Tetra Tech 2015b)

Geomorphic Reach 7 (Reach 7), from Mile 122.7 to Mile 107.8, is a laterally confined single channel with limited sediment storage in mid-channel bars and non-continuous bank-attached floodplain segments. As this reach is more confined, there is a less diverse range in channel conditions and geomorphic surfaces compared to Reach 6.

Table 1. Geomorphic characteristics of studied reaches in Middle Susitna River.

	Geomorphic Characteristics				
	Length (km)	Bed Slope	Valley Bottom Width (m)	Active Channel Width (m)	Number of Channels
Reach 6	27.8	0.0020	716	300	2.4 +/- 1.1
Reach 7	24.0	0.0016	625	258	1.8 +/- 1

2.2 Monthly Temperature and River Flows

The contributing drainage area of the Susitna River near the closest gaging station at Gold Creek (Mile 140) is roughly 16,000km^2. The average annual flow of the Susitna River at Gold Creek is 277 cms with high seasonal variability. Average monthly temperature nears 0^{o}C in October and fluctuates between -4^{o}C and -12^{o}C through the winter. Flows remain low through the ice-covered period with an average monthly low in March of about 40 cms. By April temperatures have just risen above freezing and continue to rise to roughly 16°C by July. Peak flows correspond with the rise in temperature and melting of snow through the basin, with an average monthly flow of 745cms in June. Average monthly flows are plotted with the open-water recurrence intervals at the Gold Creek Gage in Figure 4. Typical ice cover, ice break-up window, and open-water periods are also illustrated in Figure 4. These time periods operate on a sliding scale depending on temperature and runoff.

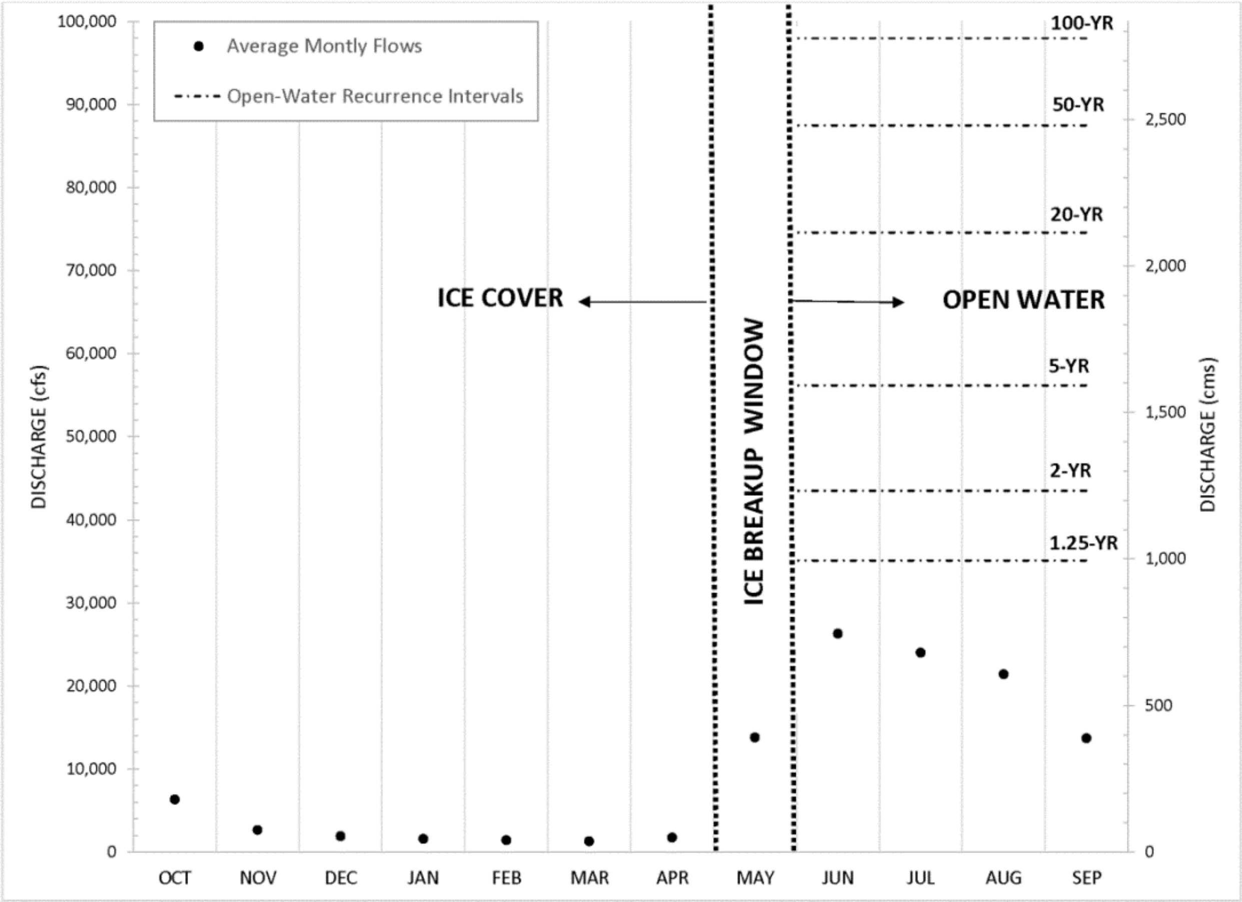

Figure 4. Monthly average flows with open water recurrence intervals through the Middle Susitna River at Gold Creek Gage. (Data source: Tetra Tech 2013)

2.3 Overview of Ice Processes

A summary of freeze-up and break-up ice processes along the Middle Reach was synthesized from University of Alaska Arctic Environmental and Data Center 1984, HDR 2014a-c, and HDR 2015.

