CGU HS Committee on River Ice Processes and the Environment
21st Workshop on the Hydraulics of Ice Covered Rivers
Saskatoon, Saskatchewan, Canada, August 29-September 1, 2021

Fluvial geomorphological responses to river ice dynamics downstream of a hydroelectric facility, southwest Yukon

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The morphology of gravel-bed rivers in northern environments is a result of a complex interaction between the physical setting (geology, topography, climate) and mechanisms of change. The effects of river ice and flow regulation on fluvial geomorphological processes add further complexity. Aishihik River, in southwest Yukon, Canada, became regulated for production of hydroelectricity in 1975. Flow regulation has altered the downstream winter flow regime and, in turn, increased the thickness of river ice and extent of overbank ice accumulation during most winters. Detailed historical analyses starting in the late 1940s reveal a spike in geomorphological adjustment along Aishihik River in the decades after regulation began. Geomorphological responses to flow regulation in the upper reaches have manifested as a reduction in sinuosity (1.68 to 1.26), an increase in the occurrence of meander cut-offs (0.08 to 0.26 cut-offs/year), an increase in unvegetated width (47 m to 76 m), and a reconfiguration of localized channel pattern (single- to multi-thread). Through time, channel instability has progressed downstream. The nature and timing of observed geomorphological adjustments cannot reasonably be explained by natural variability alone. The key driver of the observed geomorphological change is likely ice accumulation in the active channel and in floodplain areas, combined with higher winter flows, which induces meander cut-offs and exacerbates bank and bed erosion during the winter and spring. Ongoing data collection is informing the development and implementation of monitoring and adaptive management plans aimed at reducing geomorphological effects of wintertime flow regulation over the long term.

1. Introduction

Downstream landscape responses to hydroelectric facilities have been researched worldwide over the past quarter-century, especially in temperate climates. Diverse responses have been attributed to different operating regimes, physical structures, and the intended functions of the facilities (Petts and Gurnell 2005). However, site-specific geological, climatological, and ecological conditions limit the transferability of the results of downstream geomorphology studies from one region to another (Brandt 2000). In northern environments, the morphology of gravel-bed rivers is a result of complex interactions between the physical setting (geology, topography, climate) and mechanisms of change. The effects of ice and flow regulation on fluvial geomorphological processes in cold climates add further complexity.

Aishihik River, located approximately 110 km west of Whitehorse, in southwest Yukon, Canada, has been regulated for hydroelectric generation at the Aishihik Generating Station (AGS) since 1975 (Figure 1). In 2016, Yukon Energy Corporation, in collaboration with Champagne and Aishihik First Nations, commissioned a geomorphological investigation aimed at characterizing and, where possible, quantifying changes in downstream geomorphological conditions and processes since flow regulation. The investigation was completed as part of an environmental and socio-economic effects assessment associated with relicensing of the AGS.

The geomorphological investigation focused mainly on Aishihik River but also included East Aishihik River and Dezadeash River downstream of the AGS, as well as two unregulated references reaches: West Aishihik River and Dezadeash River upstream of their respective confluences with Aishihik River. This paper focuses on reach-scale geomorphological processes and adjustments. Additional geomorphological analyses, including winter sediment transport analyses, were completed as part of the relicensing investigations to better understand observed reach-scale geomorphological adjustments.

2. Regional Setting

The landscape surrounding Aishihik River is dynamic and is evolving as result of deglaciation processes, climate change, and forest fires. The physiography of the region is largely a product of repeated Pleistocene glaciations, with the most recent occurring 25–10 ka (Hughes 1990). During the most recent deglaciation, Glacial Lake Sekulmun-Aishihik inundated the Aishihik area as much as 200 m above the existing ground surface and deposited large amounts of silt and clay (Bostock 1966, Hughes 1990). Thus, the surficial geology of the area is dominated by glaciolacustrine varved silt, sand and clay or massive silt deposits (Hughes 1990).

The rivers are confined by bluffs at the edges of glaciolacustrine terraces up to about 40 m in height. Till units are locally exposed in valley bluffs along West Aishihik, East Aishihik, and Aishihik Rivers (Hughes 1990). The glaciolacustrine sediments in the West Aishihik River and Aishihik River watersheds generally appear to have low ice contents based on a lack of thermokarst features (Hughes 1990). The Aishihik River (Figure 2) and Dezadeash River valley bottoms are dominated by alluvial sediments and coarser lag deposits from high-energy meltwater channels or localized erosion of till. East Aishihik River exhibits extensive exposures of bedrock along its bed and banks as a consequence of millennia of incision. Exposures of bedrock along Aishihik River are isolated to a few sites where large meanders impinge along the base of the high valley walls.

