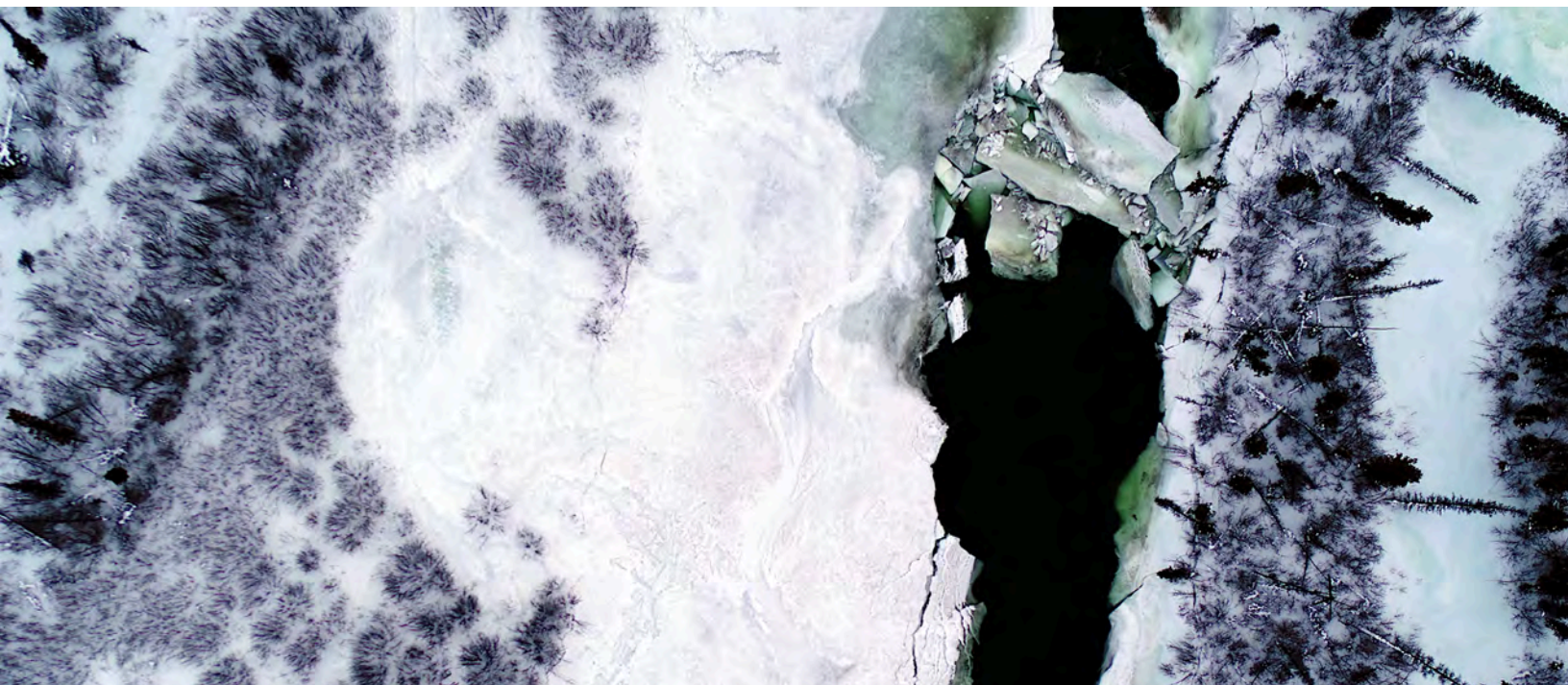




The Äshèyi Chu/Aishihik River - River Ice Model

YukonU Research Centre's RIMA

Final Report | October 2025



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Executive summary

The Äshèyi Chu carries water from Canyon Lake (Ädäts'ür Män) to the Dezadeash River (Titl'ät Män Tágà). Its flow has been controlled since the 1970s for hydroelectric production. Its morphology has undergone significant evolution over the last 50 years, and winter flooding has become recurrent in recent years. It appears that a feedback loop exists between the river's alignment and slope, ice processes, winter flows (significantly influenced by the winter operation of the Aishihik Generating Station), and winter flooding, with negative impacts on the environment, as well as on the Traditional Territory, cultural values, and Settlement Lands of the Champagne and Aishihik First Nations.

The objective of this project is to develop a model that quantifies ice and water levels in the Äshèyi Chu under winter conditions, informing future AGS flow management in a perspective of reducing ice-related flooding and promoting the stabilization of the river in the context of climate change. This objective represents a significant technical challenge, as no existing river ice model has been adapted to the winter regime of a small, regulated, alluvial river.

The Hydrology team of the Climate Change Research Group at the YukonU Research Centre (YRC) designed a physics-based empirical river ice model in the Microsoft Excel numerical environment. The development and calibration of the model are informed by observations and data obtained from a monitoring program implemented by Morisson Hershfield (now Stantec) over several consecutive winters. The YRC complemented this program by collecting drone imagery. Water level and water temperature data series, as well as the channel's ice coverage and the occurrence of overflow events, derived from remote cameras, represent the primary sources of information for developing the model.

The vision behind the River Ice Model for the Äshèyi Chu (RIMA) is that it should remain simple to operate, rely on readily available input parameters, and simulate realistic ice processes and associated water level variations. Some characteristics of RIMA include:

- A 24-hour time step and the division of the Äshèyi Chu into 5 reaches of simplified geometry
- A linear heat budget module and a water cooling and warming module
- An ice production and ice melt module
- Reach-specific ice coverage equations that do not depend on ice production rates
- The consideration of four types of stationary ice: surface ice, anchor ice, frazil storage, and frazil jamming
- A multi-threshold, partial breakup module
- An ice mass balance and downstream ice transfer module
- A simple ice-hydraulic module based on the Manning equation
- The identification of overflow and overbank icing (aufeis) events
- A simple interface that provides key information about water or ice levels along the river

With over 200 parameters, RIMA is developed sequentially, from upstream to downstream, calibrated using data from four winters (2019-2020 to 2022-2023), and subsequently tested with data from winter 2023-2024. Some expected model limitations are identified; however, the results suggested that the model is accurate enough to be tested. A conceptual form of the model presented in this report includes several operational considerations for seasonal management of AGS to reduce the probability of overflow and flooding. Recommendations are also listed, including potential future improvements of RIMA.

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1. Context

The Äshèyi Chu and its source, Äshèyi Mǎn (Aishihik Lake), represent the heart of the traditional territory of the Champagne and Aishihik First Nations (CAFN). The construction of the Aishihik Generating Station (AGS) in the mid-1970s, its operation by the Yukon Energy Corporation (YEC), and the addition of the third turbine in the 2000s were generally done without consultation with CAFN. Specific operational flow measures were developed by YEC in late 2019 based on experience. Meanwhile, collaborative agreements between CAFN, YEC, and YG have been signed in 2022.

The winter hydrological regime of the Äshèyi Chu (Aishihik River) is significantly influenced by hydropower generation (Morrison Hershfield, 2018). Compared to a natural system, higher and diurnally fluctuating winter flows are altering the river ice regime of this 31-km-long watercourse. This impacts water levels, channel stability, water quality, and culturally significant sites along the length of the river. Morphological impacts of AGS on the downstream fluvial environment have been described in Palmer (2018), and they will be further characterised by NHC (2025) in a context where they continue to affect the Äshèyi Chu, with cumulative consequences to aquatic habitat. High winter water levels (and overbank icing) are common in the Äshèyi Chu, including on CAFN settlement lands, impacting floodplain habitats, wildlife, and access to the land.

This collaborative effort was framed around a Project Charter (Appendix D), which content and language were agreed upon by all parties: The YukonU Research Centre (YRC) and the University of Alberta (UofA), representing the Modelling Team, the Core Team composed of CAFN, YEC, and the Government of Yukon (Department of Environment), and the Supporting Contributors including experts hired by Core Team members. In Fall 2021, funding was secured from the Climate Change Preparedness in the North (CCPN) program administered by Crown Indigenous Relations and Northern Affairs Canada (CIRNAC) to advance the project.

The project's objective, as described in the Project Charter, is to prepare and deliver two models that quantify ice and water levels in the Äshèyi Chu under a wide range of hydrometeorological conditions to inform future AGS strategic flow management (and possible future co-management). This report describes and explains the development and use of an empirical ice model developed by YukonU. The team at UofA has prepared a stand-alone report focusing on their modelling efforts and products using a different approach (both models are based on the physics of river ice, but the UofA model is adapted from River1D, a hydrodynamic model, whereas the YRC model has more empirical components). Shared project values include a recognition, by all parties involved, of historical mistakes negatively impacting CAFN as well as to work towards reconciliation. This includes sharing the data collected through monitoring campaigns and making the project results available to project partners and CAFN citizens.

This project was supposed to end in March 2024. All parties agreed upon a one-year project extension, at no added cost and in exchange for enhanced deliverables (e.g., the YRC model includes the breakup period, and a complementary, simpler model is presented in Section 6). The rationale for this extension included the need to acquire an additional winter of hydrometeorological data. This document is the final report of the project prepared by the YRC.

2. Background

This section of the report takes a step back by emphasizing the known impact of hydropower generation on downstream environments as documented in the literature. The second subsection zooms back into the case of the winter regime of the Āshèyi Chu, explaining hydrological processes as seen through observations and data collected over recent years. The last subsection emphasizes river ice models and specific needs related to a Āshèyi Chu-adapted model. Readers can refer to Appendix A for general knowledge and terminology related to river ice processes.

2.1 Cold regions hydropower downstream environments

Huokuna et al. (2020) prepared a review paper about the impact of regulation on upstream and downstream environments. It mentions that the impact of hydropower generation during winter has an impact on ice processes and water levels by altering the thermal (with a limited downstream extent, because heat is eventually lost) and hydrological regimes (with a significant downstream extent, because the flow, or flow variations travel long distances). The paper also summarizes that a higher discharge at freeze-up could delay or prevent the formation of a complete ice cover, support the production of greater frazil amounts, and lead to thicker stationary accumulations and, therefore, to higher winter water levels compared with what is observed in a natural (unregulated) environment.

The impacts of hydropower generation on winter water levels are known to happen on several regulated rivers in cold regions. Table 2.2.1 presents a partial list of where such impacts have been documented, explained, simulated, and partially mitigated. Manitoba Hydro, BC Hydro, and Hydro Québec, among the prominent hydropower corporations in Canada, are facing hydrological challenges from winter hydropower production. From a channel size perspective, the experience gained in Norway may be the most relevant for the Yukon. However, the Scandinavian climate is much milder.

Asvall (1997) and Daly et al. (1997), among others, stated that a means to attenuate downstream consequences of regulation was to reduce the discharge (and therefore energy production), at least temporarily. This approach has also been adopted in two power plants located in the Yukon: In January 2001, a freeze-up flood was reported in the Marwell sector of Whitehorse. Yukon Energy Corporation (YEC) now applies a protocol to adapt the discharge when the freeze-up front approaches the Marwell area of Whitehorse (YEC, pers. com., 2019) and a stage threshold is set for this purpose at the Water Survey of Canada station 09AB001. Mayo has been affected by winter flooding caused by ice conditions in the Mayo River downstream of the Mayo Generating Station in recent years. YEC and their consultants introduced a relatively strict hydro-production protocol to apply at the beginning of each winter to promote the formation of a surface ice cover that could subsequently resist (float) to a higher discharge corresponding to the station's installed capacity (Morissette et al., 2017).

The case of the Aishihik Generating Station (AGS), the third hydropower station in Yukon, is unique for several reasons, as described next.

Table 2.1.1. Partial literature review of reported river ice problems downstream of hydroelectric dams.

River	Location	Reference	Reported downstream problem
Otta	Norway	Asvall (1997)	Massive frazil production causing flooding
Alta		Asvall (2007) Alfredsen and Saha (2021)	Lack of ice cover affecting Salmon
Orkla		Alfredsen and Stickler (2013)	Lack of ice cover, increased frazil production affecting Salmon
Koke-mäenjoki	Finland	Huokuna et al. (2020)	Ice-induced flooding
Missouri	South Dakota, US	Daly et al. (1997)	High downstream water levels caused by ice accumulation
St. Maurice	Québec	Hydro Québec (pers. com., 2016)	Freeze-up jamming along Road 155 between Shawinigan and La Tuque
Nelson (multiple sites)	Manitoba	Girling and Groeneveld (1999), Malenchak et al. (2011), Lees et al. (2019) Peters et al. (2021), Stafford et al. (2023),	Anchor ice formation at Sundance Rapids causing high water levels; Freeze-up consolidation below Jenpeg Generating Station
Peace	BC-Alberta	Keenhan et al. (1980), Andres et al. (2003), Jasek et al. (2007), She et al. (2012) Beltaos and Carter (2021), Jasek et al. (2021)	Increase occurrence of freeze-up jams and reduced occurrence of breakup jams (including associated floods); Historical impact of hydro-peaking on freeze-up consolidation
Yukon	Yukon	No known publication	Freeze-up flooding
Mayo		Morissette et al. (2017)	

2.2 Winter hydrological conditions in the Äshèyi Chu

Several case studies listed in the previous subsection identify high water levels and floods caused by a dynamic freeze-up scenario (e.g., freeze-up jams) or frazil accumulation (hanging dams) as the main impact of regulation on the downstream environment during winter. However, no scientific report was found mentioning the occurrence of overflow (and consequent aufeis) within and outside regulated river channels far downstream of the ice edge, a common process in the Äshèyi Chu.

One particularity of river ice formation in the Äshèyi Chu, beyond its general downstream to upstream sequence governed by upstream heat, is the occurrence of several distinct and overlapping freeze-up processes, some of which influenced by the formation of many ice bridges. Those can be initiated by 1. ice dams, 2. the merging of border ice from both sides of the channel, and 3. the interception of a large border ice slab released from upstream. Process 1 is complicated to predict in an alluvial channel with undefined steps and constrictions, and Process 3 is largely variable between years. The stochastic aspect of these processes is important because the number and location of ice bridges influence frazil interception and, therefore, the upstream formation of a complete ice cover. Moreover, the fact that the ice cover could be floating in one year and fixed (grounded) in another makes the prediction of overflow events and under-ice flow conditions

extremely complex to define and predict. Nonetheless, Process 2 is generally easier to predict and simulate, and the location of ice bridges at low-velocity locations may be similar from year to year.

Also, few case studies have emphasized the morphological consequences of high and/or unstable winter flows through altered river ice processes or the existence of a feedback loop between a modification of the channel characteristics and changes to the ice regime. This seems to be happening along the Äshèyi Chu downstream of AGS (Palmer, 2018; McParland et al., 2021). These sediment transport and channel stability aspects are important because hydrodynamic (and ice) conditions can change relatively fast along the river.

First, it is important to explore what contributes to aufeis formation in cold region streams:

- **Thermal context:** Aufeis are mainly reported in permafrost environments (e.g., Ensom et al., 2020). The occurrence of winter overflow and the upward thickening of an ice cover may not only be caused by the presence of frozen ground near stream channels; it may also be due to the limited heat available in the Äshèyi Chu valley (Turcotte et al., 2023).
- **Morphological contexts:** In the Yukon, aufeis are frequently observed in 1. small rivers located downstream of large lakes (e.g., Drury Creek) and 2. shallow, anabranching or braided river segments (e.g., Dezadeash River, or Titl'at Män Tágà, Blackstone River, North Klondike River, Engineer Creek). This compares with what is found in the literature (e.g., Daly, 2013b).
- **Hydrological conditions:** Some studies report intense overflow events during dry years (e.g., on the Klutina River in Alaska, Carey, 1973), but a high flow prior to and during freeze-up is also associated with a significant overflow and aufeis intensity at many other sites (including observations are Drury Creek and on the Titl'at Män Tágà in December 2022). Different hydrological processes may explain the development of aufeis in wet years (massive frazil ice production and storage) and dry years (ice freezing to the bottom of the channel).
- **Weather conditions:** Stream aufeis development in general seems more intense in the presences of 1. a low snowpack (e.g., delayed snowfalls), 2. an intense, early-season cold spell (to maximize heat loss), and 3. significant air temperature variability during winter (but generally cold). Turcotte et al. (2023) suggest that alternating cold and mild conditions cause flow fluctuations, generating overflow events in a non-floating ice-cover environment.

The previous list is important for this study about the dynamics of the Äshèyi Chu for several reasons:

- **Thermal context:** The Äshèyi Chu valley contains permafrost and limited (cold) groundwater that cannot significantly contribute to melting a river ice cover or to promoting its floating state. From a different angle, prior to AGS, the East Aishihik River was providing 0°C water to the downstream environment during winter, which is different from what the tailrace supplies.
- **Morphological contexts:** The Äshèyi Chu channel is generally shallow and wide, and it is apparently getting wider (Palmer, 2018) and, therefore, shallower. These changes maximize heat loss. In addition, the channel is getting steeper (sinuosity is declining), which promotes the formation of anchor ice and ice dams as well as the transport of frazil slush under an existing ice cover to a location where it accumulates and blocks the flow. These changes could explain the occurrence of overflow events far downstream of the open water (ice cover-free) channel extending a few kilometres downstream of the AGS tailrace during winter.
- **Hydrological conditions:** Winter flows in the regulated Äshèyi Chu are higher than what they would be in a natural system, which delays the formation of a static ice cover, promotes the

production of frazil and the formation of freeze-up jams, anchor ice and ice dams, all of which can cause channel congestion, overflow, and aufeis.

- **Weather conditions:** Flow regulation in small rivers tend to generate hydrological instabilities that are more significant compared to those occurring in natural environment, especially during the second half of winter, when the natural flow recession becomes monotonic. Therefore, regulation is a known cause of winter overflow (Turcotte et al., 2023). In addition, periods of high flow in the Äshèyi Chu generally correspond to the coldest periods (because of energy generation), which means a combination of frazil production, dynamic ice congestion, overflow, and massive heat loss. Finally, the Äshèyi Chu valley is generally dry, which means that the insulation provided by the snowpack is often limited. Interestingly, She et al. (2012) proposed that weather could play an equally important role as hydro-peaking in causing ice cover consolidation events in the large Peace River. This needs to be considered the other way around for the smaller Äshèyi Chu, with hydro-peaking having a much greater impact in such a small alluvial river than weather variability alone.

It is stated by McParland et al. (2021) that the Äshèyi Chu “should have narrowed following the construction of AGS.” However, the winter regime of the river completely reversed this theoretical expectation, proving the complexity of hydropower generation (and hydropeaking) in a sub-arctic alluvial context. The combination of thick, non-floating ice accumulations along the banks, a partially floating ice cover above the thalweg (main channel), and varying flow conditions significantly impact bank stability, sediment supply, and sediment transport capacity. During winter, flow instabilities could generate sediment transport events (Palmer, 2018). When the mid-channel ice cover frees itself from the bank, generally at the end of winter, diurnal discharge fluctuations lead to its overflow and, potentially, to its thickening. This could result in pushing more water towards the channel edges and undermining the banks. This may explain why turbid overflow is visible in March and why rows of bushes and trees are lost in the spring along the Äshèyi Chu.

McParland et al. (2021) mentioned that a sediment transport-related feedback loop may exist between channel widening and overbank ice (aufeis). The authors of this report believe that this feedback loop may be more complex: unstable banks resulting from ice processes and high winter flows do contribute to straightening and widening the channel, but a shallower channel results in more heat loss and, combined with high and unstable flows, to a thicker ice cover and overbank flooding. Under current flow management and climate conditions, the possibility and characteristics of a stable morphology for the Äshèyi Chu remains largely uncertain.