Freeze-up: Floating frazil is typically observed in the Middle River when average daily air temperatures reach 0°C at Talkeetna Airport. Frazil and anchor ice are largely generated upstream in Devils and Vee Canyons. This ice accumulates in loosely bounded slush floes and either passes through Middle River into the Lower River and down to Cook Inlet or may melt away. Once discharge drops to around 142 cms at the Gold Creek station (Mile 140) around late October or early November, ice-cover progression begins, starting in the Lower River. Border ice usually begins to form by the accumulation of frozen slush layers along the shore before the passage of the ice front. An ice bridge usually forms upstream of the Three River's Confluence (downstream extent of the Middle Susitna River) and forms the leading edge of an ice front that eventually progresses upstream into the Middle River. Ice-cover progression begins in the Middle River as early as late October in very cold years but has occurred as late as January in warm years. Typically, ice cover progression in the Middle River occurs sometime in November and progresses upstream to Gold Creek by mid-December. Discharge decreases through December, averaging between 40 to 70m^3/s at the Gold Creek gage. Despite the very low discharges, the increased resistance due to the ice cover can cause the stage to increase between 1 to 2.5m at times. This can cause many sloughs and side channels to become overtopped. Though many sloughs may never experience freeze-up induced flooding at their upstream ends.

***Ice Cover*:** While the ice cover typically remains stable through the winter, open water leads persist where the flow is fast and turbulent (velocity leads) and where groundwater upwelling occurs (thermal leads) in sloughs, side channels, and bank toes. The discharge decreases through the winter and reaches a minimum sometime in mid- to late-March. Accumulation of frazil and anchor ice beneath the ice covers continues in slower velocity areas.

***Break-up*:** A pre-break-up period usually occurs sometime in April, when snowmelt first occurs at lower elevations in the basin. As water levels rise due to snowmelt and precipitation, overflow often occurs onto the ice. Standing water appears in sags and depressions on the ice cover, which eventually deteriorate into open leads. As the water levels rise and erode the ice cover, blocks break-up and drift downstream forming ice jams. When discharges are high enough to break and move the ice sheet and jams, the break-up drive begins. This break-up drive is largely driven by climatic conditions and typically occurs between late April and late May.

Water levels can increase rapidly behind an ice jam bringing water and ice into side channels, sloughs, and onto the floodplain. With the absence of other high pulse flows to flush the ice out of the side channels or slough, they typically will melt in-situ, leaving a film of silt and sediment that accumulated on top of the ice floes. In contrast, continued high flows and break-up jam flooding can flush the ice floes from the side channels and overbank, causing fluvial entrainment of bank materials, as well as delivering large ice blocks into the banks and trees. This process of ice jam formation and releasing occurs until all the jams are swept downstream and only rafted ice blocks remain in some side channels, sloughs, gravel bars, and overbank until they melt in place.

2.4 Channel Mobility

The Susitna River has remained relatively stable vertically (last 30 years) and laterally (last 60 years). Since 1951, when the first large-scale aerial imagery was collected, the Middle River has been subjected to some, but rather limited, large-scale channel change. For example, over 61-years, while lateral retreat has occurred, rarely have entire islands been removed (Tetra Tech, 2014d). In contrast, vegetated islands on unregulated, gravel-bed channels typically last no more than about 20-years; e.g. the Fiume Tagliamento River draining the Southern Alps (Gurnell et al. 2001). Additionally, there has been no reach-wide trend towards aggradation or degradation. Cross-sections surveyed in the 1980s were compared to cross-sections surveyed in similar locations in 2012 and 2013 and evaluated for changes in average bed elevation (Tetra Tech 2014e); of the 18 cross-sections through Reaches 6 and 7, 11 of the cross-sections showed no to minimal change (less than 1ft in change), 4 cross-sections aggraded while 3 cross-sections degraded. Further, incipient motion calculations using results from a 2D numerical model of open-water flow, indicate that shear stresses even at the highest flows, are unable to mobilize the bank toe at locations that have historically eroded (Tetra Tech 2015c).

Erosion at these historical locations is likely not only fluvially induced (e.g., continued cantilevered failure from entrainment of the sandy bank material) as many of these locations have heavily vegetated banks with extensive protective rootmats. Many roots are ice-abraded or have a downstream directional bent. Ice-scars are prevalent on trees on mid-channel islands and bank attached floodplains (R2 Resource Consultants, 2015). Thus, given the rather large open-water hydraulic forces present on the Susitna River, the limited large-scale change is of interest and suggests that ice forces may be necessary in order to exceed the river's erosion threshold to mobilize the bank toe or shear away bank material.

3. Aerial-Monitoring Method

The method used aerial photographs of two reaches of the Middle Susitna River: Reaches 6 and 7. The photographs were collected in June 2011, September 2012, and September 2013. Due to intermittent, above-freezing temperatures during April 2012, and cool temperatures in May 2012, the ice cover weakened and decayed in place before larger discharges passed through. The break-up that did occur was gradual – thermal break-up – due to weak ice blocks that could not form large jams. The river was largely ice-free by May 9, 2012. In contrast, cold weather in April and May 2013 maintained much of the snowpack until temperatures swiftly increased to well above freezing and initiated rapid snowmelt and major runoff flow. The ice cover, still relatively strong when it began to break, was able to form large jams that broke and reformed, as ice progressed downstream – dynamic break-up. The river was largely ice-free nearly three weeks later than 2012, by May 29, 2013. Both one-year periods experienced high open-water flow events (above the 5-yr recurrence interval). Thus, the main hydrologic distinction between the time periods was the intensity and severity of the ice breakup.