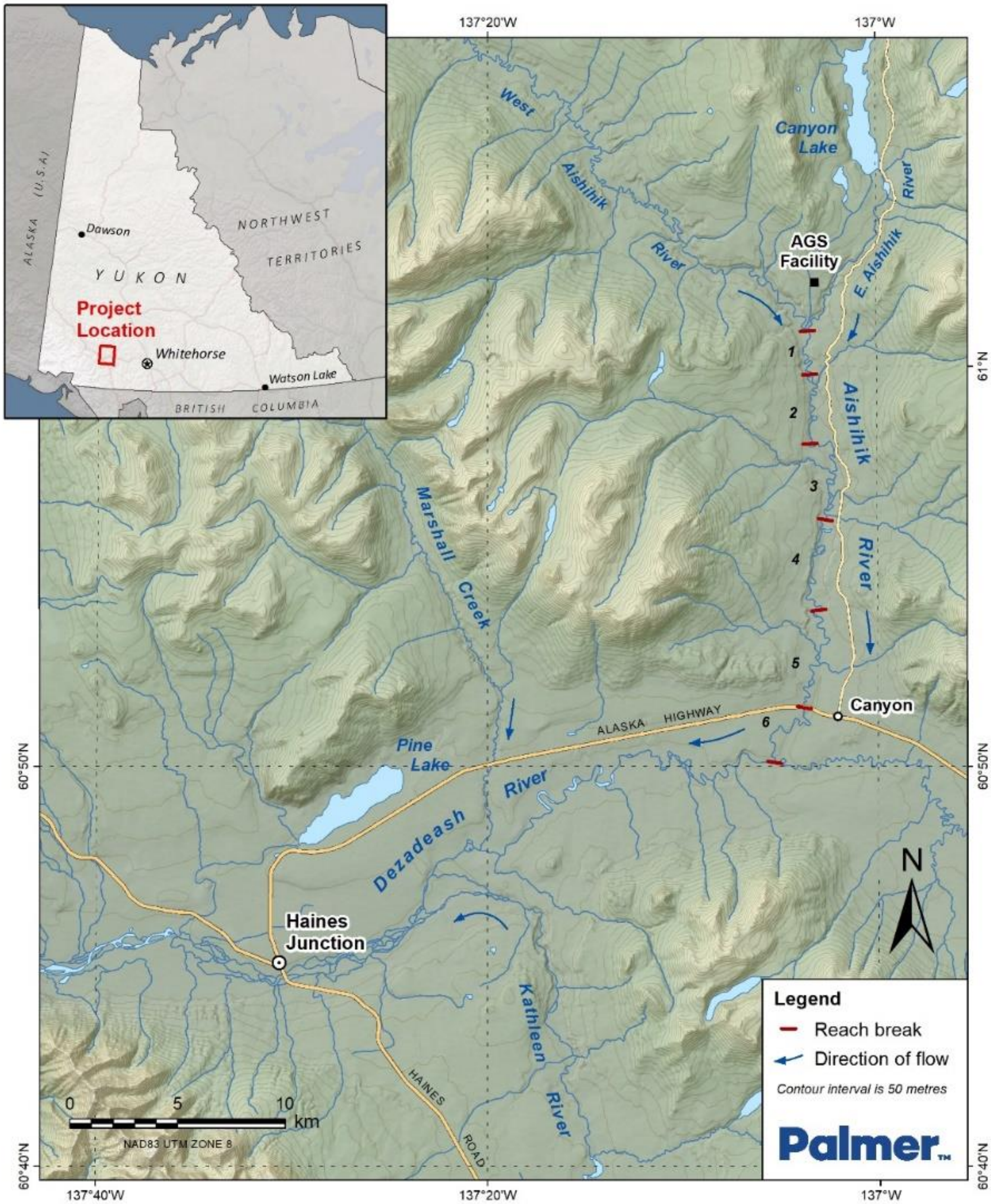

Figure 1. The study area for the geomorphological investigation. Six reaches were established for Aishihik River based on channel geomorphology and observed ice dynamics.

Figure 2. Looking downstream along the Aishihik River valley near a large meander cut-off in Reach 2 (September 22, 2016).

The study area is within the rain shadow of the St. Elias Mountains. Most precipitation (30-60 mm) falls as rain from June to September (Horton 2017). Mean annual temperatures of -2.0 to -2.5°C have been recorded between 1981 and 2015 at a climate station, approximately 7 km downstream of Canyon Lake (Horton 2017). The monthly temperature throughout the year ranges from 12.0°C in the summer months to -16.5°C in the winter months. Mean annual temperature in the Aishihik area has increased by ~2.0°C since the 1940s and is projected to increase by 1.0 to 1.5°C by 2050 (Horton 2017).

The Aishihik region is within the zone of discontinuous permafrost (Heginbottom et al. 1995). According to 30 m-resolution permafrost modelling conducted by Bonnaventure et al. (2012) for southern Yukon, the probability of permafrost presence within the Aishihik River valley ranges from 20-40%. Permafrost is generally restricted to inactive portions of the floodplain or low terraces, where surface organics insulate the ground during the snow-free, summer season and moisture is retained in underlying fine-grained (silt) flood deposits. Much of the permafrost that persists along the bottoms of the Aishihik and Dezadeash River valleys is likely decoupled from current climate (i.e. it would not re-form if thawed) and particularly sensitive to changes in the ground thermal regime. The influence of permafrost on channel geomorphology is limited to those sites where the channel comes in contact with inactive floodplains or low terraces where it still persists.

3. Hydrology and Flow Regulation

Aishihik River drains a series of large headwater lakes. A portion of the outflow from Canyon Lake is diverted by a control structure to the AGS's power canal, thereby limiting flows in East Aishihik River. East Aishihik River, West Aishihik River (unregulated), and the AGS tailrace join at a confluence south of the AGS, forming the watercourse referred to as Aishihik River. Aishihik River flows approximately 30 km southward though the rural community of Canyon and drains into Dezadeash River. The total drainage area of Aishihik River at Canyon is 4,300 km^2, approximately 3,000 km^2 of which is regulated. Tributaries from both the western and eastern slopes drain into Aishihik River between the AGS and Canyon. Dezadeash River drains Dezadeash Lake and flows northward to the rural community of Champagne and then westward through Haines Junction and outlets into Alsek River. The total drainage of Dezadeash River at Haines Junction is 8,450 km^2.