2.3 River ice models

In most unregulated cold region rivers, the simulation of the formation of an ice cover is relatively simple compared with the simulation of breakup. Indeed, freeze-up is often dominated by thermal and gradual processes, whereas breakup has a dynamic component that can be extremely difficult to predict in space and time. In regulated environments, especially in small rivers like the Äshèyi Chu where multiple ice processes can take place (see subsection 2.1), the technical challenge can be reversed: Developing a numerical model to simulate (a dynamic) freeze-up is more complex than it is to simulate (a thermal and spatially sequential) breakup.

The occurrence of ice jam floods is likely the first reason why river ice models were first developed. River ice equations were likely based on knowledge developed around pulpwood rafting (e.g., Kennedy, 1962). Then, Pariset et al. (1966) and Uzuner and Kennedy (1976) developed ice jam stability equations. The original form of these equations is still used in several deterministic river ice models developed in recent decades. River ice models from the deterministic family may:

- Include a river ice module combined with a hydrodynamic model in a 1D or 2D environment;
- Use steady state (static ice conditions, constant flow) or unsteady state (changing ice and flow conditions) equations;
- Simulate a few or multiple ice processes;
- Simulate ice production (and melt) by heat loss (gain) or only assume a constant ice volume.

For example, HEC RAS (Hydrologic Engineering Center's River Analysis System, publicly accessible through the US Army Corps of Engineers website) is a one-dimension ice-hydraulic steady state model that relies on Manning's equation (see Section 4). It can simulate a complete, floating ice cover and a static ice jam (both conditions are imposed by the user between specific channel cross-sections). This model could be used to simulate winter water levels in the Āshèyi Chu, but the ice cover roughness and thickness would have to be manually imposed to represent the two- or even three-dimensional ice environment of the river, overflow ice (aufeis) could not be simulated, and operating the model would be time-consuming and significantly iterative.

Environment Canada's RIVICE model was developed in the 1990s and early 2000s with the support of KGS Group (RIVICE Model – User's Manual, Environment Canada, 2013). This model can simulate the production and melt of ice, the formation of an ice cover involving a dynamic interception of incoming ice, and breakup processes in an unsteady flow context. Despite the complexity of the targeted ice processes, RIVICE could have been adapted to the Āshèyi Chu. However, users would need to set up about 40 ice-related parameters (or more if the model included aufeis), including the location of ice bridges and ice deposition velocities (which is impractical for the Āshèyi Chu). Moreover, the model, programmed in Fortran, would have to be understood by model users.

The YukonU modelling team anticipated that developing an updated hydrodynamic model of the Āshèyi Chu would be challenging for many reasons, including the spatially heterogeneous and fast-evolving morphology and geometry of its channel, and considering the lack of hydraulic data to support model calibration. Moreover, to the knowledge of the YukonU team when the project started, no existing deterministic river ice model could simulate the diversity of overlapping and apparently chaotic ice processes in a small, steep, regulated channel without substantial code adjustment.

Another family of river ice models, usually referred to as data-driven, includes threshold methods, statistical models (e.g., regression equations), Artificial Neural Networks (ANN), and Fuzzy Logic. These models could generally ignore most or all the physics controlling river ice processes by being trained on large data sets. Developing a reliable river ice model for the Āshèyi Chu that relies on Machine Learning or Artificial Intelligence to determine a probable range of water levels at any given location along the river would require a significant amount of accurate data and observations. Therefore, entirely ignoring the physics of freeze-up and breakup would not be suitable in the current context, and a hybrid approach (both data-driven and physics-based) would be preferable.

The YukonU Research Centre, therefore, decided to develop an entirely new model combining empirical (data-driven and threshold-based) components and physical aspects in a largely simplified hydrodynamic context that would cancel out some levels of complexity. A comparable model had been developed by Turcotte and Morse (2016) for an unregulated river. Despite adopting a similar structure, this new model would have to include several additional modules, as described in Section 4. The reasoning behind this decision was similar to what had been stated by Turcotte and Morse (2016): “It is sometimes easier to develop a simple model that emphasizes context-specific processes than to adapt an existing model to fit immediate needs”. The amount of data collected over the years, including water levels, water temperatures, and observations of ice conditions (described in the next section), could support the development of this type of model.

The modelling team from the University of Alberta chose to adapt the deterministic River 1D model (e.g., She and Hicks 2006) to the specific context of the Åshèyi Chu. This model had been tested in a small, regulated stream in Norway (Alfredsen and Saha, 2021). Modifications to the River 1D model to simulate ice processes in the Åshèyi Chu are presented in a sister report and recent paper (Fang et al., 2025a,b).

3. Data and data processing

The YukonU modelling team is grateful for the data collected by Morrisson Hershfield (MH, now Stantec) and the Champagne and Aishihik First Nations (CAFN) since (at least) 2017 in the AGS downstream (and upstream) environment. Some data was also collected by the Government of Yukon (YG), Department of Environment, during the winters of 2018-2019 and 2019-2020.

The data used to develop and calibrate the model was classified in comprehensive, winter-specific Excel files, each including graphs that allowed users to visualize water levels, water temperatures, air temperatures, and discharge data (AGS and East Aishihik River) at a 15 minute-time step for variable periods (a few to several consecutive days between October to May). Eight files were produced (2017-2018 to 2024-2025).

The type of data sets used for the development and calibration of the model described in Section 4 are presented in Table 3.1. The most critical parameter for the development of the model was the water temperature of the AGS tailrace, as described in Section 4. Therefore, winters during which this parameter was not monitored could not be used for model development (e.g., 2017-2018).

Table 2.3.1. Data used to develop and calibrate the YukonU river ice model. Winter 2023-2024 (shaded) is used for model validation and result analyses.

		2019-2020	2020-2021	2021-2022	2022-2023	2023-2024
Tailrace & East Ashihik River discharge		X	X	X	X	X
Tailrace & East Aishihik River water temperature		X	X	X	X	X
Water depth and water temperature	Kp 5 (Reach 2)	X	X	X	X	X
	Kp 8 (Reach 3)	X	X	X	X	X
	Kp 15 (Reach 4)		X	X	X	X
	Kp 20 (Reach 5)		X			X
	Kp 25 (Reach 5)			X	X	X
	Kp 26 (Reach 6)	X	X	X	X	X
Photos from automated cameras	Kp 5	X	X	X	X	X
	Kp 8 upstream	X	X	X	X	X
	Kp 8 downstream	X				
	Kp 12	X		X	X	X
	Kp 15				X	X
	Kp 18			X		
	Kp 20		X		X	X
	Kp 25		X	X	X	X
Kp 26	X	X	X	X	X	
Tailrace air temperature		X	X	X	X	X

Readers may have noted that some data sets collected by MH, CAFN, and YG during recent winter monitoring campaigns are not presented in Table 3.1. This includes several water level and temperature records from upstream reaches of the Äshèyi Chu during winter 2019-2020 and from the Dezadeash River (Titl'at Män Tágà) starting in winter 2020-2021. Although these data sets were not directly used for model development and calibration, they were all referred to for model validation. For instance, Titl'at Män Tágà records were used to 1. evaluate whether a significant amount of frazil was exiting the Äshèyi Chu during freeze-up and 2. Confirm that Titl'at Män Tágà was not receiving a meaningful quantity of frazil once the freeze-up of the Äshèyi Chu was mostly completed.

The requests to deploy instruments at new, low vulnerability, or remote locations expressed by the modelling teams over five winters were justified. Data records from Km 12 to Km 20 of the Äshèyi Chu were crucial for developing the YukonU model because it was identified that continuous water data and ice condition observations would be needed for each river reach defined in Palmer (2018), especially near their downstream boundary.

In addition to what is presented in Table 3.1, two important data sets needed to be created prior to the development of the river ice models: time-dependent ice coverage data and reconstructed West Aishihik River winter hydrograph. The ice coverage estimation procedure is defined as follows:

1. Select daily pictures (ideally at the same time every day) from a specific site;
2. Visually identify the main channel boundaries (exclude dry areas) as well as the upstream extent over which the channel is visible;
3. Identify days without any ice cover on or above the main channel and set the ice coverage to 0% for those dates;
4. Select about five days spread over the freeze-up period (with distinct and increasing ice coverage ratios) and estimate the ice coverage (%) for each date;
5. Evaluate the ice coverage for each day of the freeze-up period independently of the values obtained at stage 4;
6. Compare the partial assessment from step 4 and the continuous assessment from step 5, and harmonize both data sets so that the ice coverage is established as objectively as possible for each day of the freeze-up period.
7. Define the ice coverage during the mid-winter period (may not apply to upstream reaches; some challenges may arise when snowfalls happen as they tend to hide open water leads);
8. Estimate the ice coverage during breakup (usually drops suddenly and never recovers);
9. Compare the ice coverage from different camera sites and identify outliers;
10. Use drone surveys, visible satellite imagery, or radar-derived products (Saal et al., 2023, 2024 describe the work done to estimate the ice coverage based on the channel surface backscatter) to define reach-specific ice coverage values for specific dates.
11. Use date-specific, reach-average ice coverage values defined in Step 10 and site-specific, continuous ice coverage values defined in Steps 6 to 9 to create a reach-average, continuous ice coverage data set. Knowledge of ice processes and judgment are needed.
12. Repeat steps 1 to 9 for each camera and steps 10 and 11 for each reach to develop continuous ice coverage data sets for all reaches. This generates a 24-hour time step ice coverage data set for all reaches of the Äshèyi Chu (if cameras were available and records contained no gap).
13. Repeat all previous steps for each winter.

A sample result from this focus-intensive but critical exercise is presented in Figure 3.1.

Discharge records prepared by the Water Survey of Canada (WSC), or any agency responsible for producing flow estimates, can be highly imprecise during winter (e.g., Turcotte and Rainville, 2022). This also applies to station 08AA01 on the West Aishihik River. The flow of the West Aishihik River was re-assessed using i. continuous stage data, ii. winter flow measurements provided by the WSC, and iii. air temperatures measured near the AGS tailrace using a technique described in Turcotte and Rainville (2022). This procedure was initially applied to four winters (2019-2020 to 2022-2023), with results (Figure 3.2) meant to minimize model input uncertainties.

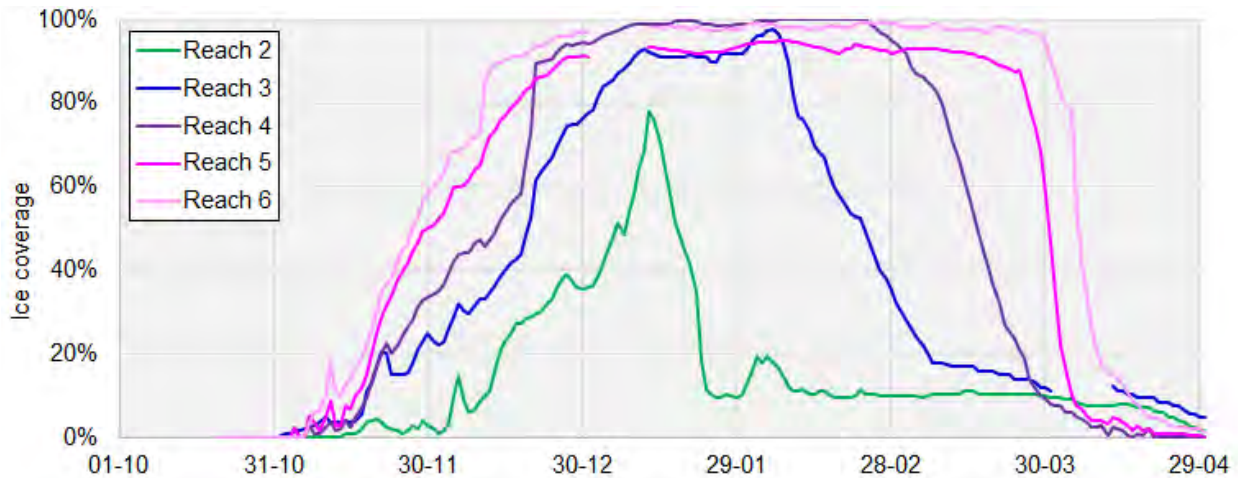


Figure 3.1. Ice coverage over time for each reach of the Äshèyi Chu during winter 2021-2022 as estimated following the procedure described above.

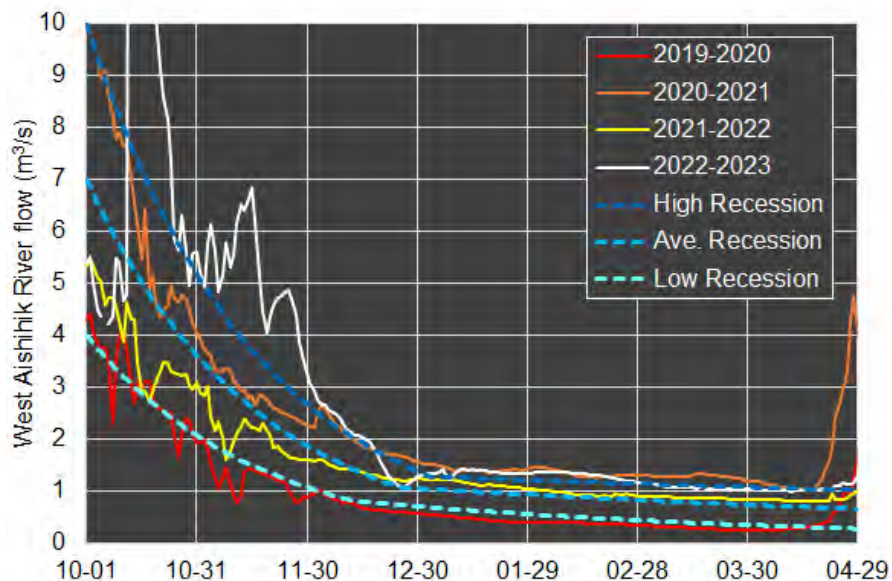


Figure 3.2. Reassessment of four winter hydrographs for the West Aishihik River and development of three dual-reservoir recession curves for above average (high), average (ave.) and below average (low) winter flow conditions.

It was later established, while developing the model (refer to Section 4), that asking model users to create a West Aishihik River flow record in real-time would be impractical. Instead, through simplifications, it was concluded that defining three possible winter flow recessions (using the dual-reservoir approach presented by Rainville and Hamilton, 2019) for the West Aishihik River, based on the pre-freeze-up discharge (high, average, low), would not affect the accuracy of the model (Figure 3.2). Indeed, it is well known that, if the streamflow is higher than average at the onset of freeze-up, it will remain above average during the winter period as the recession shape is generally a property of the watershed. This only applies in the absence of runoff from rain-on-snow events, which have been either rare, or of low intensity in recent years in the Yukon. Readers will be reassured that when the West Aishihik River flow rises in the spring, the breakup in the Äshèyi Chu is generally over, and therefore, the snowmelt runoff can be ignored.

4. RIMA Model

The River Ice Model for the Äshèyi Chu (RIMA) developed by Yukon University is an empirical model framed around physical equations. It relies on numerous thresholds that are either established using field observations or theoretical river ice principles. The model circumvents the complexity of a hydrodynamic simulation to calculate the amount (considered here as mass) of ice that accumulates in different reaches of the Äshèyi Chu, with a consequent impact on water levels. The following subsections of the report describe different aspects and components of the model.

4.1 Model structure

Numerical environment

The model was developed in Microsoft Excel. Three reasons justify this choice: 1. The report's principal author had developed comparable models in Excel, although not as complex (e.g., Turcotte and Morse, 2016); 2. Most people are, to different degrees, familiar with Excel; 3. This numerical environment enables a quick identification of which equation or time step (i.e., which cell) is problematic when using the model with input parameters that are outside of the expected range. A downside of this choice is the difficulty of understanding the link between all the equations, which is overcome by adequate documentation (e.g., Notes in Excel columns and this report). The empirical nature of the model means that it has been built iteratively, by progressively adding parameters and equations that were needed to calculate a heat budget, an ice volume, and then water levels.

Time and space considerations

The first stage of model development was to identify an appropriate time step. Although sub-daily data was available, it was established that this would add too much weight to the model file and that a sub-daily time step would not provide a significant benefit. In turn, it could generate model instabilities and increase the complexity of conditional functions (e.g., "if"). For instance, for a daily time step, the exact celerity of flow variations could be ignored (they depend on several factors, including changing ice conditions). This does not mean that the model only considers daily-averaged conditions, as this would not have been strategic in the context of hourly fluctuations in power generation and consequent flow variations. Therefore, daily minimum, mean, and maximum flows, as well as daily-averaged air temperatures, represent input parameters in the model.

In terms of spatial aspects, in an empirical context, it was identified that calculating ice and water level conditions at a reach-averaged scale would be easier to program and that this would not compromise the result accuracy or the usefulness of the model for CAFN and YEC (model calibration could emphasize past years' monitoring sites or other critical sites). Those reaches, however, would need to present some longitudinal consistency in terms of morphology and gradient (which control ice processes through hydrodynamic conditions). The definition of these reaches was based on the report provided by Palmer (2018) to Morrison Hershfield. It was acknowledged that the alignment, depth, and width of those six reaches (R1 starting at the AGS tailrace and R6 ending in the Dezadeash River, or Titl'at Män Tágà) are evolving over the years as the river adjusts to altered flow and ice conditions. The model was built so that these parameters could be updated if needed. Since ice accumulation in the upstream-most reach (R1) is rare, reaches 1 and 2 were regrouped.

Figure 4.1.1 presents the structure of RIMA (development stage 16). The various variables are presented in the following subsection. Green variables are input parameters, whereas blue variables are model outputs. The model's equations are the same for each reach (5 sheets in the Excel model), with heat and ice transferred to the downstream reach at the same time step (during the same day).

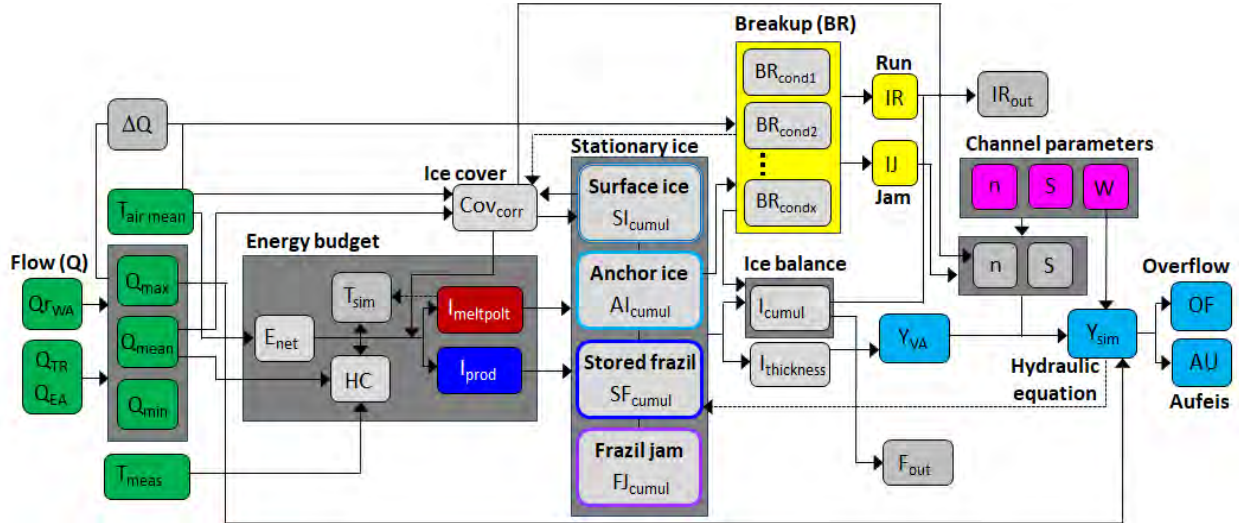


Figure 4.1.1. Structure of Rima (development stage 16) developed in the Excel environment. This structure is identical for all 5 reaches of the Äshèyi Chu.