Vegetated features were delineated from 2011, 2012 and 2013 aerial photography. For each year land features were then categorized as a vegetated feature with tree stands (i.e., a floodplain) or a vegetated feature with low-lying vegetation (i.e. vegetated bar). The shapefiles from each year were overlain to identify channel change. As very thin polygons can form due to slight differences in delineation (stemming from the scale the feature was delineated at [1:1000 to 1:4000] or errors due to the tree canopy or shadows), any polygons less than 930 sq. meters (10,000 sq. ft) were removed from the analysis. Additionally, polygons roughly 15m (50 ft) in width were categorized as "less than 15 m". These polygons often were slivers that extended along the banks of most features throughout the reach and were likely due to slight differences in delineation rather than actual channel change. Polygons larger than 930 sq. m that indicated channel change (e.g., 2012 vegetation to 2013 channel, or 2012 trees removed to 2013 low-lying vegetation) were reviewed to assess whether change did in fact occur. If polygons roughly 15m or less were found to have observed channel change, they were then flagged. Possible errors due to delineation or feature categorization were also possible with the larger polygons therefore features were identified as "yes" for observed channel change, "no" for no channel change, or "unclear". All locations flagged with observable channel change were reviewed using reconnaissance videos. Thus, the areas of observable channel change provide a minimum value for the total amount of erosion that occurred over the two one-year periods given that areas designated as "unclear" or "less than 15 m" may in fact have eroded but were not included in the total erosion summation. To compare this one-year vegetation change data with the longer-term turnover data developed as part of Tetra Tech (2014d), polygons within the turnover shapefile between 1951, 1983, and 2012 were summed only for areas greater than 930 sq. meters.

Videos of the river corridor, taken during helicopter reconnaissance flights of ice-freeze up, ice-break-up, and during the open-water season were then assessed to identify whether the channel change occurred pre ice-freeze up, during ice-break-up, or post ice break-up. Instances of channel change that were roughly 15 m or less in width, or were along a continuous bank line with no distinguishing geometric differences in bank shape or composition (e.g. various fallen or removed trees), between the imagery flights, were found to have an indistinguishable time period of channel change. Accordingly, periods of channel change fell into four categories: pre-freeze-up, ice-break-up, ice-break-up through the next imagery flight (i.e., fall), or unclear. Erosion categorized during an unknown time period could be due to fluvial, ice, or a mixture of both processes. Erosion categorized as “ice-break-up through Fall” (when the next aerials were flown) was likely largely driven by the ice break-up due to the nature and extent of erosion, however no definitive photographs during the likely time period of erosion (due to poor visibility or no visibility) were acquired.

4. Results

Results include observations and data for two classic conditions of ice-cover break-up along the Middle River:

1. Thermal break-up, by which an ice cover largely weakens and disintegrates in situ; and,
2. Dynamic break-up, by which the ice cover is relatively strong when broken by substantial increase in flow, and ice rubble was then conveyed abrasively downstream, forming multiple break-up ice jams.

Not surprisingly, the latter condition caused by far the greatest changes in channel morphology, especially for multi-channel Reach 6. These observations are compared with observations made since 1951.

4.1 Extent of Channel Change

Erosion from 2011-2012 and 2012-2013 are presented with historical erosion rates in Table 2. Historical erosion rates were developed and presented in Tetra Tech (2014d). For both geomorphic reaches, erosion during 2012 to 2013 constituted nearly 4 to 8 times the historical erosion rates while erosion during 2011 to 2012 was nominal. Total erosion during 2012 to 2013 ranged from 10-30 percent of the total amount of historical erosion. Between 2011 to 2012 erosion rates and total erosion was only a fraction compared to historical erosion. While gradual lateral retreat may occur along the Susitna River, these rates indicate that large-scale erosion is episodic.

Table 3 summarizes the area of erosion in addition to the area of vegetation that has been removed over each one-year period of analysis. Of the eroded area, 75 percent was characterized as mature tree stands (young floodplains, mature floodplains, and old floodplains) while 25 percent was low-lying vegetation (i.e., vegetated bars). The amount of low-lying vegetation converted to channel over the one-year period, indicates that more erosion could have occurred between the 30-year time periods, however it would not be accounted for if vegetation established sometime before the next set of aerials was flown. Therefore these erosion values are minimum thresholds for the total area of land converted to channel.

Table 2. Total valley bottom land area, 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 (m^2/km/yr)	Eroded percent of 1951-1983 Erosion	Eroded percent of 1983-2012 Erosion
MR-6							
1951-1983	13,306,400	1,192,800	9.0%	42,800	1,300		
1983-2012	13,844,000	538,700	3.9%	19,300	700		
2011-2012	14,694,600	6,500	0.0%	200	200	0.5%	1.2%
2012-2013	14,694,600	158,100	1.1%	5,700	5,700	13.3%	29.3%
MR-7							
1951-1983	9,471,200	318,200	3.4%	13,300	400		
1983-2012	9,418,000	151,100	1.6%	6,300	200		
2011-2012	9,978,800	0	0.0%	0	0	0.0%	0.0%
2012-2013	9,978,800	33,900	0.3%	1,400	1,400	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 2012 for both 2011-2012 and 2012-2013
3. Data sources for valley bottom land area historical erosion rates can be found within Tetra Tech (2014d)

Of note is the similar magnitude of vegetated area that has been removed in Reach 6 (i.e., vegetation removed and eroded to low-lying brush while the bar formation was not significantly changed morphologically) in comparison to that which has been eroded (i.e., both the vegetation and bank composition removed completely and converted to channel).