The construction of the AGS in the mid-1970s resulted in alteration to the pre-development flow regime of East Aishihik River and Aishihik River, as well as Dezadeash River downstream of the Aishihik River confluence. Flows from the AGS depend on energy demands. During the winter months when energy demand is high, outflow from the AGS greatly increases winter flows in Aishihik River (Figure 3) and, to a lesser extent, Dezadeash River in comparison to pre-AGS conditions. Since the construction of a third turbine in 2011, maximum winter flows in Aishihik River can reach 24 m^3/s and winter diurnal flow variability can be high. Yukon's electrical demand decreases in the spring, which allows water storage in Aishihik and Canyon Lakes and has reduced the spring freshet and summer flows of Aishihik River and, to a lesser extent, Dezadeash River.

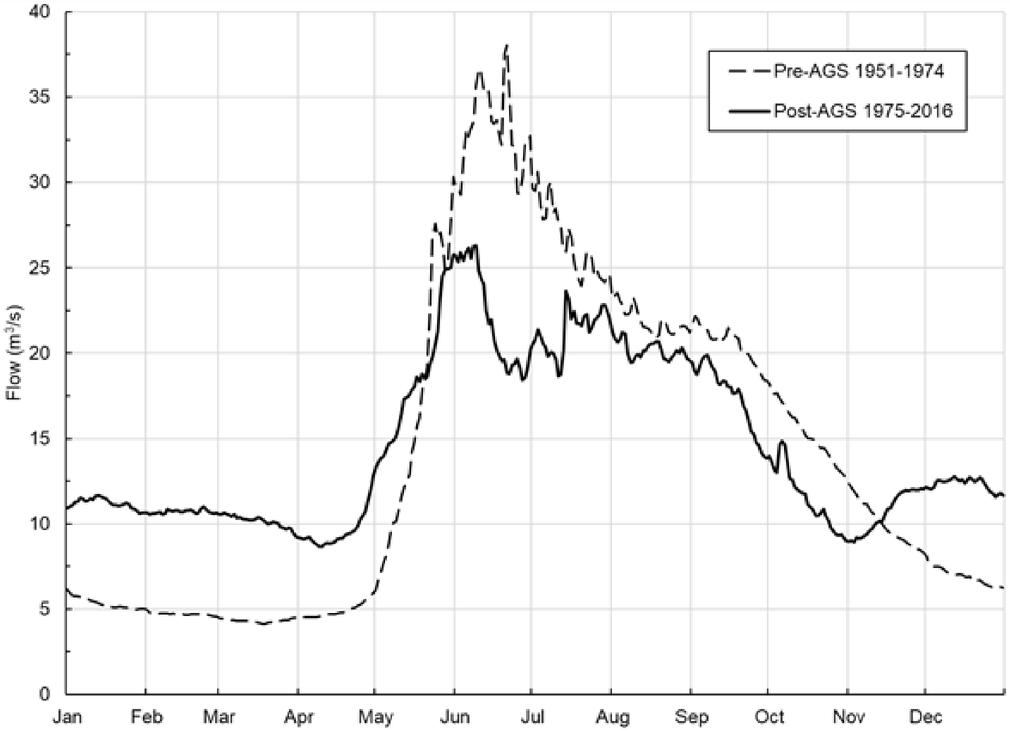

Figure 3. Average hydrographs for Aishihik River at Canyon before and after flow regulation.

Flood frequency analyses suggest 2-, 5-, and 10-year return peak flows in Aishihik River are lower magnitude following AGS construction, which is attributed to storage in Aishihik and Canyon Lakes. The magnitudes of 20-, 50-, and 100-year peak return flows have likely increased following AGS construction, which could be explained by large releases from Aishihik Lake in late summer when intense or prolonged rainfall events coincide with high reservoir levels.

4. Methods

An initial understanding of Aishihik River morphology was gained through a review of 1:100,000-scale surficial geology mapping (Lipovsky and Bond 2014), permafrost probability modeling for southern Yukon (Bonnaventure et al. 2012), and field notes and photographs compiled by Champagne and Aishihik First Nations. Helicopter-supported field reconnaissance was completed in September 2016, during relatively low flows along Aishihik River, and in June 2017 during relatively high flows. Annual river ice monitoring has been completed since 2016.

Fundamental to the assessment of existing and historical channel geomorphology was a set of recent and historical aerial photography. High-resolution (0.5 m), colour, ortho-rectified imagery from summer 2013 was available. Ortho-rectified satellite imagery (3 m resolution) from July 25, 2017 was obtained to help interpret geomorphological change following the installation of the third turbine in 2011. Historical aerial photographs were obtained from the Yukon Government Energy, Mines and Resources library for the following years: 1947-48 (pre-regulation), 1972 (pre-regulation), 1979, and 1986-88. Thus, the period of photographic record extends from 1947/48 to 2017. Ortho-rectified mosaics were created for each historical period by utilizing a 10 m-resolution digital elevation model.