4.2 Model components and development methodology

1. Ice coverage equations

Calculating the ice coverage in the main channel of the Äshèyi Chu is a central component of the model. The total amount of ice that can be stored in the channel depends on it, and it is also used to calculate the area of open water where heat loss generates ice production (presented next). The formation of border ice, anchor ice, ice dams and ice bridges, the storage of frazil under an existing surface ice cover, and the occurrence of overflow and aufeis thickening events depend on several interacting factors related to weather, hydraulic, mechanical, but also, ice conditions. This represents a chicken-and-egg situation. This complexity was circumvented by creating empirical equations that would evaluate a reach-averaged ice coverage over time using simple and accessible parameters (air temperature and flow), therefore making the coverage independent from the simulated ice production. There was a risk associated with this decision: What if the progression of the simulated ice cover (independently of the freeze-up process) was limited by the calculated heat loss and ice production? Different conditions were imposed in the model to prevent the infrequent occurrence of such a situation. Why infrequent? Because, during cold days, it has been consistently observed that a ratio of the frazil produced by a given Äshèyi Chu reach is transported downstream, which means that there is more ice produced than what the local ice cover needs in order to form.

The equation adopted to calculate the ice coverage (formation and melt, Cov_{sim}) takes the following empirical form (it is acknowledged that it is not dimensionally correct):

$$Cov_{sim}(t) = \frac{(-T_{air\ mean}(t-1) + T_{eff}(t-1))}{CDDF_R} + Cov_{sim}(t-1) < Cov_{max} \quad [1]$$

In Equation 1, $Cov_{sim}(t-1)$ is the ice coverage (in % of the channel width) of the previous time step, $T_{air\ mean}(t-1)$ is the mean temperature of the previous day, $CDDF_R$ is a reach-specific cumulated degree-day threshold (see values in Appendix B), and $T_{eff}(t-1)$ is the effective air temperature on the previous day calculated as followed:

$$T_{eff}(t) = \frac{T_{air\ R}}{\left(\frac{Q_T}{Q_{mean}(t) \leq Q_{high}}\right)^{a_{QR}}} \quad [2]$$

$T_{air\ R}$ is an air temperature threshold that is reach specific (see values in Appendix B), $Q_{mean}(t)$ is the daily-averaged flow (the higher Q_{mean} , the higher is T_{eff} , and the lower is Cov_{sim} for a given $T_{air\ mean}$), Q_T is a discharge threshold applied to all reaches (to make the discharge non-dimensional), Q_{high} is the maximum flow considered for Cov_{sim} calculation, and a_{QR} is a reach-specific exponent constant (the higher its value, the more impact a low Q_{mean} has on T_{eff} and therefore on Cov_{sim}). It is important to mention that the first border ice to form in the river (generally over less than 15% of the channel and often ephemeral) is not considered in equations [1-2] because this thin ice has been observed to form even when the water temperature (T) is above 0°C. Therefore, the value of Cov_{sim} may initially be inaccurate, and this does not affect the model results.

The calculation of the ice coverage was also adapted to simulate the occurrence of breakup events (imposed reduction in Cov_{sim}). At a later stage of the model development, based on observations obtained from photo sequences, it was decided to impose a calculation of Cov based on ice melting rates when spring (or consistent melting) conditions occur. This corrected parameter is called $Cov_{corr}(t)$. It essentially considers that the ice coverage during the second half of winter is linearly proportional to the simulated total amount of ice at any timestep t , relative to the maximum amount of ice in the reach during winter. This means that the model considers that the ice in the channel melts entirely at the open water-ice cover (streamwise, longitudinal) transition because of warm water coming from upstream rather than at the ice-air interface because of warm air and sun insulation. Heat from upstream and observations (the presence of reflective snow on the ice cover, not accounted for in the model, protects the ice from melting) justify this simplification.

II. Heat budget equations

The second step of the model was to develop energy exchange equations (which control water warming and cooling as well as ice production and melt). At an early project stage, it had been identified that a full heat budget (relying on multiple weather parameters) did not significantly improve the accuracy of water-cooling simulations (e.g., Figure 4.2.1). Therefore, a linear energy equation was adopted:

$$E_{net}(t) = a_E(T_{air\ mean}(t) + T_{corr}) \quad [3]$$

Here, $E_{net}(t)$ is the estimated net energy budget at the water surface (in Watts per square meter) for that day, $T_{air\ mean}(t)$ is the daily-averaged air temperature, and T_{corr} is a time-dependent correction that takes into account the sun angle in a linear way (T_{corr} increases linearly from 0°C prior to February 15 to 3.6°C on April 15, to consider the sun power). The constant a_E was calibrated to 14 W/m² °C for all reaches (see resulting calibration in Figure 4.2.1 for early-winter water temperature T simulations). This constant assumes average wind, cloud, and humidity conditions, which is convenient as including these parameters in the model is costly, and it could increase its complexity with limited

benefits on accuracy. For simplicity, no heat exchange at the air-ice cover (or snow) interface was calculated. Initial border ice cover thickening was considered in an alternative way (described below). This also means that the model assumes that the ice temperature in the Āshèyi Chu channel, floating or not, is stable at 0°C (which is reasonable if one compares its heat capacity [4.187 KJ / °C Kg] and its latent heat of fusion [333.5 KJ / Kg]).

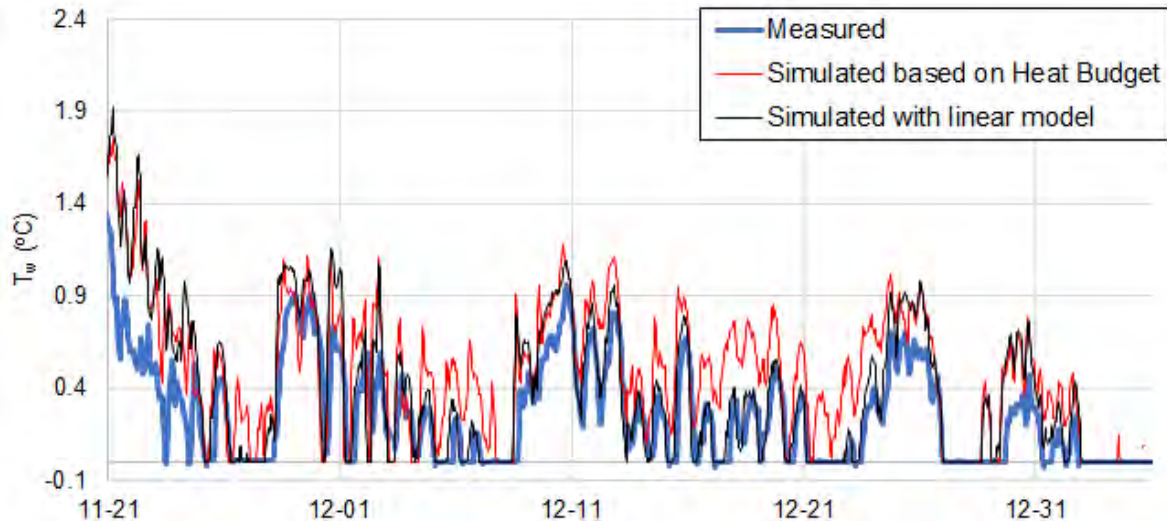


Figure 4.2.1. Measured and simulated (with heat budget and with equation [3]) water temperature at Kp 7.8 (Reach 3) between Nov 21, 2021 and Jan 14, 2022).

Water temperature calculation

Early model development efforts presented in Figure 4.2.1 do not consider that, in order to warm the water above 0°C, the ice in contact with the water needs to melt first. The model calculates the amount of heat (in kWh/day) carried in the flow entering and leaving each reach, first by considering local (reach-scale) heat loss without ice considerations, then adding ice melt into the heat calculation. Generally, the heat available from upstream will have to melt the ice in the reach before being transferred to the downstream reach. Several parameters are involved in this calculation:

- The length (L) of each reach (in metres, m, a constant)
- The open-water width (W_{ow}) of each reach (m, initially depending on the water level in an imposed triangular cross-section shape, Figure 4.2.2A)
- Tailrace flow (Q_{mean} , a model input parameter provided by YEC) and West Aishihik River flow (m^3/s estimated based on three possible scenarios imposed by the model user, considering late-fall flows [measured by the Water Survey of Canada station 08AA011](#): above average, average, and below average)
- The simulated reach-averaged ice coverage (Cov_{corr} , in %, derived from equation [1])
- The simulated amount of stationary ice in the reach at the previous time step (in kg or tons, to be defined next)
- The specific heat capacity of water (a constant, 4.186 KJ / °C kg), with a Watt = 1 joule(J)/s
- The latent heat of fusion of the ice (a constant, 333.5 KJ / Kg)
- The simulated amount of ice (in tons or kg) transported from the upstream reach, in the flow, either as frazil (slush, F_{in} , in tons per day) or ice runs (from breakup, IR_{in} , in tons per day)
- The heat content from the upstream reach (HC , in kilo Watts, kW, a simple calculation)

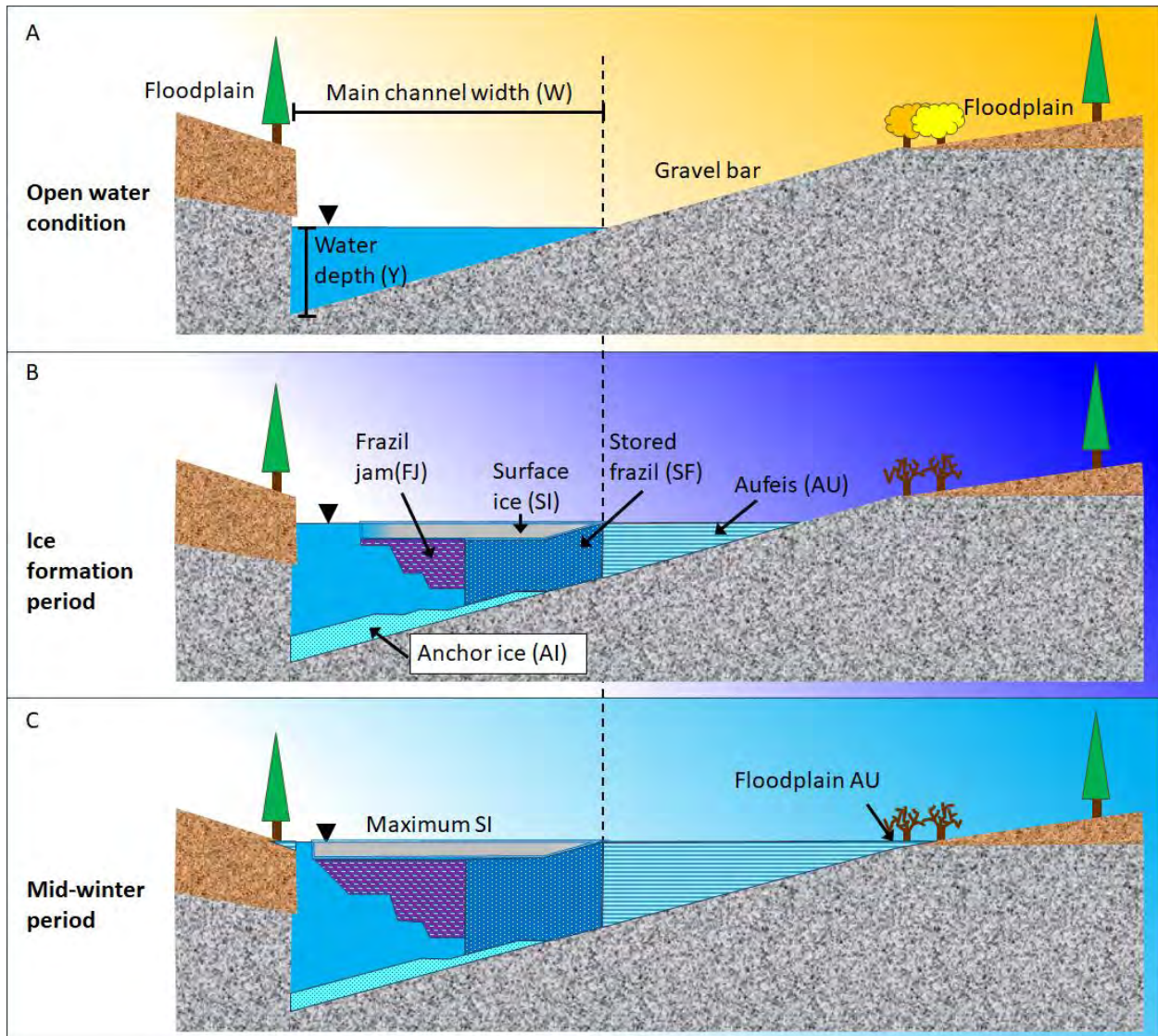


Figure 4.2.2. Simplified cross section of the river channel showing how the model simulates five different forms of stationary ice (Surface ice, anchor ice, stored frazil, frazil jam, and aufeis), with a consequent rise in water level (black triangle). The flow is towards the audience.

- The water temperature from the upstream reach (simulated T_{Kpx} , or measured from the tailrace, $T_{tailrace}$; note that the West Aishihik temperature is assumed to be 0°C for the entire simulation because its ice cover tends to form first and melt last)
- The heat loss or gain at the air-water interface (based on Watts/ m^2 of open water area)

The model can calculate the daily-averaged water temperature at any location in a reach (T_{Kpx}), and it can also determine the location where the water temperature drops to 0°C ($L_{T=0}$), a point beyond which ice can be produced. Figure 4.2.3 presents the water temperature simulation results for Reach 1-2 during winter 2021-2022. Readers will note some differences between the no-ice simulation (yellow) and the ice simulation (in red). The difference between the ice simulation (red) and the measurement (blue) partially results from of a difference between the simulation and measurement locations. Before Jan 29, the stationary ice between Km 5 and 6 was melting.

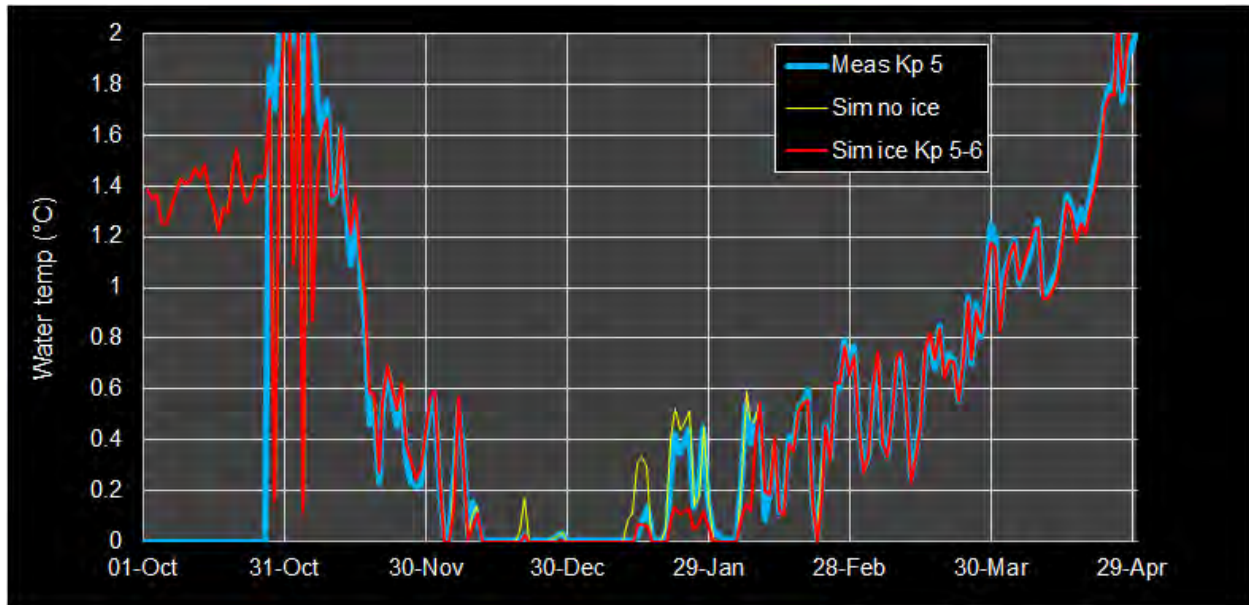


Figure 4.2.3. Measured and simulated water temperature in Reach 1-2 (Kp 0 to Kp 6) during winter 2021-2022.

III. Ice production and ice melt

Ice can only be produced in flowing water once it has cooled to 0°C. The amount of ice produced in a reach every day (I_{prod}) depends on the rate of heat loss (E_{net} , W/m², from equation [3]), the open water area available for heat loss (m²), and the latent heat of fusion of the ice (333.5 KJ / kg). This calculation is straightforward since a Watt (W) equals a joule (J) per second (there are 86,400 seconds in one day). The colder $T_{air\ mean}$ and the lower is Cov_{corr} , the more ice is produced. The model assumes that all the ice produced is initially frazil ice (FI, small ice crystals in the flow). Generally, high values of I_{prod} are in the order of 10,000 tons (1 ton = 1,000 kg) per day for one reach. Depending on numerous environmental and ice conditions, this I_{prod} ($= FI$) will be stored in different forms of stationary ice in the same reach or transported in the same form (frazil slush in the flow) to the next downstream reach (F_{out}).

The mass of ice melted in a single day also relies on a relatively simple heat calculation. The heat gain in a reach is expressed in W per day (or kW per day). The model evaluates a melting potential ($I_{melt\ pot}$) for a reach every day. When the $T_{air\ mean}$ is cold, this value is 0. For high $T_{air\ mean}$ and E_{net} , the melting potential departs from 0 and is proportional to $1 - Cov_{corr}$ (open water ratio). The model first melts the ice contained in the flow (i.e., from upstream, F_{in}), if any, then melts the ice and calculates a residual heat content (HC) to be transferred to the next reach. On most spring days, the HC in a reach, either gained from upstream or from local heat exchange, does not manage to melt the entire amount of ice in the reach. It generally takes several warm days to melt some 100,000 tons of ice.

The time step of 24 hours introduces a model limitation during melting events. It happens that more or less ice is melted than the $I_{melt\ pot}$ calculated from the HC ($I_{melt} < \text{or} > I_{melt\ pot}$). The actual I_{melt} is based on the quantity of all forms of ice during the previous time step. An additional source of error, with limited impact on the model results, is that the model considers that some anchor ice (stationary ice form 2, described below) and some of the frazil jam (stationary ice form 4) melts because of heat supplied by friction and groundwater. These minor heat sources are independent of heat exchanges at the water-air interface but are part of the ice balance calculation for every timestep. This weather-

independent melting was introduced to simulate the gradual drop in water levels during winter unrelated to ice settlement (or compaction). Generally, the error introduced in the calculation of I_{melt} is less than 1% of the total amount of ice contained in the reach for every time step, with larger numbers occurring during the last days of melting (when the amount of melted ice approaches the total amount of ice left in the channel).

The following subsections describe how the model simulates the development of four forms of stationary ice, as presented in Figure 4.1.1. These ice forms are presented schematically in Figure 4.2.2.

IV. Stationary ice form 1: Surface Ice (*SI*, or border ice)

The first stationary ice form that develops in any given reach of the Āshèyì Chu is surface ice (*SI*). The module that calculates the amount of *SI* (in tons) relies on a single variable, the calculated ice coverage COV_{corr} (%) (independent of the calculated heat loss or water temperature). It also depends on numerous constants, including the total area of channel surface (reach length and channel width at a flow of 22 m³/s). The initial surface ice thickness $t_{SI\ ini}$ is imposed for each reach (0.15 to 0.2 m; Figure 4.2.2B), and so is the initial border ice porosity SI_p (40% to 50%; refer to Appendix B). If E_{net} is smaller than an SI_{ETR} threshold (another constant), the new border ice freezes solid, and the porosity of its frazil matrix becomes 0%. Where the water depth is smaller than $t_{SI\ ini}$ (close to the right shore), the amount of ice is multiplied by 0.5 to take the triangular shape of the cross-section into account (Figure 4.2.2B). For each time step, the new border ice segment is added to the total ice mass SI_{cumul} for that reach (in tons).