Table 3. Area of erosion and vegetation removal for two one-year periods.

Type of Channel Change	Type of Ice Break-up Year	
	Thermal	Dynamic
Reach MR-6		
Erosion (m^2)	6,500	158,100
Vegetation Removal (m^2)	0	141,000
Reach MR-7		
Erosion (m^2)	0	33,900
Vegetation Removal (m^2)	0	0

Note: All values are rounded to the nearest hundred

From 2011-2012, no large-scale bank retreat occurred in Reach 7 and only 4 locations were identified in Reach 6. The locations that experienced lateral bank retreat were along the sides of mid-channel islands or bank-attached floodplain units. Lateral retreat did not exceed 10m. Due to the nature of channel change, the time period of erosion could not be distinguished from the reconnaissance videos or photographs.

Figures 4a&b are pie diagrams illustrating the time period of erosion between 2012 and 2013. In Reach 6, only 3% of eroded area (corresponding to one location) could be attributed solely to fluvial processes (i.e., occurring pre-freeze up during the open-water regime). Roughly 40% of erosion occurred between the break-up window (May 25, 2013 – May 29, 2013). Another 20%, categorized as "Ice break-up 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 break-up). Review of the videos and photographs indicated that, for many of the locations that eroded during the period ice break-up to fall, erosion initiated during ice-break-up. Videos during break-up viewed the locations via oblique angles of observation, thus hampering definitive categorization of erosion during ice break-up. Erosion at these locations could also have been corroborated by the subsequent high-flow event (nearly 50-year event) following break-up. If the geometric nature of the bank remained the same (e.g., a concave banked remaining a concave bank), then identifying an erosion timeframe was problematic and the location was categorized as "unclear; this category constituted 36 percent of the erosion in Reach 6. Insights from 2D modeling of open-water flow indicate that even very rare high flow events were unable to mobilize bed material at many locations in a multi-channel reach (Tetra Tech 2015c). Therefore, it is likely that many locations identified as "unclear" actually eroded from a mix of ice and fluvial processes during ice-break-up.

In Reach 7, about 7% of the eroded area occurred during break-up. As the nature of erosion at most of locations within Reach 7 involved the shearing of floodplain material from along the side of mid-channel islands or bank attached floodplain units, rather than large-scale erosion at the head of an island (as was the case for many erosion locations in Reach 6), it was often difficult to discern when the erosion occurred. Nearly half of the erosion appeared to start during ice-break-up but its exact timing was unclear; consequently the erosion was categorized as "Ice break-up through fall." No eroded locations in Reach 7 occurred during pre-freeze-up.

Overall, a mixture of ice and fluvial processes account for a majority of erosion through both geomorphic reaches. All vegetation removal in both reaches occurred during the ice-break up window. Additionally, for any time period, Reach 7 had less of its total valley bottom area (by percentage) eroded in comparison to Reach 6. Thus, erosion is occurring less in single channel meandering reaches or split-channel reaches in comparison to multi-channel reaches. As the study reach runs west-southwest, it is possible that local temperature gradients may cause Reach 7 to begin thawing and breaking up before subsequent ice floes from upstream begin moving downstream. The simplified geomorphic nature of Reach 7, may also limit the magnitude of ice jams that form, break, and form again.

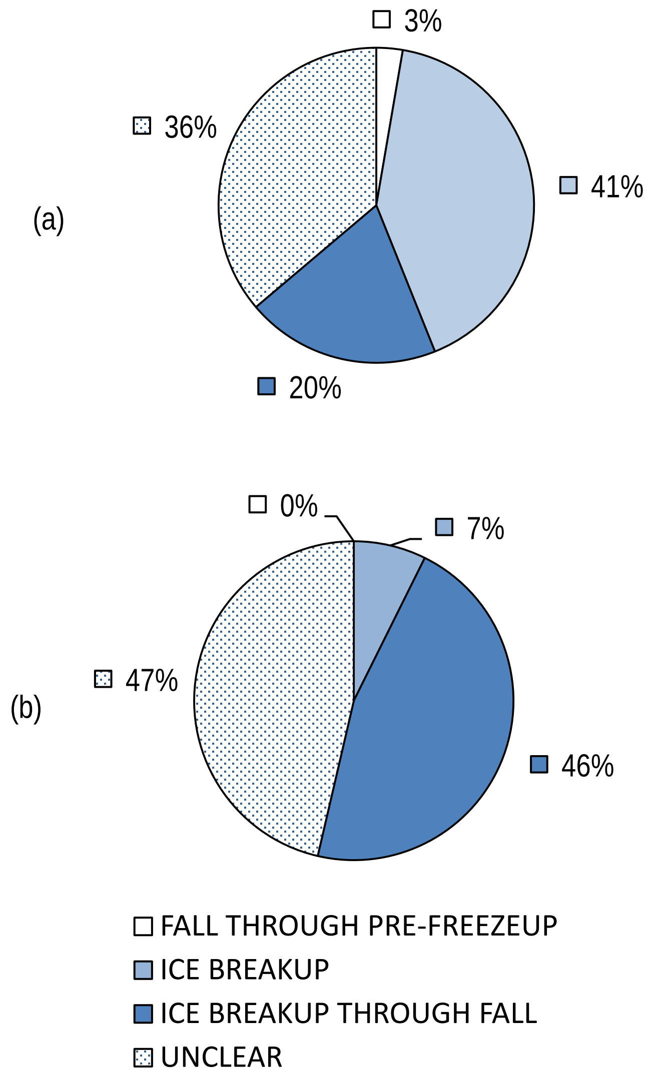

Figure 4. Pie diagrams quantifying time periods of erosion for Reaches 6 and 7 during the period 2012-2013: (a) Reach 6; and, (b) Reach 7.