A systematic photograph comparison and comparative overlay analysis were completed using all six sets of imagery (1947-48, 1972, 1979, 1986-88, 2013, 2017) to strengthening our understanding of the locations, mechanisms, and implications of greatest change in river planform. For the comparative overlay analysis, both banks of the main channel, the perceived channel thalweg, and any observed side channels were delineated in GIS. Following channel delineation, the sinuosity (channel length along thalweg/valley length) and number of cut-offs were determined for each reach/watercourse to inform changes in channel planform through time. Unvegetated channel widths were systematically measured perpendicular to the direction of the channel every 50 m in GIS to document changes in lateral extent of the reach through time.

5. Results

Aishihik River was divided into six reaches (Figure 1). The Aishihik River reaches were primarily defined based on degree of channel confinement, channel slope, and observed ice dynamics (e.g. presence of overbank ice, anchor ice, continuous ice cover, etc.). Reach 1 is generally devoid of ice year-round under current AGS operating conditions. In Reaches 2 and 3, shore ice, accumulations of frazil and anchor ice in the active channel, and overbank ice are observed under current AGS operating conditions. In Reaches 4 to 6, the in-channel ice cover is more stable than along the upper three reaches, but extensive overflow ice has still been observed under current AGS operating conditions.

Prior to flow regulation, Aishihik River had a sinuous planform with sinuosity values similar to West Aishihik River (Figure 4). In the decades following regulation, the sinuosity of Reaches 1 to 3 decreased substantially. The combined sinuosity of Reaches 1 to 3 decreased from 1.68 in 1972 to 1.26 by 2017. Changes and trends in the sinuosity of Reaches 4 to 6 are less pronounced and occurred more gradually following regulation. In contrast, the sinuosity of West Aishihik River and East Aishihik River have remained largely unchanged over the period of record. The total length of Aishihik River (AGS tailrace to Dezadeash River) decreased by 4.7 km (13%) from 1972 to 2017. This large reduction in channel length has steepened the channel (the gradient is now 0.0026 m/m) and has led to more homogenous bed morphology (Figure 5).

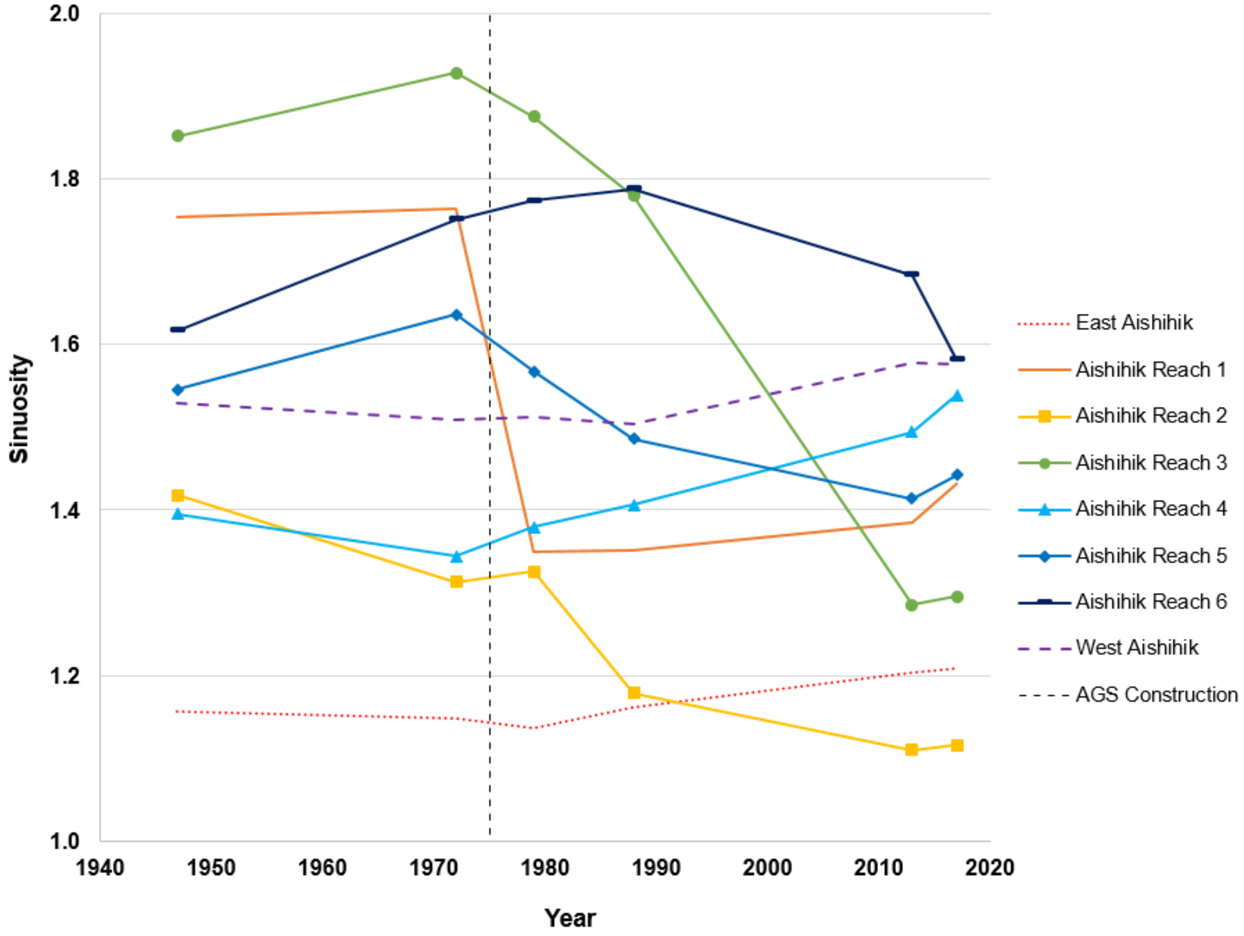

Figure 4. Channel sinuosity through time for East Aishihik River, Aishihik River, and West Aishihik River (unregulated). Reaches are numbered in the downstream direction. Reach 1 is immediately downstream of the AGS facility.