The *SI* module also calculates a reach-averaged SI_{cumul} thickness (in metres). This SI_{cumul} cannot be greater than $t_{SI\ ini}$ (the ice cover does not grow thermally after the day of its formation, which is reasonable when one considers the porosity of the ice generally found in the river and along its banks). This parameter is used to correct the ice-induced blockage (in m) of the water column when calculating the water depth (final step of the model). *SI* melt (SI_{melt} , in tons) and *SI* breakup ($SI_{breakup}$, in tons) are also calculated and subtracted from SI_{cumul} at each time step. In the first case, melting is imposed by a warm E_{net} (during winter) and warm water (in the spring), causing a reduction in Cov_{corr} . Breakup is imposed by another module, and the associated sharp reduction in Cov_{corr} either causes an ice run (when Cov_{corr} is low) or an ice jam (when Cov_{corr} is high and broken ice pieces are intercepted). Spring breakup ends when $Cov_{corr} = 0\%$, which imposes $SI_{cumul} = 0$.

Minor simulation errors can result from situations where I_{prod} is smaller than the added SI_{cumul} imposed by a rise in Cov_{corr} . In this case, the model ignores the I_{prod} limitation and imposes a more porous ice. This simplification usually results in an average SI_{cumul} error of about 0.01 m by mid-winter, which is acceptable.

V. Stationary ice form 2: Anchor ice (*AI*)

The simulated ice produced (I_{prod}) by the model in a reach of the Āshèyì Chu that is not stored at surface ice (*SI*) is transferred to a second module called *Anchor Ice (AI)*. This porous type of stationary ice forms on the substrate of a riverbed (Section 2.1). The theory of river ice suggests that, for large rivers, this anchor ice is released from the bed and floats away when the sun rises (e.g., Michel, 1971). However, anchor ice can form over many days in small and steep watercourses and attain a thickness greater than the original water depth (e.g., Turcotte et al., 2013).

The *AI* module is based on this anchor ice and ice dam theory but ignores the *in-situ* growth process. From a thermal perspective, this simplification is defensible because the heat loss that supports the growth of ice crystals must equal the heat loss that produces an equivalent mass of new frazil crystals (in the end, ice production is related to the latent heat of fusion). The first computational step for the storage of frazil ice in the form of anchor ice to be initiated is a reach-specific binary *AI* conditions (refer to Appendix B for constants value): *AI* would form in open water conditions ($Cov_{corr} < AI_{covTR}$) when the air temperature ($T_{air\ mean}$) is cold ($E_{net} < AI_{ETR}$, an approximation of supercooling conditions, e.g., Daly, 2013a) and until a maximum *AI* thickness ($AI_{thickness} < AI_{tTR}$) would be achieved. This *AI* formation period could be extended by a second set of conditions beyond the maximum, reach-averaged *AI* thickness threshold (AI_{tTR}) as long as the daily value of $E_{net} < AI_{ETR2}$ (and $AI_{ETR2} < AI_{ETR}$). The rationale behind these superimposing thresholds is that once the ice coverage Cov_{corr} is too high, once the $T_{air\ mean}$ is not cold enough, or once the flow of water is already slowed down by ice dams, *AI* stops accumulating. However, if the $T_{air\ mean}$ remains very cold when the thickness threshold AI_{tTR} is attained, *AI* could keep forming until the $T_{air\ mean}$ warms up because of massive heat loss through overflow. This corresponds to what is observed along the Āshèyi Chu, especially in upstream reaches (constants are presented in Appendix B).

Once the model establishes that *AI* can form, it imposes a constant ($T_{air\ mean}$ -independent), maximum accretion or growth rate (AI_{grR} , based on theory and measured water level datasets, e.g., Dubé et al., 2015), which is in the order of 0.3 cm per hour (or 7 cm per day, refer to Appendix B for reach-specific values). The porosity of the *AI* (AI_p) is also a reach-specific constant. This AI_{grR} only applies to the channel area that is not ice-covered ($1 - Cov_{corr}$) and where the water temperature T_{kp} equals 0°C. After the *AI* blanket (or ice dams) is stable, the *AI* module allows it to settle (be compacted under the weight of above-lying ice). The settled *AI* thickness ($AI_{settled}$) is limited to an *AI* settlement rate ($AI_{settleRR}$) and total loss in volume ratio (AI_{volRR}). These values are generally in the order of 2 cm per day and limited by AI_p .

It is known from observations that *AI* generally does not melt entirely in place; part of it is lifted and floats downstream. In large rivers, the ratio of *AI* released to *AI* melted in place (AI_{lmR}) is usually high, whereas in very small creeks, it is very small. For the Āshèyi Chu, a relatively small watercourse, it has been identified that AI_{lmR} would be fixed to 2 (the mass of lifted *AI* can be twice that of melted *AI*). *AI* melting events only occur when there is a melting potential ($I_{meltpot} > 0$), and the amount of *AI* melt (AI_{melt}) at any given time step is therefore limited by $T_{air\ mean}$ as well as by Cov_{corr} . Lifting events are less common as they occur only in the presence of recently formed *AI* (no spring condition, *AI* not settled) if the ice cover is less than a reach-specific threshold (AI_{liftTR}). As stated above, to take other sources of heat into account, a small quantity of *AI* can melt during any given day of winter at a rate (AI_{meltRR}) that is proportional to E_{net} above AI_{ETR} . Values of AI_{meltRR} for different reaches vary from 100 to 250 tons per day when $E_{net} = 0$ and are independent of Cov_{corr} because they happen at the ice-bed interface.

The model assumes that the cumulative quantity of *AI* (AI_{cumul}) that remains in the channel once it is fully ice-covered (Figure 4.2.2C) is simply integrated into the volume of ice that remains in the reach during winter. In the spring, considering the available heat (or $I_{meltpot}$), the model melts *AI* at a rate proportional to its amount divided by the sum of the amount of all forms of stationary ice.

VI. Stationary ice form 3: Stored frazil (SF)

When the frazil produced in a reach (I_{prod}) or supplied by an upstream reach (F_{in}) is not stored in the surface ice cover (SI) or intercepted as anchor ice (AI), it can be stored in a third form: It settles in low-flow velocity areas under the existing border ice (SI). Indeed, it has been observed, through photograph sequences obtained from automated cameras, that border ice is often free-floating. In other words, despite the known cycle of overflow-and-freezing (aufeis formation) at many locations, most of the border ice rises and drops with water level fluctuations induced by flow and ice condition variations. This creates space for SF under the SI (Figure 4.2.2B,C). The presence of porous frazil (catching fine sediment and organic particles) under the ice cover has been confirmed during spring and winter surveys.

The amount of stored frazil (SF) in any reach of the Äshèyi Chu is limited by the ratio of the channel that is ice-covered (Cov_{corr}). The model first calculates the frazil supply available for passive storage (SF_{supply}), including anchor ice released from the bed (AI_{lifted}). Then, it evaluates the maximum quantity of frazil that can be stored under the existing SI (SF_{max}). It assumes that no SF is possible for a low value of Cov_{corr} ($SF_{covmin} = 15\%$ for all reaches, no physical space between the SI and the channel bed) and that the flow velocity may be too high for frazil to be stored above a SF_{covmax} value that is reach specific (generally in the order of 40% or 50%, corresponding to observations and in agreement with approximate hydraulic conditions). Note that the amount of SF does not depend on the local heat budget like AI, which means that no supercooling is needed for SF to occur (the frazil does not need to be “active”).

For each time step, the model evaluates the average thickness of the SF ($SF_{thickness}$) over the reach-specific average cross-section. This is based on the amount of frazil stored SF_{cumul} (derived from SF_{max}) and a constant ice porosity (SF_p). In situations where I_{prod} would exceed what can be stored as SI, AI, and SF, the excess frazil would be transferred to a fourth stationary ice form (described next).

In the spring, SF melts (SF_{melt}) at a rate proportional to SI, and this rate is controlled by the empirical heat budget, E_{net} , more specifically by $I_{meltpot}$ that takes the residual ice coverage Cov_{corr} (on the previous day, $Cov_{corr}(t-1)$) into account. Just like SI, SF can also be affected by a partial breakup, which would lead to 1. An ice run to the downstream reach (for low values of Cov_{corr} during the freeze-up period) or 2. A local ice jam (high Cov_{corr} during winter or any value of Cov_{corr} during the spring).

VII. Stationary ice form 4: Frazil jam (FJ)

The concept of “frontal progression,” the formation of a stationary ice cover in the upstream direction by the interception of drifting ice floes, has been observed in several large rivers and expressed with empirical equations that take the flow (submergence) velocity into account (e.g., Beltaos, 2013). This represents the main mechanism leading to the formation of a full ice cover in low-gradient rivers such as the Yukon River (tens of river kilometres can be covered in 24 hours). This ice cover is often rough (jagged) because of the compaction mechanism of the ice and is often termed “freeze-up jamming”. For smaller, fast-flowing rivers where the ice supply consists of loose frazil rather than ice slabs, the process is comparable (e.g., Figure 4.2.4), so is the resulting roughness of the ice cover, but literature about the small river version of this freeze-up process is limited. It certainly takes a lower surface velocity to intercept passive frazil at the leading edge of an ice cover compared with large ice slabs. This explains why frontal progression in Äshèyi Chu is usually limited to short river

segments, generally corresponding to pools that are not yet covered. Since the morphology of the river is changing over the years and considering the generally chaotic nature of its freeze-up sequence (which depends on weather conditions), it is hard to confirm where flow velocities will support frontal progression and over what distance. Therefore, averaging this process at the reach-scale is convenient as it contributes to simulating ice-affected water levels while dodging an important degree of spatial uncertainty.



Figure 4.2.4. Frontal progression of a mid-channel frazil jam at Kp 12 of the Āshèyi Chu (looking upstream).

The first calculated parameter in this module is the incoming frazil available for dynamic (or frazil jam) supply ($F_{J_{supply}}$). Because it is known that not all the incoming frazil is stored against a surface ice cover and that a ratio of this loose ice can be transported under the (partial) surface ice cover and into the downstream reach of the river, several conditions are imposed to this process, and these are divided into four steps:

- Under a minimum ice coverage Cov_{corr} ($F_{J_{cov\ min}}$, Appendix B for reach-specific constant values), all the incoming $F_{J_{supply}}$ moves to the downstream reach as surface slush (F_{out}) (no ice bridge).
- If Cov_{corr} is above $F_{J_{cov\ min}}$, and if $T_{air\ mean}$ is cold ($E_{net} < F_{J_{E\ TR}}$), then the frazil interception ratio ($F_{J_{RR1}}$, to be multiplied by $F_{J_{supply}}$) is set to a value of 1 and all the frazil is stored in that reach (applied to all reaches but Reach 6).
- Once Cov_{corr} reaches an intermediate threshold of $F_{J_{cov\ int}}$, and for cold weather only, the frazil interception ratio ($F_{J_{RR2}}$) takes a value lower than 1 (once the ice coverage is high, some frazil is evacuated and becomes part of F_{out}).
- Finally, for a high $Cov_{corr} > F_{J_{cov\ max}}$, any additional frazil is transported downstream (which is realistic otherwise water levels would sporadically rise during the whole winter period as a result of frazil production in Reaches 1 and 2, which is not the case).

Since Cov_{corr} is calculated with an empirical equation (Equation [1]), the FJ module cannot impose a different ice coverage rate. Therefore, this frazil jam is assumed to be stored under the SI in the same reach (Figure 4.2.2B, C), representing one model simplification to support its stability. Note, however, that defining these thresholds ($FJ_{cov\ min}$, $FJ_{cov\ int}$, $FJ_{cov\ max}$, $FJ_{E\ TR}$, FJ_{RR1} , and FJ_{RR2}) during the calibration process is complex and significantly influences the model results. For Reach 6, a maximum FJ thickness ($FJ_{thickness}$, in metres) was imposed because its module behaved slightly differently from those of upstream reaches.

The FJ module also considers that this ice can freeze partially (or entirely) and, therefore, lose part of (or all) its porosity. A reach-specific E_{net} threshold of FJ_{ETR} ($<FJ_{ETR}$) was set to account for this thermal process. The module calculates an FJ relative density ($FJ_{density}$) at each time step with a maximum value of $920\ Kg / m^3$ (density of solid ice). The rate of melt of the FJ (FJ_{melt}) is two-fold. First, a small amount of FJ is set to melt (FJ_{mRR}) when $E_{net} > FJ_{ETR}$ (a reach specific threshold) to account for residual heat in the river (just like in the AI module). Then, a positive E_{net} and values of $I_{melt\ pot}$ above 0 impose an FJ_{melt} that is also proportional to the loss of SI . This explains why all the ice forms in each river reach end their melting process simultaneously. Figure 4.2.5 presents a schematic view of this melting processes as simulated in the model. Figure 4.2.6 presents an example of winter ice storage results revealing how all ice forms melt at a proportional rate in the spring until they reach 0.

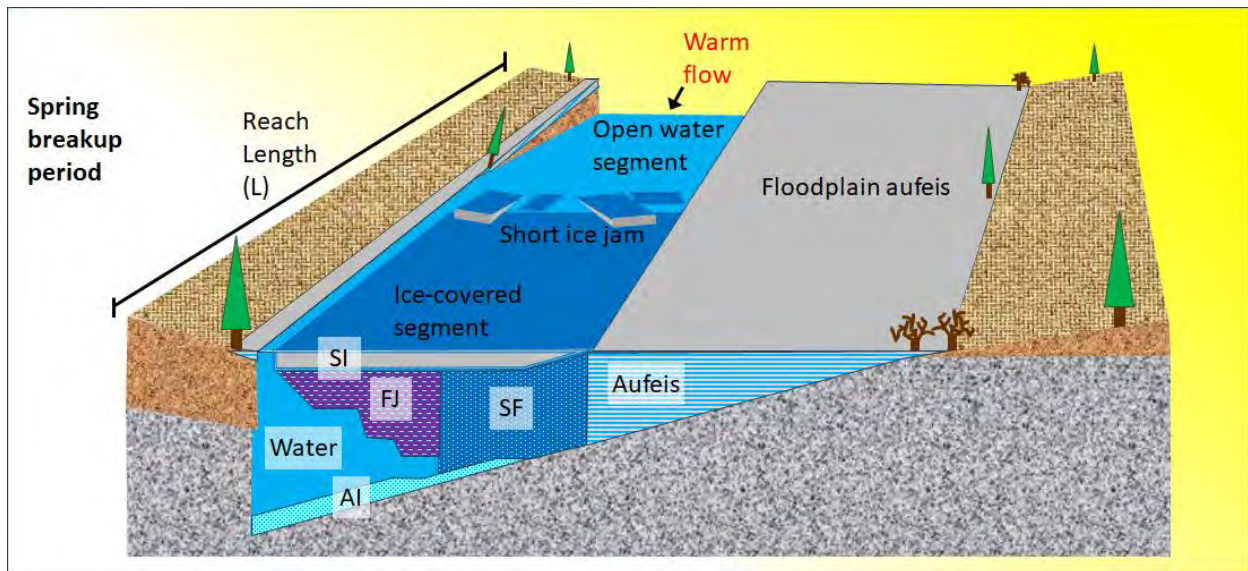


Figure 4.2.5. Scheme showing how the model simulates ice melt in the spring, from upstream to downstream, with all ice forms melting at the same time, which is comparable to what is observed along the Āshèyi Chu.

Note also that the FJ module considers frazil interception during the spring breakup period (i.e., during cold days), as long as the reach-specific Cov_{corr} is above a low value of $FJ_{cov\ spring}$ (see rises in FJ in Figure 4.2.6 in March) This corresponds to what has been observed in photographs taken by automated cameras.

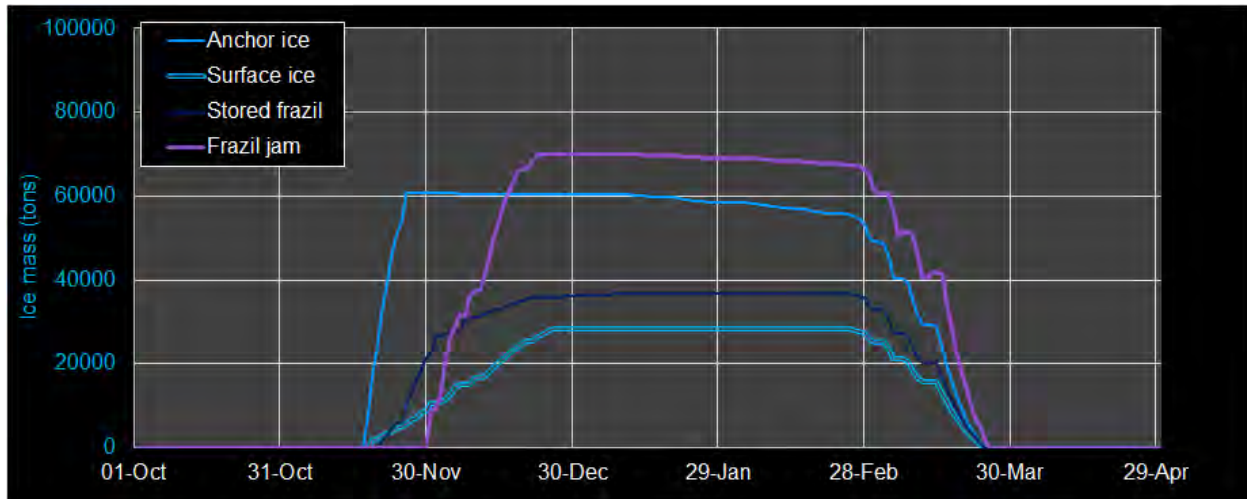


Figure 4.2.6. Simulated amounts of different forms of stationary ice in Reach 4 of the Āshèyi Chu in 2021-2022.

VIII. Dynamic breakup events (BR)

It has been seen through Equation [2] that flow (from AGS) impacts the rate at which the ice cover develops in all six reaches of the Āshèyi Chu. In turn, a lower value of Cov_{corr} means more heat loss and more frazil production (I_{prod}) and ice storage, which impacts local and downstream water levels. This aligns with the literature stating that high flows tend to delay river ice formation and/or cause more dynamic freeze-up events (e.g., Beltaos, 2013). Another impact of hydrometeorological conditions on winter water levels is through breakup events. For instance, a significant change in flow can cause newly formed border ice to break, be carried downstream, and form an ice jam against a resistant ice cover (SI extending from bank to bank).

Over the years, observations along the Āshèyi Chu, including those supported by photographs captured by remote cameras and water levels measured by aquatic sensors, were used to identify reach-specific conditions leading to partial breakup (BR) events. Four mid-winter breakup conditions (BR_{cond1} to BR_{cond4}) and one spring breakup condition were programmed for each reach. These conditions lead to a binary decision by the model: 1 = breakup, 0 = no breakup. A value of 1 for any BR_{cond} means that a breakup event occurred in that reach at that time step, with an imposed reduction of Cov_{corr} (reach-specific BR_{covR} constant ranging from 2% to 5%). The identified BR_{cond} only apply to a specific range of Cov_{corr} . Below that range ($Cov_{corr} < BR_{cov cond min}$), there is not enough ice to cause a breakup event. Above that range ($Cov_{corr} > BR_{cov cond max}$), the ice cover can form cracks but does not have the lateral or streamwise freedom to move, and Cov_{corr} remains unchanged.