4.2 Ice-Related Processes Causing the Changes

Examination of the reconnaissance videos taken during ice-break-up, when a majority of erosion occurred or was initiated, yielded clues into the dominant ice-related process that may be driving vegetation removal and large-scale channel change. The dominant process appears to be a combination of relatively high water discharge and the presence of ice rubble. Break-up ice jams raised water level sufficiently for water and ice to divert on to the floodplain and remove vegetation (Section 4.3) or divert into lateral channels where heads of islands and banks were gouged and sheared by ice. The ensuing subsections briefly elaborate ice related effects.

Ice-jam-induced diversion of flow. During break-up, jamming in the main channel caused flow and ice-blocks to move into side channels, sloughs, and overbank. This diversion of flow, even when at lower discharges, caused side channels to be inundated up to the vegetation line. If bank-attached ice had already been dislodged and transported downstream, this process exposed bank material to entrainment. Observations during 2013 show a cantilevered bank becoming further undermined from diverted main channel flow moving along the bank face. Figure 5 is a series of photos illustrating the development of a flow diversion immediately upstream of an ice jam.

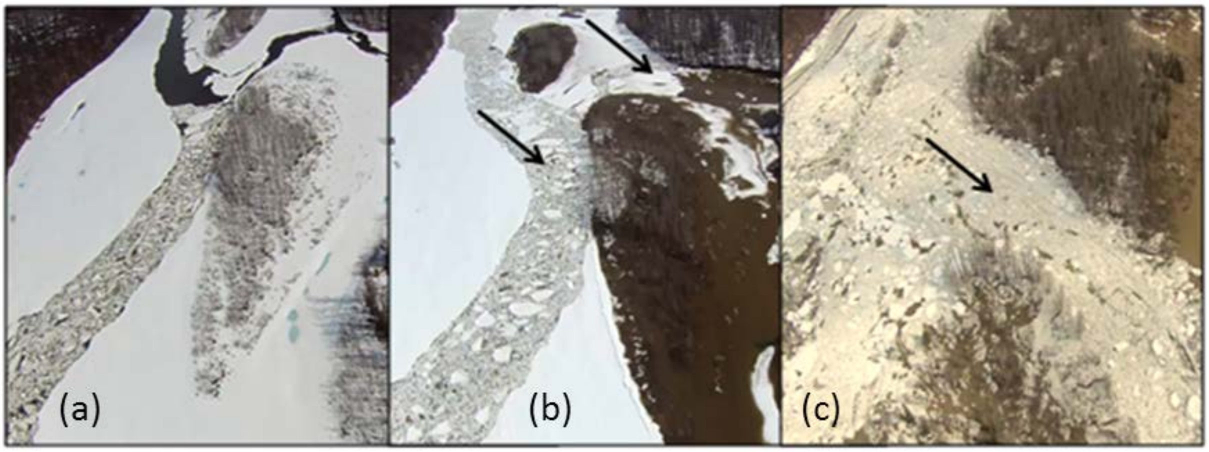

Figure 5. Series of screenshots from aerial reconnaissance of ice-break at Mile 132.5. Arrows indicate the direction of flow. (a) photo taken on May 23, 2013, with ice jam in main channel; (b) photo taken on May 25, 2013 with ice-induced diversion of flow into side channel; and, (c) photo taken on May 26, 2013 illustrating diversion of ice blocks into side channel.

Ice-block gouging. The accompaniment of large ice blocks from the flow diversion can cause significant gouging and clearing of vegetation. A chunk of the ice cover, roughly 100m in length, plowed overbank with rising flows in late May, 2013, knocking down trees and clearing low-lying vegetation. Smaller ice blocks were observed to knock over trees and transport some trees downstream on top of the ice blocks. Single ice blocks were found to ram into heads of islands and along bank faces, leaving ridges or scalloping banks and entraining chunks of bank material. Removal of bank material at the heads of islands and along bank faces acted to widen the heads of secondary channels or sloughs. Figure 6 illustrates examples of ice-block gouging.

Ice shearing of river banks. While somewhat limited in lateral extent, ice blocks were observed to shear along river-bank faces while being transported downstream. The result is an exposed bank face, sometimes with the remaining root mats scarred, broken, or removed completely. In the instances when roots remained after contact with ice, they had a downstream directional bent. Figure 7 shows several photos of ice shearing along banks of the Susitna River.