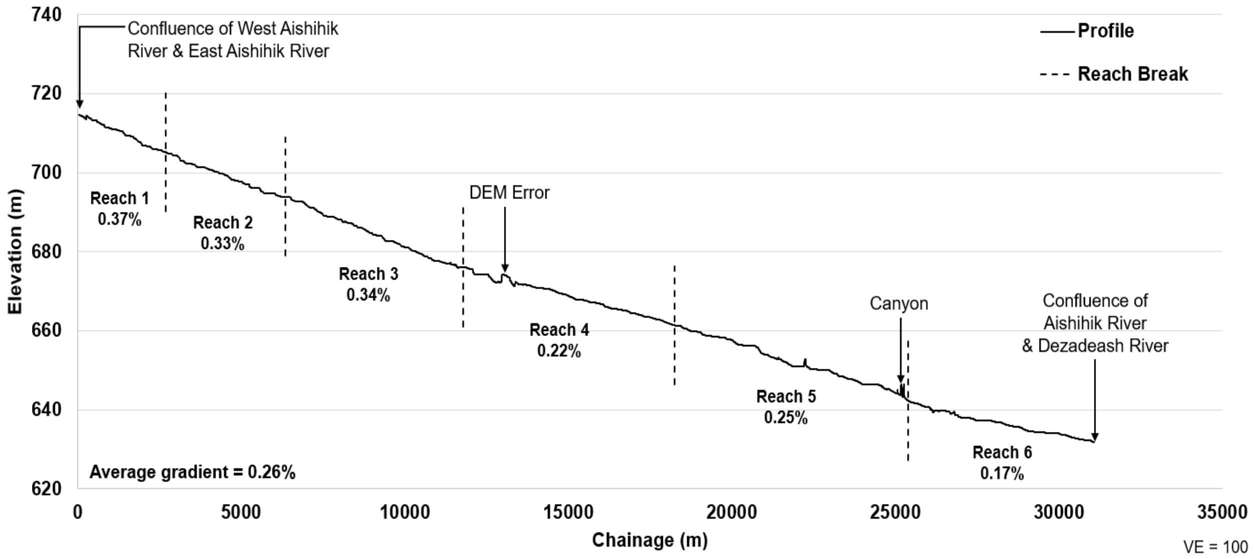

Figure 5. Aishihik River longitudinal profile extracted from a 10 m DEM (2013)

The observed reduction in sinuosity is primarily the result of increased occurrence of channel cut-offs (i.e. avulsion) following regulation (Table 1). The occurrence of channel cut-offs in Reaches 1 to 3 increased from 0.08 cutoffs/year prior to regulation (1947-48 to 1972) to 0.26 since regulation (1979 to 2017). The increase in the occurrence of channel cut-offs in Reaches 4 to 6 was more modest (0.16 cut-offs/year from 1947-48 to 1972 to 0.21 cut-offs/year from 1979 to 2017). No cut-offs were observed along West Aishihik River after 1972. The only observed cut-off along East Aishihik River was anthropogenic.

Prior to flow regulation, the average unvegetated width of all six reaches was comparable to the width of West Aishihik River (Figure 6). Since regulation, the average unvegetated widths of all six reaches has increased and the variability between reaches has increased. The average unvegetated width of Reaches 1 to 3 increased from 47 m in 1972 to 76 m by 2017. In Reaches 4 to 6, the average unvegetated width increased from 54 m in 1972 to 68 m in 2017. Increases in channel width since regulation have resulted in localized sections of multi-thread channels and have altered riparian vegetation dynamics. The width of East Aishihik River has decreased since regulation due to a reduction in flow as water is diverted to the AGS. The width of West Aishihik River has decreased through time likely due to plant colonization along the channel periphery. Fleming and Clarke (2003) demonstrated the annual flows are decreasing in non-glacierized watersheds in southwestern Yukon, leading to reduction in channel sizes through time.

Table 1. Number of channel cut-offs (i.e. avulsions) through time for East Aishihik River, Aishihik River, and West Aishihik River (unregulated). East Aishihik River and Aishihik River were unregulated prior to 1975.