Identified BR_{cond} for the winter period are (Appendix B presents reach-specific values):

- **Significant rise in air temperature ($T_{airmean}$) (R1 to R4):** If E_{net} rises by more than BR_{Erise} (e.g., 250 W/m^2) in less than BR_{EriseD} days (e.g., 7 days) when the ice coverage is between $BR_{cov Emin}$ (e.g., 5%) and $BR_{cov Emax}$ (e.g., 50%)
- **Melting conditions ($T_{airmean}$) (R5 and R6):** If E_{net} rises above BR_{melt} (e.g., 0 W/m^2) for the first time in more than BR_{meltD} (e.g., 4 days) when the ice coverage is between $BR_{cov mmin}$ (e.g., 5%) and $BR_{cov mmax}$ (e.g., 60%)

- Significant drop in minimum daily flow (Q_{min}) (R1 to R6): If Q_{min} on any given day becomes lesser than the maximum Q_{min} from the last BR_{QminD} days (e.g., 5 days) by more than BR_{Qmin} (e.g., 5 m³/s) when E_{net} is above a cold threshold of BR_{EQmin} (e.g., -300 W/m²) and when the ice coverage is between $BR_{covQminl}$ (e.g., 5%) and $BR_{covQminh}$ (e.g., 50%)
- Significant daily flow instabilities (ΔQ) (R1 to R6): If ΔQ (based on sub-hourly data) on any given day is greater than a threshold $BR_{\Delta Q}$ (e.g., 8 m³/s) when E_{net} is above a cold threshold of $BR_{E\Delta Q}$ (e.g., -300 W/m²) and when the ice coverage is between $BR_{\Delta Q min}$ (e.g., 5%) and $BR_{\Delta Q max}$ (e.g., 50%)
- Massive anchor ice (AI) release ($AI_{lift} + AI_{melt}$) (R1 to R5): If $AI_{lift} + AI_{melt}$ is greater than either $BR_{AI\%}$ (e.g., 75% of all AI in the previous time step) or BR_{AI} (e.g., 15,000 tons of AI) in any hydrometeorological and ice condition (this assumes warm weather and limited ice coverage through thresholds already programmed in the AI module)
- Rise in maximum daily flow (Q_{max}) (R6 only): If Q_{max} on any given day is above BR_{Qmax} (e.g., 18.5 m³/s) and rises above the maximum Q_{max} from the last BR_{QmaxD} days (e.g., 4 days) when E_{net} is above a cold threshold of BR_{EQmax} (e.g., -200 W/m²) and when the ice coverage is between $BR_{covQmaxl}$ (e.g., 5%) and $BR_{covQmaxh}$ (e.g., 40%)

Once a breakup condition is detected at any given time step, $CovBR$ only takes a value greater than 0 if values if $CovBR$ has been equal to 0 for the last BR_{DR} days (e.g., 4 days). This algorithm is meant to prevent consecutive breakup events, which is realistic, considering that the most fragile border ice breaks up first while more resilient/thicker ice remains. After a few BR_{DR} days, it is assumed that the remaining (or newly formed) ice cover can be broken by any of the above-listed conditions.

For positive values of $CovBR$, the model has the possibility of sending the broken cover pieces (ratio of BR_{covR}) to the downstream reach (ice run, $IR = SI_{breakup} + AI_{lifted} + SF_{breakup} + FJ_{breakup} + IR_{in}$ calculated in respective modules) or to keep this ice in the reach as an ice jam (IJ). During winter, the Cov_{corr} threshold that distinguishes IR from IJ (IR_{cov}) takes values between 35% and 50%. For IJ situations (partial to complete ice coverage), the broken ice cover remains in the reach, and the roughness of the ice cover in that reach (Manning's n , described next) is increased for IJ_D days (e.g. 4 days). This takes the additional roughness of the ice rubble into account, and it applies it to the entire reach because the exact location of the jam is not known by the model (it is unlikely that any model of the Āshèyi Chu will ever be able to predict the location and extent of ice jams). Moreover, the model also assumes that this increased roughness is a transient condition because of thermal erosion. Since flow conditions in the Āshèyi Chu generally remain below 23 m³/s, ice jams are not expected (they have not been observed) to significantly thicken; therefore, their impact on water levels is generally limited and their associated backwater is often short-lived.

In the spring, another BR_{cond} applies; it compares with the minimal daily flow condition described above for the winter period. Once the ice cover has started to melt, a partial breakup occurs if Q_{min} on any given day becomes lesser than the maximum Q_{min} from the last BR_{QminDS} days (e.g., 4 days) by more than BR_{QminS} (e.g., 4 m³/s) when E_{net} is above a cold threshold of BR_{EQminS} (e.g., -180 W/m²) and when the ice coverage is below $BR_{covQminhS}$ (e.g., 90%), but above $BR_{covQminlS}$ (e.g., 3%). The Cov_{corr} reduction is reach specific ($BR_{covR} = BR_{covQminlS}$). If Cov_{corr} on the previous day is above $FJ_{cov spring}$ (from the FJ module), then BR conditions will result in IJ . Otherwise, an IR will be sent to the following downstream reach.

Lastly, because of the none-purely-thermal (therefore, somewhat dynamic) nature of the breakup front as it moves down the river in the spring (because of warm water T_{meas} or T_{sim} from upstream), the model assumes the presence of a short ice jam at the open water – ice cover transition (Figure 4.2.5), and the Manning’s n is adjusted accordingly. This situation lasts as long as Cov_{corr} is between I_{covh} (generally high) and the minimal value of $BR_{covQmin}S$. This means to consider the possibility of overflow as the ice accumulates at specific locations during breakup, especially at high flow Q_{mean} .

IX. Ice balance

For each time step, the model calculates the net amount of stationary ice (I_{cumul}) of any type (SI , AI , SF , FJ) in tons, regardless of the density of the ice (Figure 4.2.6). This ensures that no ice is created or lost due to model instabilities. The model also compiles the amount of frazil (F_{out}) and ice runs (IR_{out}) travelling to the next downstream reach. These parameters are considered separately because they are not stored in the same form of ice (F_{out} may travel further whereas IR_{out} will be intercepted).

Note that any ice stored on a gravel bar and on the floodplain (outside of the main channel) as the water level rises is considered by the model to be *aufeis* (overflow ice or icing, represented in Figure 4.2.2). Indeed, it has been observed that the frazil produced in the channel rarely settles on the floodplain (the overflow thickness is often limited). It is also important to mention that only the stationary ice contained in the channel melts or breaks (Figure 4.2.5). The *aufeis* formed outside the channel melts in place later in the spring under warm air temperatures and sunny conditions, regardless of water temperatures and flow conditions.

X. Reach-averaged hydraulic equation

The model’s objective is to evaluate reach-averaged water levels, whose rising trend can generate overflow and flooding at one or several locations. Since aquatic sensors from which the water level data used for calibration is derived are never installed at the same depth and are often not deployed at the same exact location, no attempt was made to simulate an absolute water level. Instead, the model determines the reach-averaged rise in water levels above open water conditions (no stationary ice in the channel). This is done using the well-known Manning Equation:

$$Q = \frac{AR^{2/3}S^{1/2}}{n} \quad [4]$$

Q is the river flow or discharge from the tailrace to which the estimated flow from the West Aishihik River Q_{rWA} is added. $Q_{max}(t)$ is actually considered because the highest flow of the day causes the maximum water level on that same day. A is the reach-averaged flow cross-section, R is the reach-averaged hydraulic radius of the cross-section, S is the energy slope of the channel, and n is the Manning roughness of the channel.

Two parameters depend on the parameter of interest for this model: the water depth Y . In a wide triangular channel (which corresponds to the majority of cross-sections surveyed by MH, 2018) where the flow range is relatively constant:

$$A = \frac{WY}{2} \quad [5]$$

Where W is the channel width (a constant, since the flow range is narrow). Also,

$$R = \frac{A}{P} \quad [6]$$

Where P is the wet perimeter of the channel. For open water conditions:

$$P = Y + (W^2 + Y^2)^{1/2} \quad [7]$$

For partial ice affected conditions with SF stored under SI :

$$P = Y + (W^2 + Y^2)^{1/2} + Cov_{corr}Y - (Cov_{corr}^2W^2 + Cov_{corr}^2Y^2)^{1/2}$$

Through simplifications (refer to Appendix C), because Y is always much smaller than W , and considering the presence of SF under SI , Equation [4] can be transformed into:

$$Y = \left(\frac{Qn2^{5/3} (1-Cov_{corr})^{2/3}}{S^{1/2}W (1-Cov_{corr}^2)^{5/3}} \right)^{3/5} \quad [8]$$

When $Cov_{corr} > SF_{cov\ max}$, Equation [8] becomes:

$$Y = \left(\frac{Qn2^{5/3} (1-2SF_{max}+Cov_{corr})^{2/3}}{S^{1/2}W (1-SF_{max}^2)^{5/3}} \right)^{3/5} \quad [9]$$

The value of SF_{max} is known for each reach (Appendix B), and the value of Cov_{corr} is derived from Cov_{sim} calculated using Equation [1]. The value of W is specific to each reach as well (Appendix B), and Q is described above. Other parameters need to be explained in more detail.

The Manning's n parameter in Equations [8-9] is a composite channel roughness variable that depends on ice conditions. When the ice cover is forming, for Cov_{corr} smaller than a constant $Mn_{covrise}$ (which varies from 40% to 70% depending on the reach), n rises (variable n_{rise}) linearly from open water condition (n_{open} , a constant) to n_{icemax} (another constant). Once the $Mn_{covrise}$ is reached (high ice coverage), a thermal smoothing linear equation brings n (n_{smooth} , a variable) down to a value of n_{full} ($>$ than n_{open} , $<$ than n_{icemax}). An example of this calculation is presented in Figure 4.2.7. The values of constants n presented in Appendix B are calibrated for each reach using measured water levels and generally correspond to the range described in the literature for composite Manning's n (roughness of the bed and ice, generally between 0.02 and 0.035).

When an ice jam (IJ) forms in the reach, n takes a higher value ($n_{jam} > n_{icemax}$, usually in the range of 0.035 to 0.042), and this leads to a temporarily higher value of Y for IJ_{nDR} through equations [8-9]. The exact location of the jam and the extent of its backwater influence cannot be known with great certainty, as specified above, unless the jam forms during the irreversible spring thermal breakup sequence. Therefore, n_{jam} is applied to the entire reach to indicate to the model user that higher water levels are to be expected within that reach.

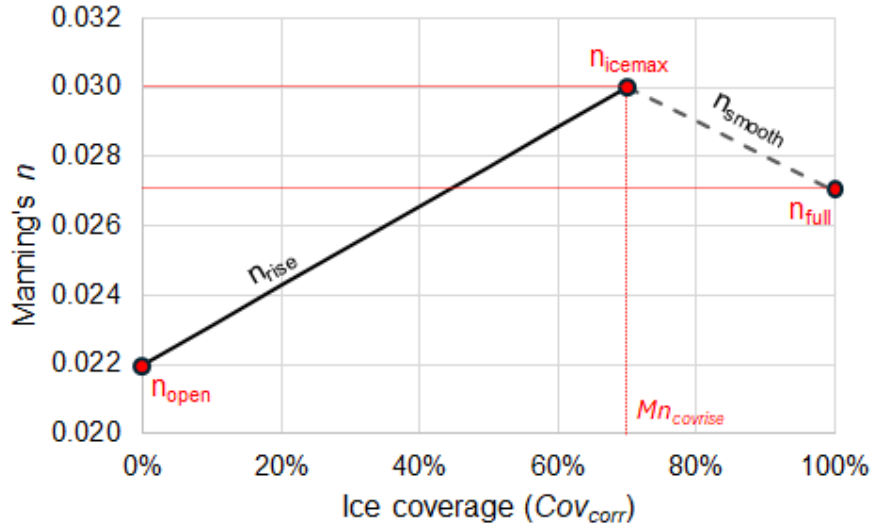


Figure 4.2.7. Example of the variation of the channel roughness (n) as a function of ice coverage (Cov_{corr}).

The impact of an ice jam is not only simulated through a rise in n but also by a modification of S , the energy slope of the river. Under normal open water or ice conditions, S takes the same value as the reach-averaged gradient S_R (provided by Palmer, 2018; Note that this value can be updated in the model, just like the length of any river reach, as the Āshèyi Chu morphology evolves). During a transient ice jam situation, S takes a slightly lower value (S_{jam}) to account for the segment of lower velocity upstream of an ice jam' head (also often upstream of the ice jam toe in situations where the ice jam is heavily grounded). Most ice jams observed in the Āshèyi Chu are not characterized by a significant intensity (limited shoving and compaction). Therefore, the impact of an ice jam is usually limited in terms of its effect on Y (e.g., in the range of 0.5 m). However, the formation of an ice jam, depending on its timing during the freeze-up period, can contribute to storing more frazil in the form of SF for a few days.

XI. Reach-averaged ice blockage and water level simulations

Water levels are not only calculated based on Equations [8-9]. The model considers a vertical adjustment (Y_{VA}) of the averaged cross-section thickness of each ice form (SI , AI , SF , and FJ , Figure 4.2.2B, C) in the final calculation of the reach-averaged water level Y_{sim} :

$$Y_{sim} = Y + Y_{datum} + Y_{VA} \quad [10]$$

Here, Y is the water depth obtained from the simplified, ice-adapted Manning Equations [8-9], Y_{datum} is a vertical adjustment used for calibration of the model using measured water levels (it can be used to adjust Y_{sim} to an absolute elevation at a specific reach location by model users), and Y_{VA} represents the “+0.92 multiplied by the ice cover thickness” used to calculate winter water levels with the Manning Equation. It is obtained through this empirical equation:

$$Y_{VA} = a_{SI}(SI_{thickness})^{b_{SI}} + a_{AI}(AI_{thickness})^{b_{AI}} + a_{SF}(SF_{thickness})^{b_{SF}} + a_{FJ}(FJ_{thickness})^{b_{FJ}} \quad [11]$$

The values a_x (factors) and b_x (exponents) are calibrated for each stationary ice form and for each reach (20 factors and 20 exponents in total). If the model were perfect and the channel geometry stable and consistent, values for a_x would be 0.92 and values for b_x would be 1, meaning that the ice

thickness would have an equal, linear impact on backwater and Y_{VA} . In turn, if the model assumptions were unrealistic, values of a_x and b_x would significantly depart from 1 (e.g., 0.3 or 1.5) because Equation [11] would need to bring the model back to some form of reality. After model calibration, using four winters of data, all a_x factors b_x exponents varied between 0.9 and 1.1, which appears reasonable.

The model also calculates Y_{max} , which is the maximum Y_{sim} attained during the winter period. This can help identify if a new Y_{sim} maximum is (or could be, in the context of a forecast) attained during the winter period.

XII. Overflow events and overbank flooding

The model identifies overflow events (OF , once the value of $Cov_{corr} > OF_{covmin}$) daily. Initially, these events are contained in the channel, but as Y_{sim} rises (as winter progresses), overbank overflow events can occur. Then, the model identifies aufeis (AU) development events (icing cycles), which represent OF events taking place when $T_{air\ mean}$ is above a threshold of AU_{Tair} (generally -5°C). In reality, this temperature threshold would probably vary based on the thickness of the OF layer (daily rise in Y). It could also depend on the occurrence of snowfall or the presence of snow on the ice cover and floodplain. Since Y usually rises when stationary ice forms, and because stationary ice forms at low $T_{air\ mean}$, the model generally assumes that OF layers freeze entirely. The exception is when a new Y_{sim} maximum (Y_{max}) is caused by an IJ in the spring, which would lead to overflow without freezing.

The elevation of the floodplain relative to the typical (open) water level varies significantly along the Äshèyi Chu, but it is generally between 0.5 and 1.5 m. This means an ice-induced backwater of comparable range would initiate overbank flooding and aufeis development outside of the river channel at different elevations at different sites, just like open water flooding does not occur everywhere along a watercourse for a given high flow. To take this process into account, the model requires the user to manually enter a reach-specific bank elevation (Y_{bank}): this can either be a known low Y_{bank} or a measured Y_{bank} at a vulnerable site or property along that reach. Once these constants are specified, they should not vary from year to year unless the model user decides to perform a readjustment, potentially based on new observations. Based on specified bank elevations, the model evaluates the cumulative thickness of the overbank AU ($AU_{overbank}$) at each time step by subtracting the maximum Y_{sim} (at any point during winter) by Y_{bank} . $AU_{overbank}$ remains at 0 as long as the AU does not overtop the bank (e.g., Figure 4.2.2B), and it remains at its maximum value when Y_{sim} drops later during winter or spring. It can only rise back if a new Y_{max} is reached.

4.3 Model results and interface

RIMA’s first components and equations were developed and calibrated using winter 2020-2021 data. Once the draft module for Reaches 1 and 2 was finalized, it was calibrated and optimized using three other data sets (2019-2020, 2021-2022, and 2022-2023). Then, the module structure was transferred to Reach 3, and significant improvements were needed, in addition to a recalibration of the Reaches 1 and 2 modules. Model development proceeded downstream reach by reach, but all model components for every reach were adapted and improved at all iterations of calibration steps.

Figures 4.3.1 to 4.3.4 present a sample of reach-scale calibrated results compared with reach-averaged estimated ice coverage (Cov_{est}) and site-specific measured water levels ($Y_{meas\ KpX}$). These results are representative of the model’s general accuracy and reveal how over-calibrating the model for a specific year could worsen results for another year. Therefore, manually calibrating the most evident and sensitive parameters was prioritized.

In Figure 4.3.1 (Reach 3, 2022-2023), the calculation of Cov_{corr} through Equations 1 and 2 is generally responsible for the poor mid-winter fit between Y_{sim} and $Y_{meas\ Kp8}$. However, the timing of the spring breakup (considering that all the ice needs to melt in the reach for Y_{sim} to drop back to open water conditions) indicates that the amount of ice in Reach 3 was adequately simulated. Readers will also note that the fair results presented in Figure 4.3.2 (Reach 6, 2022-2023) confirm that model error occurring upstream (Figure 4.3.1) is not inevitably carried or amplified downstream. This is partly because Equations 1 and 2 in RIMA are independent of upstream ice production and storage, and this was the idea behind RIMA’s structure: it would remain generally stable if some error occurred.

The results presented in Figure 4.3.2 reveal that the simulated end of the spring breakup occurs a few days earlier than what was recorded. This error becomes significant (about 5 days) when considering that the water level was measured at Kp 26, whereas the reach outlet is located at Kp 31. This means the backwater associated with the calculated ice mass (I_{cumul}) was reasonably defined, whereas that mass itself could have been underestimated.