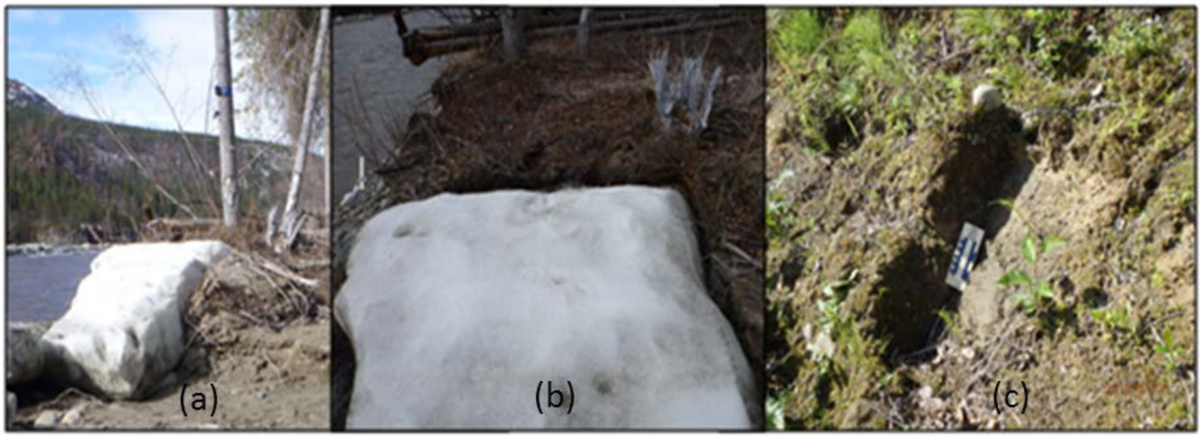

Figure 6. Illustrations of ice-block gouging: (a) and (b) are photos taken on May 5, 2012 of ice block gouging the head of an island at Mile 185.9; and, (c) a photo, showing a gouged bank, taken on July 23, 2013 at Mile 109.

Figure 7. Illustrations of ice-block shearing of river banks: (a) and (b) photos taken on May 5, 2012 of ice-block shearing of a mid-channel island at Mile 185.9; and, (c) a photo taken of sheared bank vegetation, on July 24, 2013 at Mile 109.

4.3 Resetting the vegetative succession regime

Overbank ice floes tend to shear low-lying vegetation, bending, breaking, and removing previously established plant communities. This process is present throughout the Middle River and is dominant on lower, younger floodplain surfaces as well as the periphery of more mature, older floodplains. All locations where vegetation was removed occurred during the ice-break-up window due to overbank flow transporting ice rubble (Figure 8). Locations of re-set and removed vegetation, as expected, are adjacent to ice jam locations, where the effects of flooding and release of ice blocks from a jam can be most severe. The lack of vegetation removal in Reach 7 compared to that in Reach 6 (as Table 3 indicates) could be due to limited ice-jamming within the reach, a lack of ice in-channel when released ice floes from jams upstream arrive in the reach, and the limited extent of lower, younger floodplain surfaces due to more confinement than Reach 6.

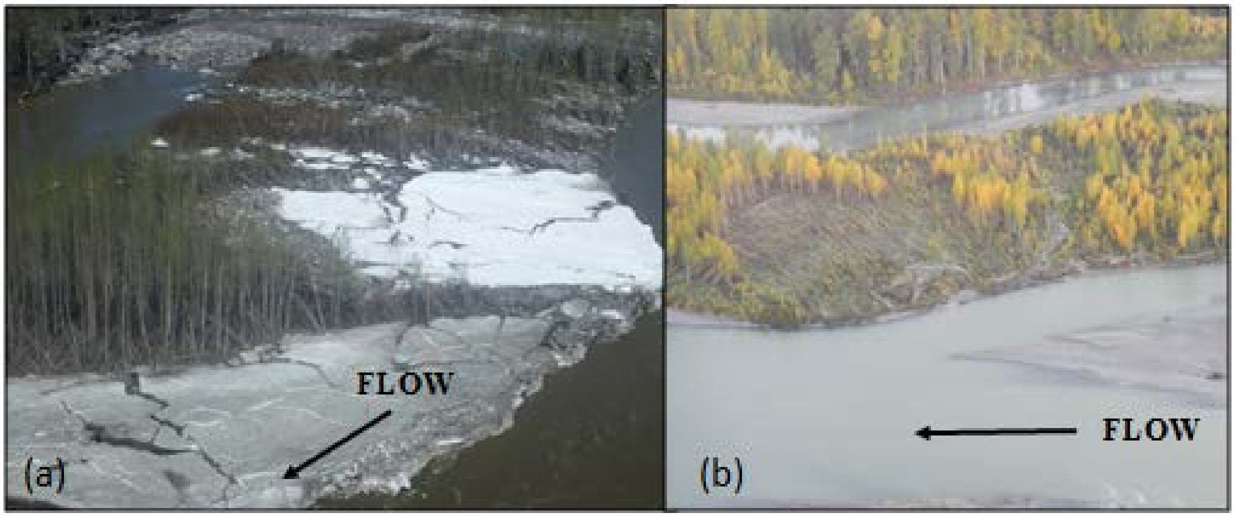

Figure 8. Photos illustrating ice inundation of vegetation on a low island: (a) ice cover shearing vegetation on a mid-channel island at Mile 135.3, taken on May 29, 2013; and, (b) sheared vegetation viewed at the same location on September 19, 2013.

4.4 Erosion-mitigation effects

Several effects acted to mitigate the erosive effects of ice moving along the Susitna River.