River	**Reach**	**Number of Channel Cut-offs**				
		194748 – 1972	**1972 – 1979**	**1979 – 1986/88**	**1986/88 – 2013**	**2013 – 2017**
East Aishihik River		0	1	0	0	0
Channel Cut-offs per year		*0.000*	*0.143*	*0.000*	*0.000*	*0.000*
Aishihik River	**1**	0	1	0	1	0
	Channel Cut-offs per year	*0.000*	*0.143*	*0.000*	*0.038*	*0.000*
	2	1	0	1	1	0
	Channel Cut-offs per year	*0.041*	*0.000*	*0.125*	*0.038*	*0.000*
	3	1	0	1	6	0
	Channel Cut-offs per year	*0.041*	*0.000*	*0.125*	*0.231*	*0.000*
	4	2	0	0	1	0
	Channel Cut-offs per year	*0.082*	*0.000*	*0.000*	*0.038*	*0.000*
	5	2	1	0	5	0
	Channel Cut-offs per year	*0.082*	*0.143*	*0.000*	*0.192*	*0.000*
	6	0	0	0	1	1
	Channel Cut-offs per year	*0.000*	*0.000*	*0.000*	*0.038*	*0.250*
West Aishihik River (unregulated)		1	0	0	0	0
Channel Cut-offs per year		*0.041*	*0.000*	*0.000*	*0.000*	*0.000*

Although not thoroughly discussed in this paper, similar analyses were completed for Dezadeash River. Sinuosity, channel cut-off frequency, and unvegetated channel width for Dezadeash River remained relatively consistent over the period of record (1947 to 2017) both upstream of the Aishihik River confluence (unregulated) and downstream of the Aishihik River confluence to Haines Junction (regulated). A stable ice cover with minimal overbank ice was observed along Dezadeash River over multiple years of winter field reconnaissance.

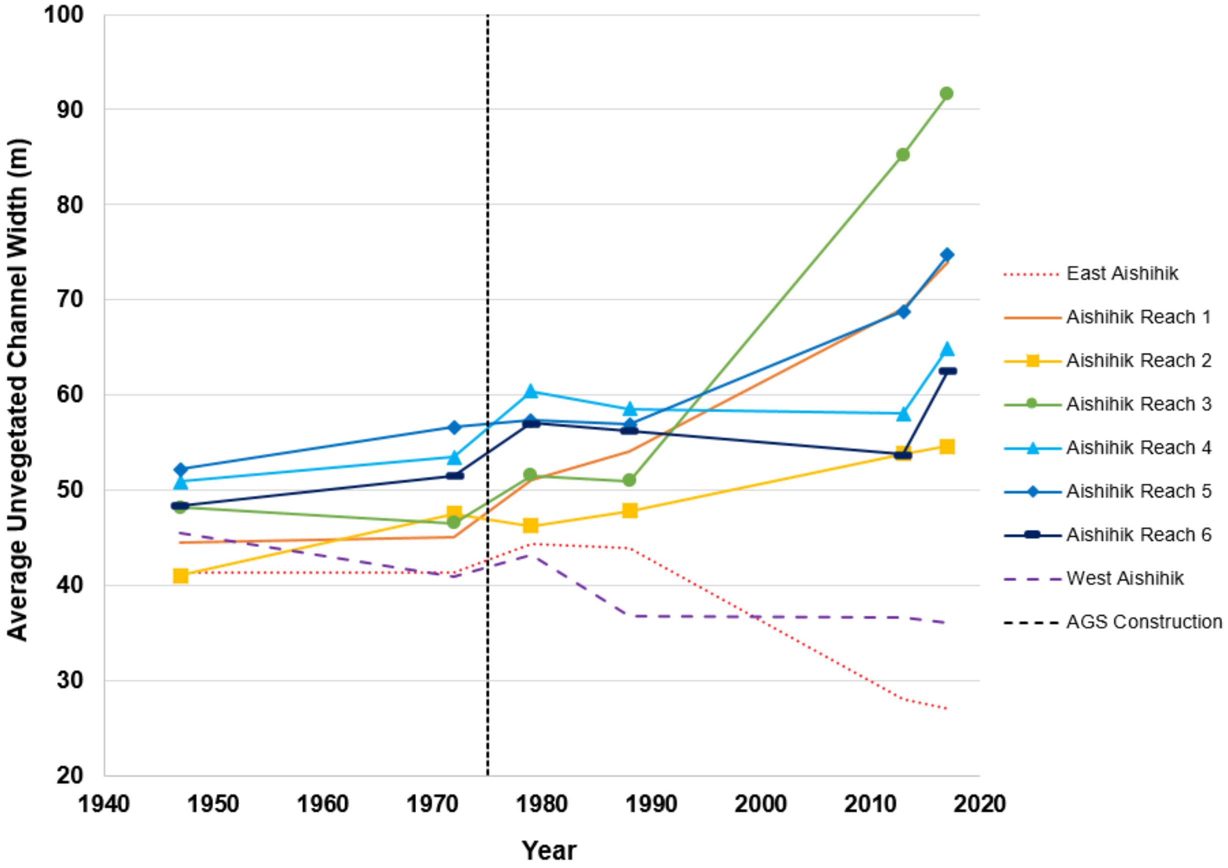

Figure 6. Average unvegetated width through time for East Aishihik River, Aishihik River, and West Aishihik River (unregulated). Reaches are numbered in the downstream direction. Reach 1 is immediately downstream of the AGS facility.

6. Discussion

6.1 Spatio-temporal Changes

Along Aishihik River, there has been a general downstream trend in channel destabilization since flows became regulated. Large channel cut-offs in Reaches 1 and 2 (Figure 2) in the decades following regulation led to notable reduction in sinuosity (Figure 4). Reach-scale channel restructuring occurred along Reaches 3 and 5 (Figure 7) and, to a lesser extent, along Reaches 4 and 6 between 1987 and 2013 (although there is a 26-year gap in the photographic record) mainly as the result of channel cut-offs. Instability and a large cut-off were observed along Reach 6 between 2013 and 2017.