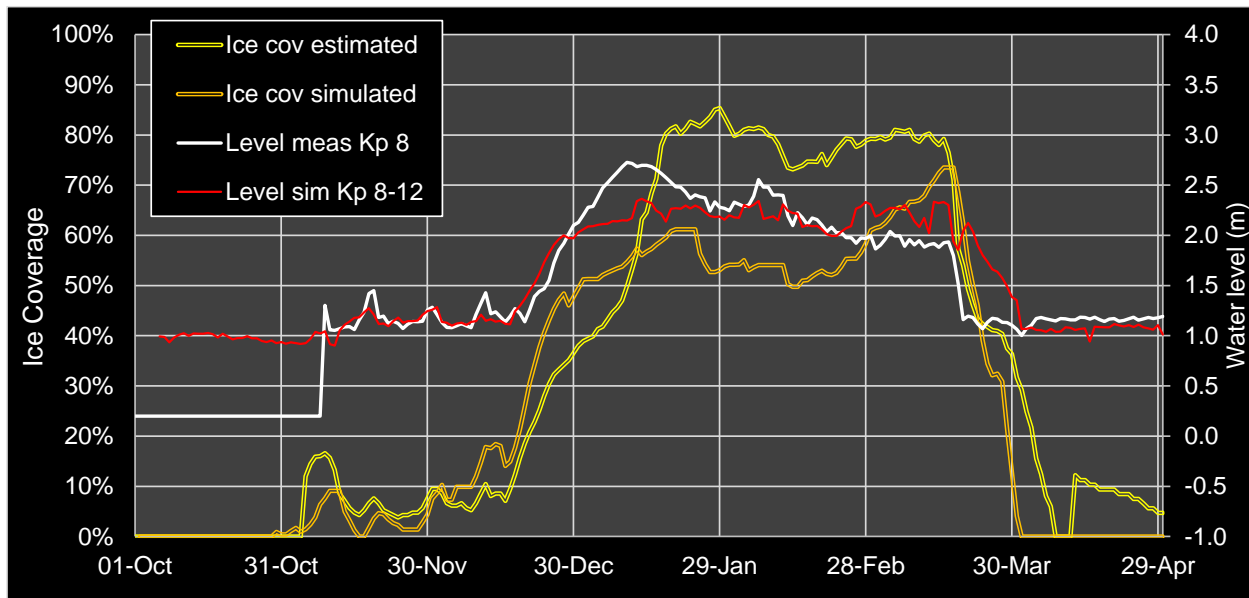


Figure 4.3.1. Simulated ice coverage (Cov_{corr} in orange) and calculated water levels (Y_{sim} in red) compared with estimated ice coverage (Cov_{est}) and measured water levels ($Y_{meas\ KpX}$) for Reach 3 for winter 2022-2023.

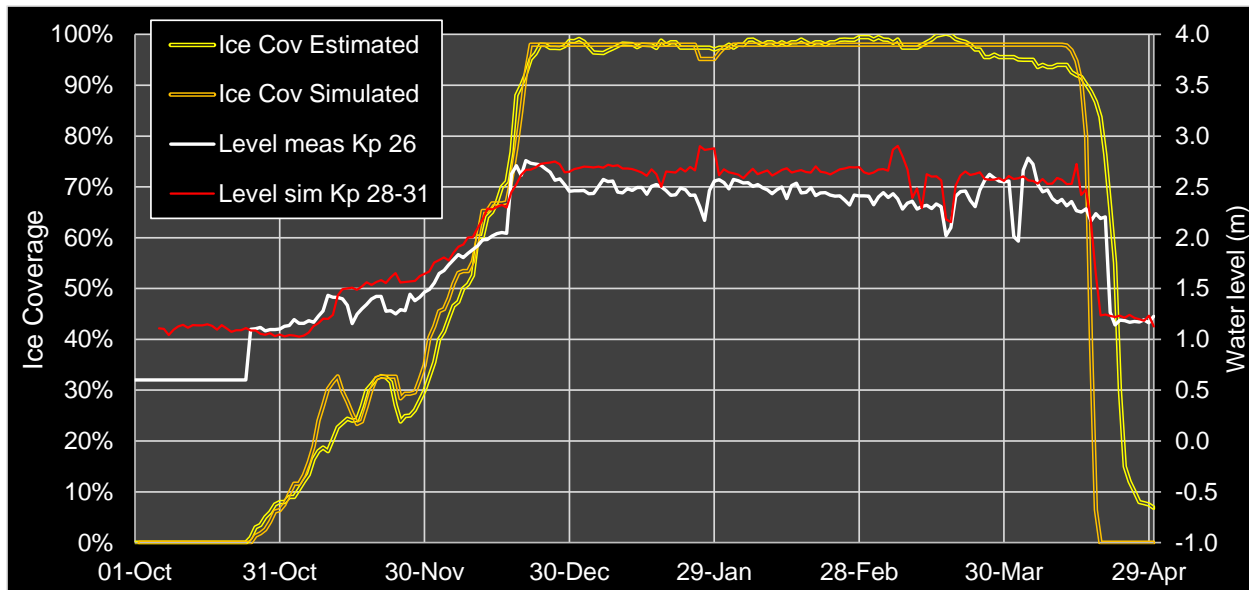


Figure 4.3.2. Simulated ice coverage (Cov_{corr} in orange) and calculated water levels (Y_{sim} in red) compared with estimated ice coverage (Cov_{est}) and measured water levels ($Y_{meas KpX}$) for Reach 6 for winter 2022-2023.

The simulated water level Y_{sim} in Figure 4.3.3 (Reach 4, 2021-2022) appears to overestimate $Y_{meas Kp 15}$ by about 0.5 m. This range or error could appear problematic. However, readers should be reminded that the model was also calibrated using photographs recorded by remote cameras, and the camera at Kp 18 revealed that the water level only stabilized after mid-December 2021 at that location. The results presented in Figure 4.3.4 (Reach 5, 2020-2021) are also satisfying to the model development team, considering the timing and amplitude of ice-induced simulated water levels. In this case, just like in Figure 4.3.3, Y_{sim} was calibrated for the Heritage Bridge area (not Kp 20), and photographs from that location showed a significant rise in ice-induced backwater at the end of January. The timing of the 2021 breakup is also accurately simulated at that location.

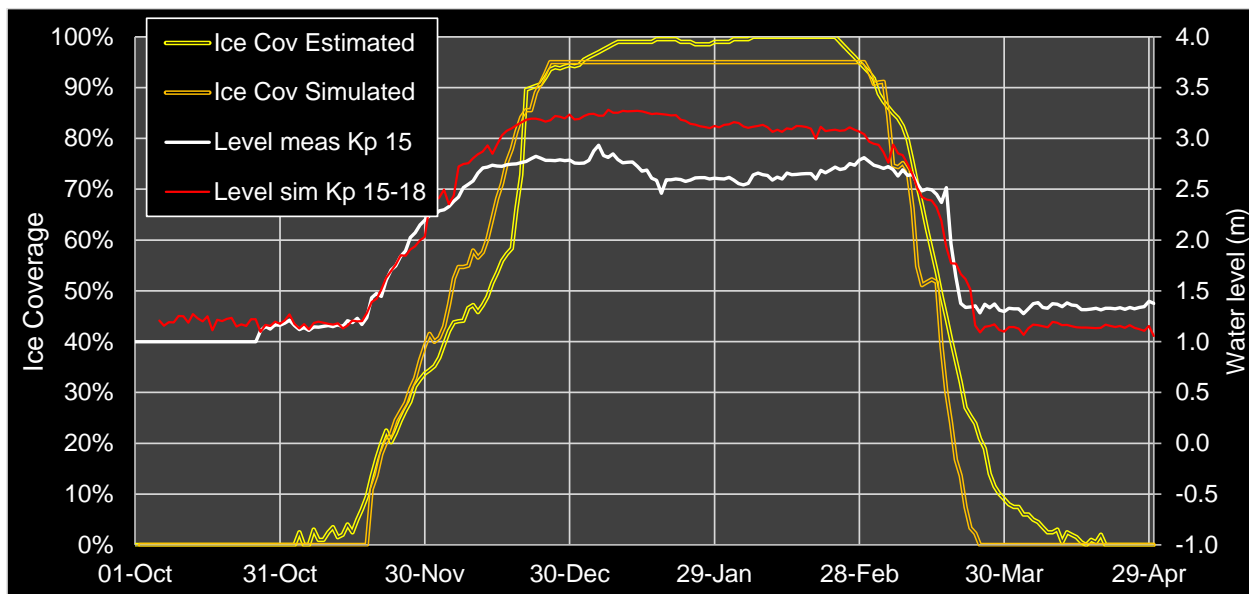


Figure 4.3.3. Simulated ice coverage (Cov_{corr} in orange) and calculated water levels (Y_{sim} in red) compared with estimated ice coverage (Cov_{est}) and measured water levels ($Y_{meas KpX}$) for Reach 4 for winter 2021-2022.

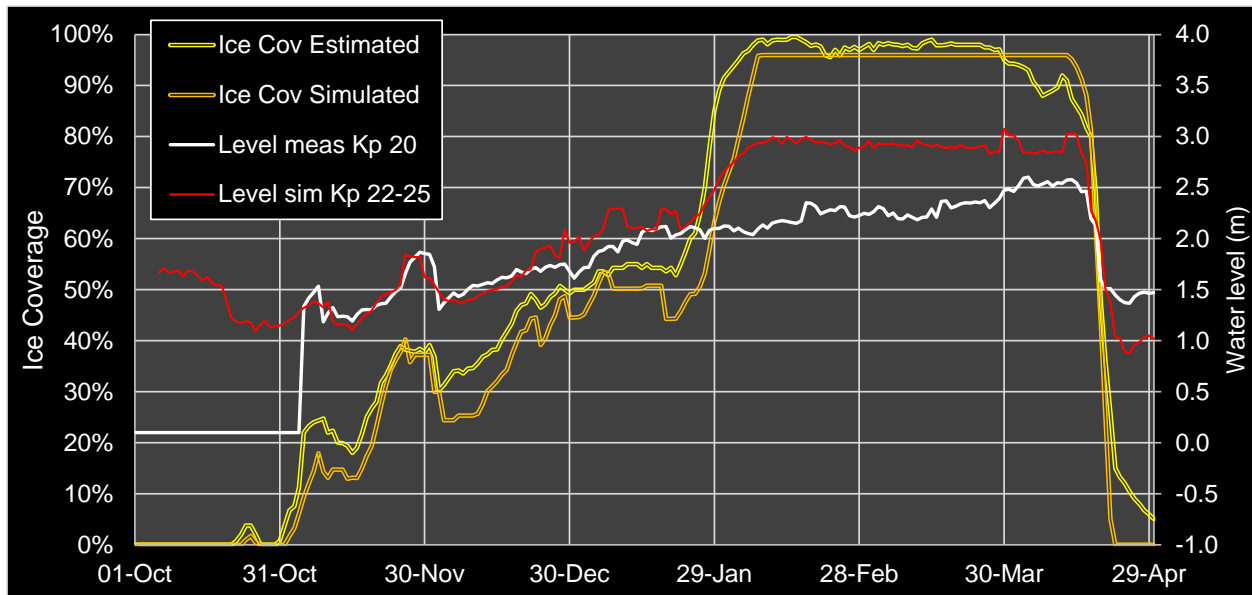


Figure 4.3.4. Simulated ice coverage (Cov_{corr} in orange) and calculated water levels (Y_{sim} in red) compared with estimated ice coverage (Cov_{est}) and measured water levels ($Y_{meas KpX}$) for Reach 5 for winter 2020-2021.

Comparably to what is presented in Figure 4.2.6, detailed model results are available for any reach of the Äshèyi Chu in RIMA so that model users can consider specific ice processes or stationary ice forms influencing the timing and amplitude of water level fluctuations. Table 4.3.1 summarizes the results of the model for four different winters.

Table 4.3.1. Partial results from the RIMA model for four winters (data in brackets are measurements or estimates)

	Units	2019-2020	2020-2021	2021-2022	2022-2023
Maximum cumulated degree-days of freezing and date	°C-days	2252 on Apr. 12	2414 on Apr. 11	2119 on Apr. 21	2050 on Apr. 14
Initial freeze-up in Rach 6 (date of 20% coverage)	Date	Dec. 1 (Nov. 29)	Nov. 9 (Nov. 4)	Nov. 20 (Nov. 17)	Nov. 7 (Nov. 11)
End of freeze-up in Reach 3 (80% or maximum* coverage)	Date	Jan. 27 (Jan. 27)	Feb. 13 (Feb. 10)	Jan. 3 (Jan. 2)	Mar. 16 (Jan. 18)
Maximum ice coverage in Reach 2	%	78% (85%)	66% (73%)	55% (78%)	39% (41%)
Timing of peak water levels in Reach 6	Date	Mar. 10 (Jan. 14)	Apr. 14 (Feb. 1)	Mar. 14 (Feb. 24)	Mar. 10 (Apr. 4)
Timing of peak water levels in Reach 3	Date	Feb. 14 (Feb. 3)	Mar. 2 (Mar. 2)	Jan. 13 (Jan. 27)	Jan. 13 (Jan. 11)
Maximum mass of ice stored in the Äshèyi Chu	Tons	750,000	765,000	730,000	760,000
Total mass of frazil transported to the Titl'at Män Tágà (Dezadeash River)	Tons	24,000	23,000	30,000	40,000
End of breakup in Reach 6 (less than 20%)	Date	Apr. 21 (Apr. 24)	Apr. 23 (Apr. 24)	Apr. 5 (Apr. 9)	Apr. 18 (Apr. 26)

Generally, development stage 16 of RIMA, based on four winters of calibration, proved satisfactory enough to recommend its testing for winter 2023-2024, which was completed during the spring of 2025. Figure 4.3.5 presents an example of model results as seen from the user interface, which allows the user to visualize reach-specific ice coverage and reach-averaged (emphasizing calibration locations) relative water levels over an entire winter as well as over a user-specified two-week window. The model highlights the occurrence of ice movements in specific reaches (breakup events, ice runs, and ice jams) on a map (for a specified day) as well as in the form of icons in graphs, and it calculates the maximum overbank flooding at critical locations relative to a user-defined bank elevation. More detail about the use of the model is provided in Sections 5 and 6.

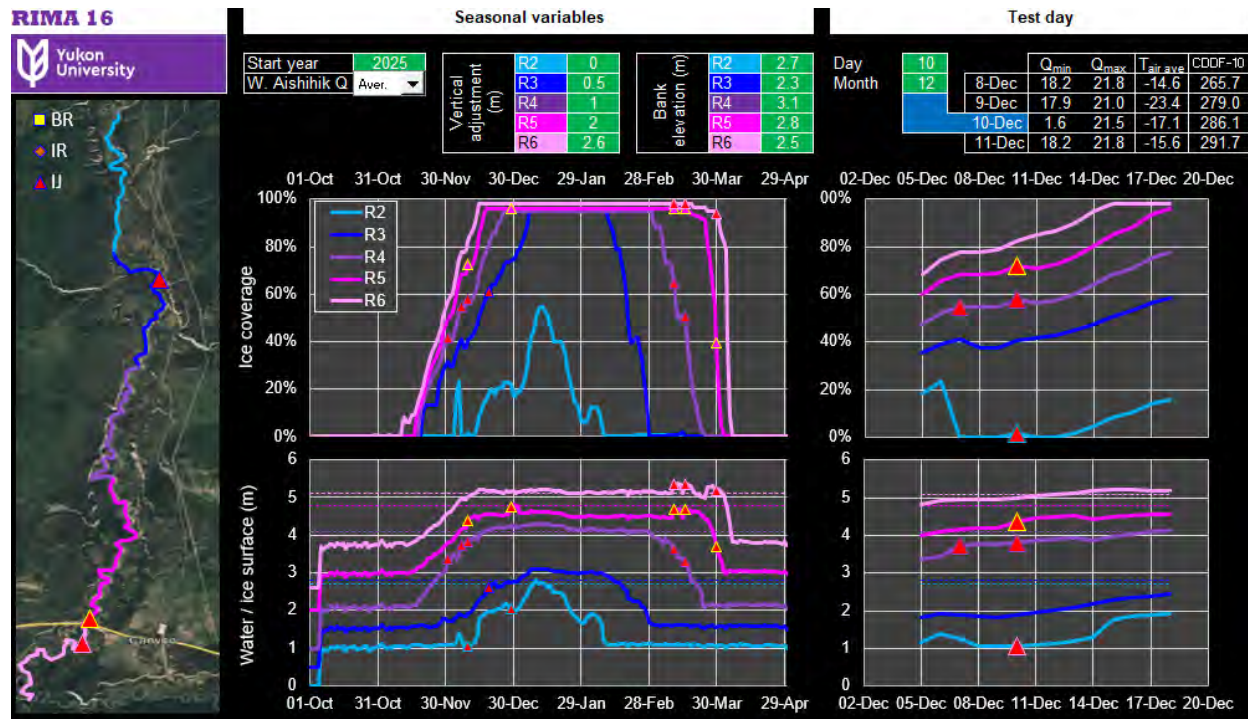


Figure 4.3.5. Rima 16’s operational platform where users enter input data and visualize results.

4.4 Model limitations

RIMA is a physics-based empirical model that does not consider hydrodynamic conditions. It is intended to be robust for a range of input variables corresponding to normal winter conditions as seen in past years. The following list presents some of the main model limitations:

Unusual flow conditions: The model may underestimate the progression of the ice cover when the mean daily flow is below the recent-historical hydropower production range of 15 to 23 m³/s. This happened in the fall of 2018 when the flow was well below that range for several weeks, including during the first seasonal cold spells, which caused a swift surface ice cover development in early November. However, not enough data was collected back then (winter 2018-2019) to calibrate the model. The underestimation of Cov_{corr} by the model for low-flow scenarios likely translates into an overestimation of the ice production and accumulation in each reach of the Āshèyi Chu, and an overestimation of maximum winter water levels. For instance, the loss of one turbine at AGS during the entire winter of 2024-25 will likely result in RIMA overestimating reach-averaged ice-induced

water levels as flow conditions in the Äshèyi Chu have consistently been below their common regulation range. RIMA could also underperform in a context where significant fall rain and runoff would cause high flow conditions that extend into the freeze-up period, which almost occurred in 2020 (this high-runoff scenario is considered in the model development and calibration, and the results are satisfactory).

MAMP: The model was calibrated using data from four winters and it was tested for a fifth winter. Over successive winter seasons, daily flow variations became generally smaller as part of the development and test of an adaptive management protocol. This was observed in the data and also considered during the model development (partial breakup conditions in the model are calibrated using these observations) with results showing fewer discharge-related breakup events over the years. It is anticipated that the model can generally simulate ice production, ice accumulation, spring breakup, and associated water levels for flow conditions that would be more stable than during previous (calibration) winters.

Hydrothermal role of tributaries during winter: The model considers the flow from Otter Falls (East Aishihik River) by summing it to the tailrace flow (discharge from the three AGS turbines). However, it also considers that its temperature is the same as the tailrace flow, which is not exact because the generally small East Aishihik flow should be at 0°C. However, it is anticipated that this simplification leads to an error that is of the same magnitude as uncertainties associated with the hydrological contribution of the West Aishihik River (estimated through a synthetic recession in the model), input from small tributaries (ignored in the model), and flow instabilities along the Äshèyi Chu that result from stationary ice formation and release or breakup (also neglected in the model). We believe that considering this level of detail would not significantly improve model accuracy because of the generally highly dynamic context and somewhat stochastic behaviour of the Äshèyi Chu. This assumption could be reconsidered in the future if observations or model results would indicate a strong hydrothermal influence that is unaccounted for in the model.

Spring heat: In the spring, RIMA calculates the warming of the tailrace water downstream and uses this simulated heat content to melt the downstream ice cover contained in the channel (Figure 4.2.6). It was written earlier in the report that the model assumes three possible discharge contribution ranges from the West Aishihik River with a water temperature equal to 0°C (because it is still ice-covered in the spring). However, the model neglects the small water inputs from tributaries, whose temperature should be at 0°C (generally cooling the Äshèyi Chu flow), as well as local snowmelt runoff (which should also slightly cool the flow). This simplification may lead to an early ice clearance (through thermal breakup) simulation, especially in Reaches 5 and 6 (e.g., Figure 4.3.2). However, this result does not appear in all calibration years.