Coarse, paved bed-material. Large ice blocks can deposit large cobbles and boulders along bank toes, effectively coarsening the bank toe sediment gradation. The presence of large ice blocks along the bank toe and channel applies large forces along the bed helping pave the armored bed-material and increasing the shear forces necessary for mobilization. In a laboratory study, Ettema and Kennedy (1982) found ice ride-up to be preceded by a building of ice slabs over armor boulders which act to protect the armor boulders from the ice-ride up event. Coarse cobble-boulder pavements have been found to be rather erosion-resistant where Mackay and Mackay (1977) speculate that some pavements may be stable for at least a century before the original boulders in the pavement are plucked and eventually replaced. While an armored channel bed can limit the depth of scour, where bank materials are less resistant, there may be a subsequent increase in channel width (Church 1972, Lawson 1983); this feature is likely common for the Susitna River, where open-water flows are unable to exceed the critical shear stress necessary to mobilize the bank toe during the open-water regime (Tetra Tech 2015c).

Bank-attached ice. The presence of bank-attached ice likely protects the banks from undermining by flows or shearing from ice blocks, leaving a smaller window for erosive forces to act along a bank face.

Vegetation root-mats. The presence of extensive, exposed wads of roots of trees along the river’s banks is fairly common for northern Rivers (Church and Miles 1982) and found to increase bank resistance (Smith 1976). Exposed rootmats act to increase local roughness and reduce velocities. Roots stabilize the bank (Simon and Collison 2002; Pollen and Simon, 2005) and deflect abrasion from moving ice-floes. The persistence of exposed and ice-abraded rootmats along the Susitna

River, especially along cantilevered banks, illustrate their effects in protecting the bank and adjacent vegetation from extensive scour, and stabilizing the upper bank from subsequent collapse. ***Channel form and local hydraulics.*** Channel sites less prone to the formation of ice-jams, and are local regions of enhanced ice conveyance, tend to reduce the local amount of large-scale erosion. Straight reaches tend to break-up first (Beltaos 2007), limiting the amount of jams that form, break, and re-form; this observation is consistent with ice break-up seen at the more straight geomorphic reach, Reach 7, which experienced less erosion than multi-channel Reach 6. During the 2013 ice breakup, jams and associated overbank flooding with ice blocks were most common in split-flow channels, at constrictions where flow is converging, and around bends. Ice jam locations on the Susitna River are consistent with locations identified in the literature (e.g., Beltaos 1995).

5. Conclusions

The majority of the banks that eroded during the winter 2012-2013 align closely to locations that eroded between 1951-1983 and 1983-2012, indicating that erosion occurs in preferential locations. These locations tend to be in the more dynamically active multi-channel reaches prone to ice jamming. While some locations along these reaches were prone to fluvial erosion (notably the outside of bends or upstream of constrictions), other locations occurred in areas prone to stability or vegetation growth (notably the inside of bends or at the heads of islands where flow diverges).

Overall, an optimum mix of water discharge, local shear stresses and ice rubble are necessary to initiate bank erosion or vegetation removal. The distribution of tree ice-scar data collected as part of the Riparian Study for the Susitna-Watana Hydroelectric Project (R2 Resource Consultants, 2015) indicates that tree ice-scars are prevalent along the Middle Susitna River. However, many areas where tree ice-scars are present do no exhibit any recent or historical erosion (dating back to 1951). If tree ice-scars occurred after 1951, they indicate that overbank flooding coupled with ice rubble may not always be erosive and may instead be marked with superficial effects such as tree ice scars.

Processes contributing to cantilevered bank conditions appear to be caused by open-water entrainment of the non-cohesive (sandy) material that causes subsequent slumping of the vegetated organic top layer. Ice processes appear to affect banks and vegetation through shearing, gouging, and stripping. Ice blocks moving adjacent to vegetated banks appear to shear material and vegetation leaving vertically exposed banks with ice-scared woody debris. Individual ice blocks appear to gouge into banks leaving distinct ridges in the bank material. Overbank flow during ice-break up, brings large ice blocks onto vegetated islands, which strip away low-lying vegetation and plow into trees, removing large swaths of trees less than 1 foot in diameter.

The dominant process causing bank erosion along the Middle Susitna River involved the combination of high level of water discharge and the dynamic break-up of river ice. The Middle River experienced a relatively large portion of bank erosion during the winter and spring of 2012 to 2013 due to high flows and dynamic ice break-up compared to the extent of bank erosion experienced since 1951. Along this extensively armored river, which has experienced limited vertical (at least since the 1980s) or lateral (since 1951) changes in alignment, and for which openwater shear stresses are unable to mobilize the bank toe at even the highest floods, the combination of high flows and competent ice blocks appear to be the drivers for causing large-scale bank erosion and vegetation removal. This finding indicates that a major effect of river ice on alluvial channel morphology is to increase channel instability or variability of alignment.

Additionally, less bank erosion occurred along the single channel, meandering reaches than in branching multi-channel reaches. The latter reaches were prone to jam-induced lateral diversion of flow and ice that readily eroded banks along branch channels.

The main processes acting to mitigate ice erosion include the presence of exposed tree-root wads along banks, bank-attached ice, and cobble armoring of the lower elevations and slope of banks.

Acknowledgments

The authors acknowledge support provided by Drs. Lyle Zevenbergen and Mike Harvey of Tetra Tech Inc. Data used for the present study were derived from publically available data developed for the Susitna-Watana Hydroelectric Project, and can be found and downloaded from http://gis.suhydro.org/. Reports developed for Alaska Energy Authority as part of the Susitna-Watana Hydroelectric Project are cited within the references and can be found and downloaded from http://www.susitna-watanahydro.org/type/documents/.