Channel cut-offs induced by ice accumulation or large open-water flow events along Aishihik River, although infrequent, deliver large quantities of fine and coarse sediments to downstream areas. The upper reaches of Aishihik River appear to be delivering large volumes of coarse sediment to lower reaches. The coarse sediments promote local- to reach-scale aggradation as they are transported downstream, thereby increasing the likelihood of channel cut-offs in Reaches 3 to 6. A loss of mature trees alongside the channel, as well as the lack of vegetation colonization where overbank ice accumulates, has reduced bank strength along Aishihik River. In turn, this has likely resulted in increased coarse sediment recruitment from channel banks.

Figure 7. Looking upstream along the Aishihik River valley at successive channel cut-offs in Reach 5 (September 22, 2016).

6.2 Deviation from Theoretical Response

The morphology of an alluvial channel is governed by formative discharge, sediment supply (volume and caliber), channel slope, and bank strength (Eaton 2006, Lane 1955, Mackin 1948). Hydroelectric facilities alter the capacity of the downstream channel to transport sediment and the amount of sediment available for transport (Petts and Gurnell 2005). Following flow regulation, the 2-year, 5-year return, and 10-year return flows decreased. The sediment supply from West Aishihik River and East Aishihik River likely remained the same or slightly declined as a result of vegetation encroachment (Canyon Lake supplied a negligible amount of sediment to Aishihik River prior to regulation).

Theoretically, Aishihik River should have narrowed following the construction of the AGS due to reduction in formative flow, a common response to flow regulation in temperate climates (Petts and Gurnell 2005). Furthermore, reach-scale vegetation colonization and channel narrowing along nearby unregulated channels (West Aishihik River, Dezadeash River) has been documented. Since

AGS construction, however, the unvegetated widths of all six reaches have increased (Figure 6), some substantially, as have their channel slopes. This suggests a governing factor beyond formative discharge, sediment supply, and bank strength is driving channel restructuring. The observed deviation from the theoretical channel response is mainly attributed to the changed river ice dynamics in the active channel and overbank zone, as well as infrequent, late summer high flow events.

6.3 River Ice

The magnitude and variability of winter flows have increased in Aishihik River since construction of the AGS. The extensive growth of thick shore ice, combined with the accumulation of frazil ice and anchor ice, reduces the cross-sectional area of the channel, most notably in Reaches 2 and 3 (Figure 8). Reduction in the cross-sectional area (hydraulic capacity) of the channel results in overbank flow, typically in early winter, leading to incremental accretion of overbank ice. Overbank ice thickness in the active floodplain ranged from 1.5 m to 2.1 m immediately adjacent the river along three transects at the end of winter 2016/17. The accumulation of ice within the active channel and in the overbank areas is believed to be accelerating channel cut-offs by redirecting high winter flows out of the active channel and across topographic lows within the floodplain (Figure 9).

Figure 8. Looking upstream in Reach 3 at overbank ice accumulation atop both banks and frazil ice accumulation (foreground) in the active channel (January 22, 2019). A complete ice cover was formed on January 27, 2019 but periodical overflows occurred throughout the remainder of the winter.