Heat budget: RIMA contains several simplifications related to heat fluxes. It generally assumes that day-to-day fluctuations in several weather parameters influencing heat exchanges between the water and the atmosphere (wind, sky conditions, atmospheric pressure, humidity) are nonexistent. It also significantly simplifies the heat contribution from the sun by including it in the linear heat budget model presented in Equation 3. The model also ignores heat exchanges between the ice cover and the atmosphere (which is fair when the ice cover is snow-covered) and most heat fluxes between the ice and the water. The reasonable agreement between the measured and simulated water temperatures (e.g., Figure 4.2.3) and water levels (i.e., influenced by heat loss through ice

production and storage) indicates that such assumptions and simplifications are adequate. It also suggests that the sun probably plays a minimal role in the heat budget from late October to February, potentially even less than theoretical shortwave equations suggest (e.g., Ashton, 2013). It is certainly possible that unusually windy, cloudy or sunny conditions, as well as intense snowfall in open water areas (i.e., low Cov_{corr}) would lead to a slight departure of the model results from reality. Other assumptions could cancel this type of result discrepancy and generally be in the error range of other model assumptions and hydrological complexities that are not fully understood.

Partial breakup events: Winter rarely settles suddenly and irreversibly in cold regions, and this means that river ice formation and melting cycles could occur several times before air temperatures drop and consistently remain below 0°C. In the presence of a significant upstream heat source (like Canyon Lake or Ädäts'ür Män), river ice formation and partial breakup cycles can occur several times during winter, even in unregulated environments. In the Äshèyi Chu valley, the impact of weather variability has often been accompanied by flow instabilities associated with varying hydro production rates, and this translates into frequent changes in water levels and heat supplies, which impacts are added to those of air temperature fluctuations.

Most of the Y_{sim} and Y_{meas} fluctuations presented in Figures 4.3.1 to 4.3.4 are at least partly associated with local ice movements, proper breakup events, or slight shifts in ice sheets. These partial breakup events are frequent along most reaches of the Äshèyi Chu when the ice coverage is low (e.g., $Cov_{corr} < 50\%$), and they can occur at any time during winter in Reach 2 because this is typically where the upstream limit of the surface ice cover is located. Mid-winter breakup events, either detected through Y_{meas} fluctuations or observed on camera records, have been associated with specific air temperature trends and changes in flow conditions in the previous section of this report. However, a minority of breakup events were also observed when no noticeable change in hydrometeorological conditions seemed to occur (an apparent stochastic or random process that is complex to include in a deterministic model).

The majority of changes in ice conditions that lead to a rise in water levels downstream of AGS are caused by *in-situ* ice formation (i.e., SI and AI) or, often more importantly, by the interception and accumulation of drifting frazil slush (SF and FJ) during the first half of winter. In turn, partial breakup events generally cause minor-to-moderate and localized rises in water levels that need to be considered in the time-dependent water level calculation because: 1. their associated rise in water levels often occurs on top of the cumulative freeze-up rise and 2. their occurrence in the presence of a partial ice cover leads to a reduction in Cov_{corr} and, consequently, to the production of additional frazil that accumulates locally or in downstream reaches.

Despite the development of a multi-condition river ice breakup module in RIMA, which includes several of the common breakup hydrometeorological controls identified through data analyses (as presented in Section 4.2), it seems that an important source of Y_{sim} uncertainty remains the occurrence (or non-occurrence) of localized partial breakup events (the module remains imperfect). The most significant benefit of pursuing the development of RIMA in the future may be improving our understanding of partial breakup events and their controls in the Äshèyi Chu.

Uncertain water level measurements: A close look at Figure 4.3.4 exposes that post-breakup $Y_{meas_{Kp20}}$ (in April) is higher than expected from hydraulic equations. The most probable causes of this type of shift are 1. a vertical movement of the instrument during winter (in this case, it would have

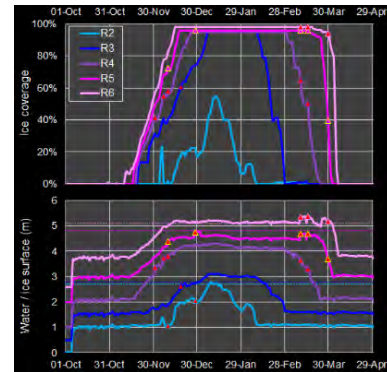
been lifted by the ice and deposited on a surface of higher elevation), 2. a significant change in the local (or nearby downstream) channel geometry, or 3. an underestimated and unusually high streamflow during breakup (i.e., an early freshet). It also occurred in the past that 4. water level sensors were installed when stationary ice (and associated backwater) had already formed. Regardless of the exact reason for a difference in elevation between pre-freeze-up and post-breakup conditions, this brought an unwelcomed uncertainty into the calibration procedure as it became challenging to assess when such a vertical shift occurred during the winter period or whether it was an abrupt or gradual shift. These unfortunate situations would generally result in the undermined accuracy of the model. That being expressed, the authors acknowledge the challenge of deploying instruments in a uniquely dynamic river environment and are thankful for the general high quality of the data sets from the Āshèyi Chu that have supported RIMA's development and calibration.

Morphological shifts: It is known that the Āshèyi Chu channel has been evolving relatively fast in recent decades, as mentioned in Section 2. On the one hand, RIMA can be adapted to future changes as the average slope, average width, and total length of each reach can be easily modified by the user. On the other hand, such channel parameter alterations could lead to changes in local and reach-scale freeze-up responses, with some ice processes that would become more dominant than others. In this case, a model recalibration could eventually be required, which could involve reestablishing an ambitious river monitoring protocol.

Model users should remember that the various sources of uncertainties in RIMA may result in Y_{sim} cumulative errors in the order of 0.5 m once the ice cover has achieved a stable state in Reaches 3 to 6. This is partly due to the model's structure, which includes a simplified ice coverage equation, reach-scale river ice modules, and basic river hydraulics. Partial breakup events may also cause localized or reach-scale, multi-hour or multi-day rises in water levels and consequent overbank flooding and aufeis thickening cycles. Breakup events, including those leading to ice jams, could cause a rise in water levels of 0.5 m, especially in Reach 2 at the end of a cold spell. The model should be able to accurately flag the most obvious partial breakup events. However, the apparent stochastic and spatially unpredictable nature of ice processes in the Āshèyi Chu represents a limitation to what RIMA (or any other model) could accomplish. Although imperfect, RIMA and RIVER 1D may represent the best tools to predict winter hydrological conditions in the Āshèyi Chu, not only because they are based on the current state of knowledge, but also in the foreseeable future and despite the increasing use of machine learning and artificial intelligence.

5. How-to-use guide

- Open the model in Excel (file RIMA16.xlsx)
- In the main sheet of the model called “Operations”, only fill up cells that are green:
 - Year
 - Estimated flow conditions in the West Aishihik River (look at October flow relative to historical average, https://wateroffice.ec.gc.ca/report/real_time_e.html?stn=08AA011)
 - Vertical adjustment of water levels for visualization purposes in graphs
 - Bank elevation (Y_{bank} above which overbank aufeis would occur at a vulnerable site)
 - Daily flow conditions (Q_{min} , Q_{mean} , Q_{max}), air temperature ($T_{air\ mean}$), and tailrace water temperature ($T_{tailrace}$)
- These graphs present the ice coverage (Cov_{corr}) and water levels (Y_{sim}) for each reach of the Äshèyi Chu following the same color index. Ice jams for each reach are presented as red triangles.
- User can investigate Cov_{corr} and Y_{sim} for a sequence of two weeks by specifying a date. The results are presented in the graphs on the right, which also includes ice jam events. The 3-day flow and air temperature data around the specified data is presented in a small table.
- A map shows spring breakup events (yellow square), ice runs (orange diamonds), and ice jams (red triangle) for each reach for the single day specified at Step 4. These events could happen anywhere in the reach.
- On the far right of the sheet, beside the input variables, the occurrence of spring breakup events, ice runs, and ice jams are presented for their respective date and reach.
- The columns on the far-right present water and ice levels above the reach-specific bank elevation thresholds defined at step 2d. The maximum overbank flooding for the season (so far) is presented in row 4 of that Table.
- Corrections to the simulated Cov_{corr} can be imposed in the sheet “Cal-Cor” for any date and any reach under “Imposed ice coverage” (green cells). The model will re-calculate Cov_{corr} from that date onward. Users can also compare water temperature and water level simulations with measurements to be entered in the Measured water data section of the same sheet.
- Reach specific sheets (R1-R2, R3, R4, R5, and R6) of RIMA can be consulted at any time to obtain information about ice balance and other information. These sheets represent the core of the model. This is also where the user can compare measured and simulated water data. None of the cells from these sheets should be modified. If this was to occur, hit Ctrl Z to reverse change.
- Other sheets of the model (CONV, WestA, Map, and Var.Graph) should not be modified.



If, for any reason, RIMA crashed (#NA, #DIV0, #NUM), the YukonU team would provide timely support. This situation has happened during the development phases of the model and different conditions have been tested to avoid such result. It usually represents a quick fix.

6. Operational considerations

This section of the report draws from observations made by the YRC gained during the preparation of the RIMA model. It presents a list of considerations for the strategic flow management of AGS that should contribute to reducing the severity of ice processes and subsequent adverse winter water levels in the AGS downstream environment. This list is mainly based on the equations, variables, and thresholds included in the model presented in Section 4, but in a simplified format. If considerations shared in this section are used to develop an impact attenuation protocol, there is no guarantee applying them, entirely or in part, will generate measurable positive impacts in the downstream environment immediately or by the end of the winter period (e.g., in terms of maximum overbank aufeis, because of uncertain variations in weather conditions). Moreover, the possibility of unexpected negative impacts cannot be excluded. It is anticipated that the below-mentioned breakup thresholds and conditions could overestimate minor breakup events by about 50% (rate of false positives) in any given reach of the river and that up to 20% of actual breakup events could be missed (false negatives), in part because of the apparent randomness of partial breakup events.

This section only focuses on ice conditions and does not include flow velocities, fish habitats, and water quality aspects. However, the YRC believes that applying all or some of the considerations may result in positive impacts on those aspects through an improved stability in channel conditions resulting from less severe ice processes.

6.1 Freeze-up period

The river ice theory, as well as observations, indicate that low flows during the freeze-up period promote the early formation of a surface ice cover, which should generally translate into a reduced production of frazil crystals and post-freeze-up water levels. For instance:

- Based on RIMA, if the flow were maintained at 20 m³/s, it would take about 280 cumulative degree-days of freezing below -10°C (CDDF-10) to generate an 80% ice coverage in Reach 6, which essentially corresponds to 28 days with an average air temperature of -20°C (a daily-averaged air temperature of -20°C is worth 10 degree-days).
- Based on RIMA, for Reach 3 and the same 20 m³/s, as much as 50 days with average air temperatures below -20°C would be needed to achieve an ice coverage of 80%.
- Also, based on RIMA, if the flow were about 15 m³/s, it would respectively take 20 days and 45 days for Reaches 6 and 3 to become 80% ice-covered.
- Based on observations from early winter 2018-19, an 80% surface ice coverage could be achieved in Reach 6 in less than a week if daily-averaged air temperatures remained below -10°C (very few CDDF-10) when the flow in the Äshèyi Chu is as low as 5 m³/s (uncertainty remains about a low flow scenario because of the limited observations and data from 2018).

Since air temperatures are rarely stable and consistently cold during October and November, it is not reasonable to expect that an early ice cover in downstream reaches (4 to 6) would remain in place for the entire winter period, independently of the flow condition. The model indicates that partial breakup events taking place in Reach 6 when Cov_{corr} is below 40%, regardless of their cause, result in ice jams in the Dezadeash River, or Titl'at Män Tágà" (rather than in Reach 6). This means that a low flow would need to be maintained between 75 CDDF-10 (corresponding to a 40% ice cover in Reach 6) and 350 CDDF-10 (corresponding to 60% ice coverage in Reach 3).

During that period (75 to 350 cumulated degree-days of freezing below -10°C), in order to avoid breakup events and minimize ice production:

- Daily average flows would need to be reasonably low. It is premature to determine an exact range, but flows higher than $18\text{ m}^3/\text{s}$ would result in freeze-up processes that compare to what has been seen in recent years (e.g., 2021-2022), and very low flows (say below $5\text{ m}^3/\text{s}$) would result in an ice cover that would be prone to melting or breaking once/if flows would increase later during the winter period.
- Daily flow variations must be kept as small as possible and ideally below $8\text{ m}^3/\text{s}$ (as per model calibration, which represents $<40\%$ when average flows at around $20\text{ m}^3/\text{s}$) unless daily averaged air temperatures are below -25°C .
- Differences in minimum daily flows over five days must be less $4\text{ m}^3/\text{s}$ (20%) unless daily averaged air temperatures are below -25°C .
- A new daily flow maximum above $18.5\text{ m}^3/\text{s}$ should only be imposed if the daily averaged air temperature is below -15°C .
- Importantly and possibly surprisingly, flows need to remain proportional to negative air temperatures (e.g., higher flows for colder local air temperatures). This is because of the heat content perspective: An ice melting potential in Reach 3 (positive I_{meltpot} values) should not become an ice production potential (positive I_{prod} values).

It is likely that adopting a daily-averaged discharge below $15\text{ m}^3/\text{s}$ during freeze-up, $12\text{ m}^3/\text{s}$ for instance, would result in lower ice-induced water levels in Reaches 3 to 6 because of a faster ice cover formation (and this would mean that the freeze-up period would last between 60 and 300 CDDF-10, approximately). However:

- The transition from $12\text{ m}^3/\text{s}$ to a more common winter hydro-production range of 18 to $22\text{ m}^3/\text{s}$ would need to be gradual, and this would not guarantee that the ice cover would remain stable or that overflow would not occur.
- Equations 1 and 2 would need to be modified or, as a minimum, recalibrated to remain accurate for this low discharge range (data from 2024-2025 could support this).

Note that warming events during the freeze-up period (either a relative warming of more than 20°C spread over a week or less, or air temperatures close to or above 0°C) would likely result in partial breakup events in different reaches as long as the ice coverage is under 50%, independently of flow variations. This means that sudden losses of border ice and the formation of small ice jams could occur in Reaches 3 to 6 during the freeze-up period, even if the tailrace flow remains low and/or stable. Extreme cold events (e.g., -35°C) have also been seen to trigger sudden cracks in border ice and occasional ice movements, regardless of upstream flow conditions.

6.2 Winter period

Beyond 350 CDDF-10, or when the ice coverage (Cov_{corr}) in Reaches 3 to 6 is above 60%, the ice cover below Kp 6 (Reach 3 to 6) would generally be less sensitive to hydrometeorological variations (this is when most breakup conditions in RIMA do not apply anymore). It is possible that the tailrace flow could then slowly be ramped up to the more common hydro-production range of 18 to 22 m³/s without causing adverse effects. However, AGS co-managers should keep in mind that:

- Reach 5 (Heritage Bridge sector) would remain sensitive to significant and rapid drops in flow for the entire winter period.
- Reach 2 (above Kp 6) could still be affected by river ice breakup events and ice jams induced by weather or flow variations.
- Frazil production in Reach 2 could be significant during cold spells, and this frazil would likely be stored in downstream reaches, therefore contributing to rising water levels and overflow events.

Therefore, during the winter period, with an emphasis on Reach 2 (9-Mile wetland), it would be suggested that:

- Daily flow variations be kept below 8 m³/s,
- Sub-daily AGS flows be generally proportional to negative air temperatures (e.g., higher flow for colder local air temperatures and vice-versa, considering the heat content),
- Flow be increased gradually (e.g., daily-averaged flow rising by less than 1 m³/s per day) when air temperatures warm up by more than 20°C over a week or less.

6.3 Spring period

It generally takes several days to weeks in March for the ice front, or breakup front, to progress over more than 2 km of river in the downstream direction. Therefore, the ice front is often located between Kp 6 and Kp 8 for half a month (depending on the coldness of the previous winter period). RIMA does not directly rely on a date or on cumulative degree-days of thaw to initiate the simulation of the thermal breakup of the Äshèyi Chu. Indeed, in addition to T_{air} , the timing and swiftness of breakup significantly depends on the extent of the open water area (or Cov_{corr} in Reaches 1 to 3) at the onset of breakup as well as on tailrace water temperatures ($T_{tailrace}$) and flow.

In 2019, 2020, 2021, and 2023, the irreversible reduction of Cov_{corr} in Reach 3 began in mid-March. However, in 2022, it started around February 10. It can be argued that breakup usually begins once daily-averaged air temperatures become consistently warmer than -5°C (which includes daily maximums close to or above 0°C). Once the breakup period has been initiated, and based on observations, as well as on the calibration of RIMA:

- The minimum flow on any given day should not drop below the minimum flow of the previous 5 days by more than 2 m³/s to avoid destabilizing the ice cover far downstream of the breakup front (with consequent possible overflow). Indeed, when the ice cover becomes isothermal (at 0°C), it can creep and bend under its own weight if the water level (or flow) drops too much.
- It has been observed that the ice cover in the center of the channel becomes vertically mobile at several locations during breakup, and this causes the channel banks to become vulnerable to erosion and loading. Therefore, independently of RIMA's structure and calibration (with water levels overlooking daily flow fluctuations and only focusing on daily maximum flows),

the flow should generally remain as stable as possible (daily fluctuations contained in a 4 m³/s range, for instance) in order to reduce mechanical constraints on the Äshèyi Chu banks. This will help protect the banks and riparian vegetation against collapse, and it could reduce suspended sediment transport rates.

Note that significant air temperature variations during the breakup period have been associated with short ice jams in the Äshèyi Chu even when AGS flows were stable. Such jams could have resulted from the transient development and release of anchor and border ice upstream of the breakup front.

The breakup period usually ends around mid-April (April 25, 2020, 2021, 2023, and April 8, 2022). This is when the central portion of the channel becomes open over the entire length of Reach 6. Rather than relying on an approximate degree-day threshold or a cumulative heat flux, it is probably safer and simpler to consider that breakup in the Äshèyi Chu ends 3 days after open water conditions are first observed at the Alaska Highway bridge (head of Reach 6). This can be justified by the fact that the higher sun angle and the longer period of daylight in mid-April seem to have more influence on breakup than air temperatures.

7 Summary and recommendations

This project was first discussed on August 31, 2020. It was officially launched in April 2021 with the support of the Climate Change Preparedness in the North (CCPN) Program and funding from ArcticNet's North-by-North program. The project was extended for 1 year and now ends in March 2025. Over four years, the YukonU (Research Centre, YRC) team, in partnership with Champagne and Aishihik First Nations (CAFN), Yukon Energy Corporation (YEC), Morrisson Hershfield (MH, now Stantec), Yukon Government's Department of Environment (YG), and the University of Alberta (UofA, Dr. Yuntong She's research team) completed several tasks, including the preparation of a project charter, multiple field trips, the organization of drone trainings with CAFN, the deployment of instruments, satellite product analyses, data production, data preparation, data and photograph analyses, the organization of meetings, the preparation of presentations (including at national and international conferences; Saal et al., 2023, 2024), and finally, the development of a physics-based empirical model as well as the preparation of the present report.

When the project started, it was known that the winter regime of the regulated Äshèyi Chu would be extremely challenging to express in the form of a numerical model and that very few river ice engineers or scientists had performed such complex technical exercise in the past. A significant effort was dedicated to better understanding ice processes and associated water levels along the Äshèyi Chu. This would have been impossible without the data collected by MH, a program supported by YEC and CAFN since 2017. Once all the data was collected, produced, and organized in a structured database, it became easier to understand the behaviour of the river, including its apparently unpredictable personality in the context of hydropower regulation. Yet, the bulk of the research effort was to translate this imperfect understanding into a numerical model with the support of the river ice literature and knowledge acquired from other cold regions' river systems.

During the development (or adaptation) of a (existing) river ice model, especially when several degrees of freedom (or parameters to calibrate) are involved, unexpected preliminary results may be generated. Those results could initially be perceived as artifacts of model defects or outcomes ensuing from unreasonable simplifications. However, in some cases, the model points out unexpected river processes that are actually true or possible. Therefore, developing and improving a model is an effective learning procedure for understanding complex physical processes. The challenges for the research team are to extract the most relevant information from apparently chaotic datasets, prioritize programming efforts, define limits when facing unexpected levels of complexity, adapt project objectives when easy solutions are not achievable, and ultimately establish a balance between simulating realistic processes and keeping the needs of model users in mind.