References

Beltaos, S, (*Ed.*), 1995. River Ice Jams. Water Resources Publications, Highlands Ranch, CO.

Beltaos, S. 2007. River ice breakup processes: recent advances and future directions. Canadian Journal of Civil Engineering, 34: 703:716, Doi:10.1139/L06-021.

Bunte, K., and Abt, S.R. 2001. Sampling Surface and Subsurface Particle-Size Distributions in Wadable Gravel- and Cobble-Bed Streams for Analyses in Sediment Transport, Hydraulics, and Streambed Monitoring. General Technical Report RMRS-GTR-74. May 2001.

Church, M. and Miles, M.J. 1982. Discussion on Processes and mechanisms of bank erosion. In *Gravel Bed Rivers*, Eds. by Hey, R.D., Bathurst, J.C., Thorne, C.R., John Wiley & Sons. New York, NY, p. 259.

Ettema, R., and Kennedy, J.F. 1982. Ice Study for the Port of Nome, Alaska. Iowa Institute of Hydraulic Research Limited Distribution Report No. 101, The University of Iowa, Iowa City, IA.

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. 2014a. Ice Processes in the Susitna River, Study Plan Section 7.6, Initial Study Report, Part A. Prepared for Alaska Energy Authority. FERC Project No. P-14241. Anchorage, Alaska.

HDR. 2014b. Detailed Ice Observations and Lower River HEC-RAS Modeling *as part of* Ice Processes in the Susitna River, Study Plan Section 7.6, Initial Study Report, Part A, Appendix A. Prepared for Alaska Energy Authority. FERC Project No. P-14241. Anchorage, Alaska.

HDR. 2014c. White Paper: Review and Compilation of Existing Cold Regions Hydropower Project Operations and Effects *as part of* Ice Processes in the Susitna River, Study Plan Section 7.6, Initial Study Report, Part C, Appendix C. Prepared for Alaska Energy Authority. FERC Project No. P-14241. Anchorage, Alaska.

HDR. 2015. Ice Processes in the Susitna River, Study Plan Section 7.6, 2014-2015 Study Implementation Report. Prepared for Alaska Energy Authority. FERC Project No. P-14241. Anchorage, Alaska.

Mackay, J.R. and Mackay, D.K. 1977. The stability of ice-push features, Mackenzie River, Canada. Canadian Journal of Earth Sciences, 14(10): 2213-2225, 10.1139/e77-190.

Pollen, N., and Simon, A. 2005. Estimating the mechanical effects of riparian vegetation on stream bank stability using a fiber bundle model, Water Resources Res., 41, W07025, doi:10.1029/2004WR003801.

R2 Resource Consultants. 2015. Riparian Instream Flow Study, Study Plan Section 8.6, 2014-2015 Study Implementation Report. Prepared for Alaska Energy Authority. FERC Project No. P-14241. Anchorage, Alaska.

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

Smith, D.G., 1976. Effect of vegetation on lateral migration of anastomosed channels of a glacier meltwater river. Geological Society of America Bulletin, 87, 857-860, doc. no. 60604.

Tetra Tech. 2013. Stream Flow Assessment. Technical Memorandum. Prepared for Alaska Energy Authority. FERC Project No. P-14241. Anchorage, Alaska.

Tetra Tech. 2014a. Decision Point on Fluvial Geomorphology Modeling of the Susitna River below Mile 29.9. Technical Memorandum. Prepared for Alaska Energy Authority. FERC Project No. P-14241. Anchorage, Alaska.

Tetra Tech. 2014b. Winter Sampling of Main Channel Bed Material. Technical Memorandum. Prepared for Alaska Energy Authority. FERC Project No. P-14241. Anchorage, Alaska.

Tetra Tech. 2014c. Update of Sediment-Transport Relationships and a Revised Sediment Balance for the Middle and Lower Susitna River Segments. Technical Memorandum. Prepared for Alaska Energy Authority. FERC Project No. P-14241. Anchorage, Alaska.

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

Tetra Tech. 2014e. Susitna River Historical Cross Section Comparison, 1980s to Current. Technical Memorandum. Prepared for Alaska Energy Authority. FERC Project No. P-14241. Anchorage, Alaska.

Tetra Tech, 2015a. Geomorphic Reach Delineation and Characterization, Upper, Middle, and Lower Susitna River Segments – 2015 Update Technical Memorandum, Susitna-Watana Hydrolectric Project. Prepared for Alaska Energy Authority, Anchorage, Alaska.

Tetra Tech. 2015b. Fluvial Geomorphology Modeling below Watana Dam, Study Plan Section 6.6, 2014-2015 Study Implementation Report. Prepared for Alaska Energy Authority. FERC Project No. P-14241. Anchorage, Alaska.

Tetra Tech. 2015c. 2014 Fluvial Geomorphology Model Development Technical Memorandum *as part of* Fluvial Geomorphology Modeling below Watana Dam, Study Plan Section 6.6, 2014-2015 Study Implementation Report, Attachment 1. Prepared for Alaska Energy Authority. FERC Project No. P-14241. Anchorage, Alaska.

University of Alaska Arctic Environmental Information and Data Center. 1984. Assessment of the effects of with-project instream temperatures on Susitna river ice processes in the Devil Canyon to Talkeetna Reach. Draft Report Submitted to Harza-Ebasco Susitna Joint Venture Anchorage, Alaska.