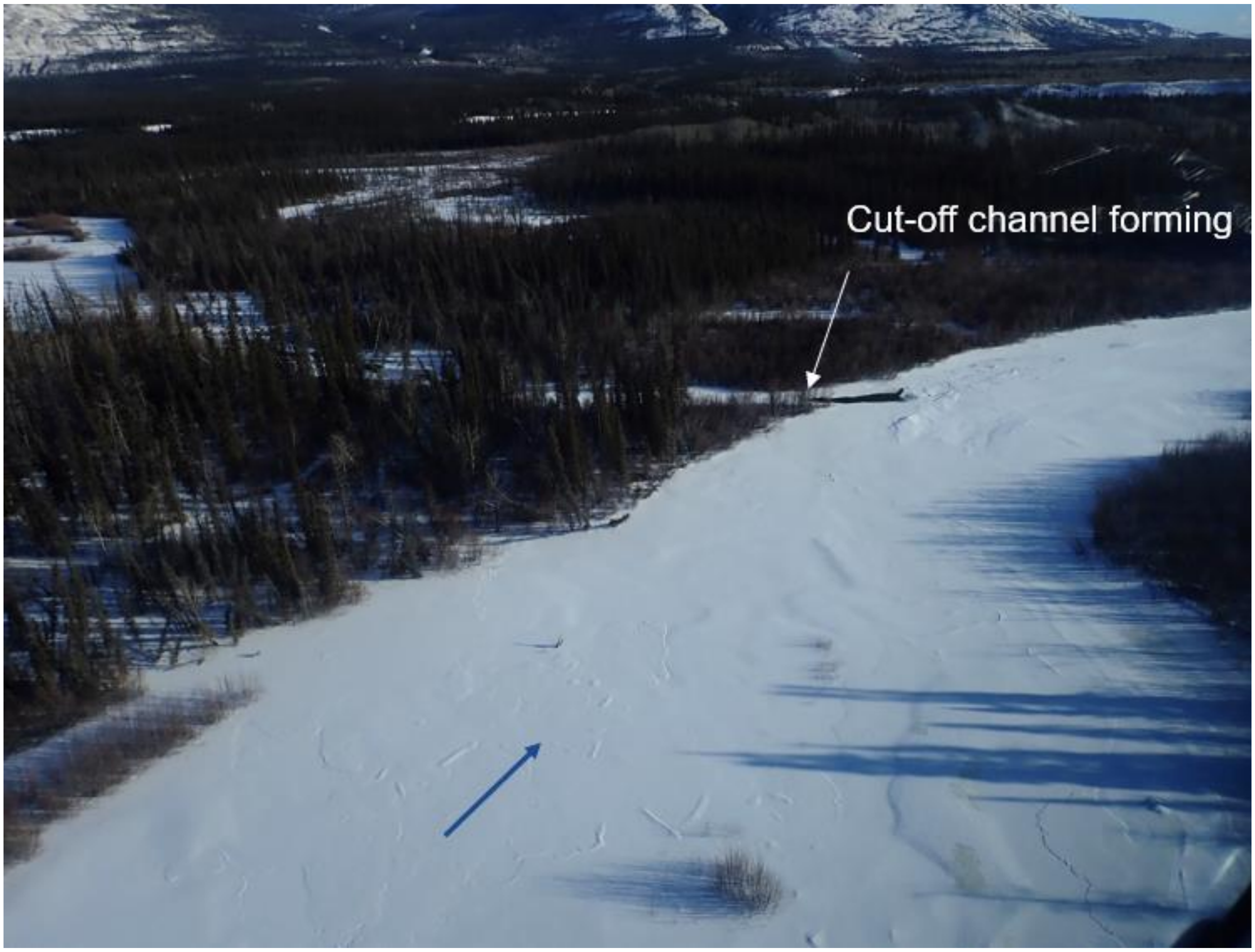

Figure 9. A newly formed cut-off channel was observed in Reach 5 in February 2019 (looking downstream). The cut-off channel enlarged throughout the 2019 and 2020 winters. In spring 2021, the majority of water passed through the cut-off channel.

The thickening of shore ice along one or both banks of Aishihik River also has important geomorphological consequences. As shore ice thickens, flows become more constricted and correspondingly deepen and accelerate. Eventually, shear stresses along the channel bed can exceed the critical shear stress of the gravel bed material, such that entrainment can begin. Winter bedload sediment transport capacity modelling (not presented in this paper) using AGS hourly tailrace data suggests sediment transport capacity of Aishihik River is an order of magnitude greater when shore ice is present relative to open water conditions for the same discharges.

Shear stress and subsequently sediment transport capacity are reduced, relative to open water conditions for the same discharges, once a stable ice cover forms as the total shear stress is divided between the water-ice (above) and water-bed (below) interfaces (Turcotte et al. 2011). Flume experiments have demonstrated that a stable ice cover can reduce sediment loads by 95% in comparison to open water conditions (Turcotte et al. 2011). The results of winter bedload sediment transport capacity modelling for Aishihik River are consistent with these empirical results.

During spring melt, anomalous mid-winter thaws, or sudden reductions in flow, shore ice attached to the channel banks, particularly where steep, collapses into the channel. Sediments and vegetation commonly calve into the channel with the collapsing ice, which reduces the shear resistance of the bank, increases unvegetated width, increases the input of sediment and woody debris to the channel, and exposes new layers of sediment that can be easily eroded (Ettema 2002, Turcotte et al. 2011). Recent shore ice collapse was observed along Aishihik River during an anomalously warm period in December 2016 (Figure 10). As well, anchor ice released from the channel bed was 'rafting' gravels and cobble downstream along Aishihik River during 2017 winter field reconnaissance. Kalke et al. (2015) observed a similar process on Peace River and North Saskatchewan River in Alberta. The rafted sediment will randomly settle to the bed in downstream reaches as the ice melts or overturns (Turcotte et al. 2011).

Figure 10. Collapsed shore ice in Reach 3 during an anomalous winter melt in December 2016.

Overbank ice has damaged existing riparian vegetation along Aishihik River, notably mature conifers, which has reduced bank strength (Eaton 2006, Turcotte et al. 2011) and has inhibited vegetation colonization along the Aishihik River periphery. Overbank ice accumulation is common along aggrading, shallow streams (Hall 1979). A feedback loop may have developed along Aishihik River, whereby overbank ice promotes channel widening, which reduces the sediment transport competence and capacity of the channel. A reduction in sediment transport competence and capacity can lead to bed aggradation, which leads to further overbank icing.

7. Conclusion

Widespread geomorphological changes have occurred along Aishihik River since flow regulation, including loss of sinuosity and widening of the unvegetated active channel. The nature and timing of observed geomorphological adjustments cannot reasonably be explained by natural variability.

Flow regulation to support hydropower generation has measurably altered the morphology of Aishihik River, largely through its effect on river ice processes. Further channel restructuring is expected with or without intervention. Ongoing data collection is informing the development and implementation of monitoring and adaptive management plans aimed at reducing geomorphological effects of wintertime flow regulation over the long-term.

8. Acknowledgments

The authors would like to thank Yukon Energy Corporation and Champagne and Aishihik First Nations for the opportunity to collaboratively support the studies necessary in the AGS relicensing process. Representatives of each contributed valuably to the approaches, field programs, and interpretations of a very complex system described herein.

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