The model, called RIMA for River Ice Model for the Äshèyi Chu, is more complex than what was originally anticipated. However, its performance was slightly above what the research team originally expected from an empirical model built from the ground up. RIMA not only simulates river ice formation and mid-winter hydrological processes, which was the original project objective, but it also simulates river ice breakup. It can, therefore, be used for the entire winter period.

The YukonU team acknowledges that the intentions for project communication with all parties were not consistently met. Meetings aiming at reporting on the project's progress did not happen as often

as originally planned and were largely held virtually due to factors such as COVID19 and the availability of project team members. In addition, weather conditions prevented using drones when the river ice cover was forming in the different reaches of the Āshèyi Chu, which affected the YukonU team's ability to produce representative ice coverage data sets that are critical for model calibration. Despite these bumps along the road, the team hopes that the outcome of this project will be perceived as valuable by all parties for the constructive co-management of AGS as well as for the reduction of winter flooding, minimization of overbank aufeis development, and stabilization of the Āshèyi Chu channel.

Immediate recommendations

As this project comes to an end, it is important to recall that RIMA can only be used if the following data is accessible in nearly real-time with a sub-daily acquisition rate:

- Air temperatures near the tailrace
- Water temperature in the tailrace (ideally near its outlet at Kp 0.0)
- Flow in the tailrace as well as from the East Aishihik River (Otter Falls)

This means that a new monitoring station with real-time data transmission would be needed near Kp 0. Users must also define, at a semi-quantitative level, if the West Aishihik River flow at the onset of freeze-up (generally in October) is higher, lower, or close to the historical average. This assessment only needs to happen once per year (refer to Section 5 for detail).

A last immediate recommendation is to test the model. The YRC cannot specify who within the Core Team (refer to Appendix D) should be responsible for this phase of the model development. However, it is proposed that this test phase could take up to three forms:

- Test different flow and weather scenarios and see how the simulated ice coverage and water levels respond for each reach (this can be done at any time of the year), then compare results for different scenarios for seasonal hydro-production planning purposes.
- Operate AGS without considering model outputs and then compare sporadic or continuous observations or measurements with those provided by model simulations in quasi real time.
- Operate AGS by considering model outputs in forecasting mode, which involves using short term weather forecasts and planned tailrace flows as model inputs. If the model suggests that a reduction in ice coverage or a rise in water levels could happen, the hydro-production plan could be adapted or not, and observations could confirm whether the model was actually accurate.

Short term recommendations

The results provided by RIMA, at its current development stage (16), could be improved by the operation of additional permanent instrumentation along the Āshèyi Chu. As a minimum, these instruments could be considered:

- A real-time water level logger between Kp 25 and 26 where there are challenging ice conditions during winter
- A real-time camera near Kp 25
- A real-time camera (or regular observations) near Kp 8.

In addition, the monitoring program that has been developed and implemented by MH (Stantec) in recent winters, with the collaboration of CAFN, YEC, and YG, could continue in order to support a subsequent optimization phase of RIMA, as well as the UofA River 1D model (ensuring the vertical stability of water level loggers would be important). The modelling team has completed his mandate and suggests testing the model for a couple of winters before being involved again, through a subsequent collaboration, in the design and implementation of an optimized monitoring program.

Longer term recommendations

The glacial legacy, the semi-arid subarctic climate, and the presence of permafrost in the valley increase the sensitivity of the Äshèyi Chu to hydro-geomorphological variations. The impact of AGS illustrates this vulnerability as the alluvial river channel has changed drastically in recent years, especially since the third turbine has been in place (Palmer, 2018). The exact role of climate change in this evolution remains unclear, but it can probably affect bank stability and groundwater pathways through the warming and loss of permafrost. In this fast-transforming fluvial environment, adaptive management of AGS is necessity, which is why the RIMA and RIVER 1D models were developed.

One research aspect that would be worth exploring is the improvement of RIMA in the future. This could include, for instance:

- Adapting Equations 1 and 2 (Section 4) to a lower discharge range and possibly including the tailrace water temperature ($T_{tailrace}$) as an input parameter. Data from winter 2024-2025 could support this improvement.
- Re-investigating the dominant causes of partial breakup events that lead to higher winter water levels in each river reach, not only because of small ice jams, but mostly because of the reduction in ice coverage that leads to more frazil production and accumulation.
- Improving the flow (e.g., water storage) balance aspect of RIMA to potentially gain some simulation accuracy.
- Confirm the frequency of spring scenarios involving a rising or warm flow (above 0°C) from the West Aishihik River before then end of breakup in the Äshèyi Chu. This could include looking back at historical spring weather, considering future weather scenarios impacted by climate change, or specific monitoring activities. In turn, the water temperature at the bottom of Canyon Lake (Ädäts'ür Män) will remain at around 4°C as per water density properties and the heat coming from the tailrace may not significantly change in the future. A similar comment applies to the possible occurrence of mid-winter runoff events in the West Aishihik River, which could affect thermal and mechanical aspects of river ice processes in the Äshèyi Chu.
- Improving the visual aspect of the operational sheet in RIMA and recalibrating and readjusting the model based on user experience.

In terms of channel stability, it is recommended to explore the following research avenues:

- Re-evaluating the morphological characteristics of the Äshèyi Chu and compare the results with those presented by Palmer (2018).
- Exploring, listing, and testing channel stabilization options adapted to the unique context of the Äshèyi Chu, including ecological perspectives.
- Explore options to cool the flow from Ädäts'ür Män, either upstream or downstream of AGS, to accelerate the formation of an ice cover and minimize ice production during freeze-up.

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Appendix A - River ice processes in cold region streams

Cooling air temperatures at the end of summer leads to a quasi-proportional cooling of water temperatures in river systems. Once air temperatures are consistently below freezing and when the sun is low, water temperatures in creeks and rivers will reach an apparent plateau at 0.0°C. Under these conditions and excluding the presence or occurrence of natural heat sources such as groundwater and large water bodies, any water at a temperature of 0°C that is exposed to an additional heat loss will generate ice. The rate of ice production is generally proportional to the heat lost to the atmosphere. However, turbulence (e.g., fast flow, wind waves) will prevent this ice from forming a stationary surface ice cover. Instead, heat loss will result in the generation of small ice crystals, called frazil, within the water column (e.g., Daly, 2013a). Buoyancy will promote their accumulation at the water surface and freezing of these particles with one another. However, turbulence can maintain them in the water column in a loose or slush state. Therefore, a surface ice cover can be anticipated to form faster in slow-flowing rivers than in fast-flowing rivers.

In a low-velocity streams, a surface ice cover will form by the lateral migration of border ice (stationary ice formed against the channel bank which extends outward towards the middle of the channel over time) and by the surface interception and congestion of frazil slush or ice floes (formed by the freezing of the ice-water combination). This later process usually happens quickly during the first weeks of winter and is known to lead to the formation of a rough type of ice cover in the middle of the channel. The formation of a complete surface ice cover slows the water down because of the roughness of this new boundary and leads to a rise in the water level that is mostly proportional to the flow velocity. This rise can vary from a few centimeters in small, meandering creeks to a few meters in large rivers with a surface flow velocity above 1 m/s. More details about this are summarized in Beltaos (2013).

In steeper and shallower streams, frazil crystals are entrained to the channel bed where they can stick to the substrate, forming masses of “anchor ice” (e.g., Malenchak and Clark, 2013). Individual anchor ice crystals can grow *in situ* to form tree-like accumulations tens of centimeters thick (e.g., Dubé et al., 2014). In channel morphologies composed of rapids, riffles, and glides, the formation of anchor ice and its spatial organization into a series of ice dams generates a reduction in flow velocities. This promotes the formation of a surface ice cover at an elevation that is higher than the pre-freeze-up water level. Once this surface ice partially insulates the channel, residual heat (including from friction) can lead to a partial melt of the anchor ice that had initially formed, which creates a new path for the flow, a consequent reduction in the water level, and the transition from a partially-floating ice cover to a free-spanning ice cover. This phenomenon is explained in Turcotte et al. (2011).

In steep and shallow sub-arctic streams where groundwater heat is limited, it is common that the ice cover thickens at a rate that constricts the channel and forces water to flow on its surface. This overflow, exposed to cold air, can freeze in layers to create a body of “overflow ice” called aufeis (Daly, 2013b, Ensom et al., 2020). Overflow leading to the formation of aufeis is not only caused by a constriction of the flow but also because of hydrological instabilities (either cause by regulation, but also by variations in air temperatures, as described in Turcotte et al., 2023), which can occur at any point during the winter period, if the groundwater reservoir is not depleted. Aufeis are often

associated with an elevation much higher than any open water condition, even during the most significant open water runoff events (e.g., Turcotte et al., 2017).

It is never simple to classify nature, and stream channels do not always fit a defined category. In the river ice literature, ice processes are often classified based on flow velocity (e.g., Lindenschmidt, 2020). This is partially impractical because 1. velocities vary significantly as the ice forms, and 2. ice processes also seem to depend on water depth and flow turbulence, which vary over time. Turcotte and Morse (2013) present a conceptual model that links stream and river gradients or morphologies with expected ice processes and ice cover types. This model proposes a hybrid morphology (generally corresponding to riffle-pool channels, common along most sections of the Aishihik River) with an approximate gradient of 0.3% where both low-gradient (e.g., ice cover including smooth border ice) and steep channel (ice dams) ice processes can occur.

The flow in river systems mainly relies on groundwater and lake (or wetland) storage and usually declines steadily during winter months in the absence of rain and snowmelt. However, as stated above, flow can be very unstable, especially during the freeze-up period. This is because it depends on the amount of water stored in upstream reaches and tributaries as stationary ice forms at a rate that largely depends on heat loss (therefore on air temperatures). Water is also stored, unfrozen, under the ice cover in the form of hydraulic storage (the water that contributes to the rise in water levels). It is not surprising to see flow fluctuations of 50% in a wide range of watercourse sizes (e.g., Turcotte et al., 2014; Prowse and Carter, 2002) during the first very cold days of winter. These instabilities usually fade during the mid-winter period as air temperature fluctuations have a lesser influence on ice formation and thickening.

In the spring, as the snowpack starts to melt, the occurrence of runoff and the weakening of the ice cover under the increasing power of the sun leads to breakup. This is a period of fast and often dynamic changes in ice conditions. Breakup rarely happens in a thermal and sequential way (i.e. from upstream to downstream) in streams and rivers that are located far downstream from large lakes or reservoirs. The spring transition to open water conditions is often partly or significantly dynamic as the ice cover is mobilized first in specific river segments and later where it is the most resistant. An ice cover starts to break and move when the mobilizing forces (e.g., flow, flow velocity, shear stress) become higher than resisting forces (e.g., structural integrity of the ice cover, link between the ice cover and the channel banks, e.g., Beltaos, 2008). Ice jams form between locations where the ice cover is mobilized and others where it remains in place. These ice accumulations (described in Beltaos, 2008 and 1995) can be many ice layers-thick, many kilometers-long, and cause a rapid and drastic rise in water levels as well as extensive flooding. Generally, slope breaks, meanders, and changing channel forms represent limitations to ice conveyance and, therefore, promote the formation of ice jams. In contrast, the upstream presence of a large body of water (with its associated heat) prevents the occurrence of ice jams over a long downstream distance.

Appendix B – Model parameters

Parameter			R1-2	R3	R4	R5	R6
Symbol	Unit	Meaning	Values				
X	date	Defining the X axis (time and date) on graphs	Fixed, depends on time step				
Δt	hours	Time step in the model	24				
CoV_{est}	%	Estimated ice coverage for adjustment purposes	Correction variable				
CoV_{sim}	%	Simulated ice coverage without breakup consideration	Variables				
$CDDF_R$	°C-days	Cumulated degree-days of freezing threshold for full cover	275	580	435	360	380
CoV_{corr}	%	Corrected simulated ice coverage considering breakup	Variables				
CoV_{adj}	%	Adjustment of ice coverage formation rate	0				
$CoV_{corrmax}$	%	Maximum ice coverage in reaches	90	96	95	96	98
Q_{min}	m ³ /s	Minimum flow of the day from tailrace and East Aishihik River	Input variable				
Q_{mean}	m ³ /s	Mean flow of the day from tailrace and East Aishihik River	Input variable				
Q_{max}	m ³ /s	Maximum flow of the day from tailrace and East Aishihik River	Input variable				
ΔQ	m ³ /s	Daily flow variability or fluctuation	Variables				
Menu	-	Flow range from the West Aishihik River (low, average, high)	Input variable				
Q_{rWA}	m ³ /s	Synthetic recession flow from West Aishihik River	Variables				
T_{wWA}	°C	Water temperature from the West Aishihik River	0				
$T_{air\ mean}$	°C	Measured air temperature at AGS tailrace	Input variable				
$T_{air\ R}$	°C	Air temperature threshold for ice cover formation	-18	-10	-10	-10	-8
Q_T	m ³ /s	Discharge reference to evaluate the ice coverage	18.5				
Q_{high}	m ³ /s	Maximum flow considered for the ice coverage calculation	22				
a_{QR}	-	Exponent in Equation 2 to calculated T_{eff}	0.25	0.50	0.75	1.00	1.50
T_{eff}	°C	Effective air temperature for ice cover formation	Variables				
$CDDF$	°C-days	Cumulated degree-days of freezing	Variables (not used in model)				
E_{net}	W/m ²	Net heat flux estimated by a linear equation	Variables				

Parameter			R1-2	R3	R4	R5	R6
Symbol	Unit	Meaning	Values				
a_E	W/m ² °C	Net heat loss (or gain) for each °C below (above) 0°C	14	14	14	14	14
T_{corr}	°C	Correction in $T_{air\ mean}$ to consider warmer air near highway	0	0	0	1.5	2
$T_{corr\ mod}$	°C / day	Daily increase in T_{corr} after Feb 15 to consider sun power	0.06	0.06	0.06	0.06	0.06
$T_{tailrace}$	°C	Measured water temperature in AGS tailrace	Input v.	Only applies to R1-2			
T_{kpX}	°C	Simulated water temperature from upstream reach	Tailrace	Variables			
$Y_{measKpX}$	m	Measured water level at a given location (KpX)	User defined / for calibration or comparison				
$Y_{meas\ adj}$	m	Adjustment of $Y_{measKpX}$ for comparison/calibration	User defined / for calibration or comparison				
$T_{measKpX}$	°C	Measured water temperature at a given location (KpX)	User defined / for calibration or comparison				
HC_{KpX}	kW	Heat content in the flow at the head of the reach	Variables				
ρ	kg/m ³	Density of water (property of water)	1000				
C_w	J/kg°C	Specific heat capacity of water (property of water)	4186				
W_{ow}	m	Reach-averaged channel width in open water conditions	Variables				
W_{slope}	m/m	Lateral slope of left bank (right bank is vertical)	27	27	27	30	27
Y_{ow}	m	Maximum channel depth in open water conditions	Variables				
S	%	Reach-averaged channel slope	0.35	0.34	0.22	0.25	0.20
A_{ow}	m ²	Open water cross-section	Variables (not used in model)				
V_{ow}	m/s	Open water average velocity	Variables (not used in model)				
T_{Kp2}	°C	Water temperature at Kp2 (entering Reach 2)	Variable	Only applies to R1-2			
HC_{Kp2}	kW	Heat content at Kp 2 (entering Reach 2)	Variable	Only applies to R1-2			
$I_{prodKp2}$	Tons	Ice production in Reach 1 (entering Reach 2)	Variable	Only applies to R1-2			
$F_{in\ KpX}$	Tons	Frazil transported from the upstream reach	NA	Variables			
$IR_{in\ KPX}$	Tons	Ice run from upstream reach	NA	Variables			
$L_{T=0}$	m	Streamwise location where water cools to 0°C without ice	Variables				
L_{down}	m	Location of end of reach along the river	6000	12000	18000	24700	30000
L_{reach}	m	Length of reach	4000	6000	6000	6700	5300
L_{up}	m	Location of start of reach along the river	2000	6000	12000	18000	24700

Parameter			R1-2	R3	R4	R5	R6
Symbol	Unit	Meaning	Values				
$HC_{Kpx\ no}$	kW	Heat content in flow at end of reach without ice	Variables				
$T_{kpX\ no}$	°C	Water temperature at end of reach (or any Kp) without ice	Variables				
L_{mon}	m	Location of a monitoring point (depth and temperature)	3000	2000	depend	2000	800
$I_{melt\ pot}$	Tons	Melting potential of the ice content of the reach	Variables				
$F_{in\ melt}$	Tons	Melting of frazil entering the reach	NA	Variables			
$IR_{in\ melt}$	Tons	Melting of ice runs entering the reach	NA	Variables			
Spring	Binary	Spring conditions when Cov_{corr} is controlled by ice melt	Variables				
$Srping_T$	%	Spring conditions may start if maximum winter $Cov_{corr} >$	20	70	80	80	80
I_{melt}	Tons	Melting of the ice content of the reach	Variables				
$EFF_{AI\&FJ}$	%	Adjustment of melt between anchor ice and frazil jam	Variables				
$Actual_{I_{melt}}$	Tons	Sum of the melt of each stationary ice types	Variables (not used in model)				
$Melt_{error}$	%	Difference between the simulated and calculated melt	Variables (not used in model)				
I_{melt}	kW	Melting of the ice content of the reach (heat loss)	Variables				
$L_{T=0\ ice}$	m	Streamwise location where water cools to 0°C with ice	Variables				
$HC_{Kpx\ ice}$	kW	Heat content in flow at end of reach with ice	Variables				
l_{ice}	J/Kg	Latent heat of fusion of ice (property of ice)	333,550				
$T_{kpX\ ice}$	°C	Water temperature at end of reach (or any Kp) with ice	Variables				
$T_{melt\ corr}$	%	Correction of water temperature if there is under melt	NA	50	50	50	50
$Area_{ip}$	m ²	Channel area (reach) where heat is lost (open water)	Variables				
$I_{prod\ T}$	%	Ice coverage above which heat loss is 0 (= Cov_{max})	90	96	95	96	98
$I_{prod\ KpX}$	Tons	Ice production in Reach	Variables				
FI to SI	Tons	Frazil production transferred into surface ice	Variables				
$\rho_{ice\ rel}$	-	Relative density of ice	0.92				
$t_{SI\ ini}$	m	Initial thickness of surface ice cover	0.15	0.15	0.2	0.2	0.2
SI_p	-	Initial porosity of frazil forming the surface ice cover	0.4	0.4	0.5	0.5	0.5
SI_{cumul}	Tons	Cumulative mass of surface ice in reach	Variables				

Parameter			R1-2	R3	R4	R5	R6
Symbol	Unit	Meaning	Values				
SI _{ETR}	W/m ²	Heat budget threshold below which SI freezes entirely	-60				
SI _{thickness}	m	Reach-averaged surface ice thickness	Variables				
SI _{melt}	Tons	Quantity of surface ice melt per time step	Variables				
SI _{breakup}	Tons	Quantity of surface ice leaving the reach as an ice run	Variables				
AI _{cond}	Binary	Condition for anchor ice to form in the reach	Variables				
AI _{covTR}	%	Maximum Cov _{corr} for anchor ice to form	30	50	35	30	30
AI _{ETR}	W/m ²	Heat budget threshold below AI forms	-220	-220	-220	-195	-190
AI _{ETR2}	W/m ²	Heat budget threshold below AI can form above AI _{TR}	-305	350	-300	280	-280
AI _{TR}	m	Maximum, reach-averaged anchor ice thickness	0.5	0.5	0.5	0.3	0.2
AI _{prod}	Tons	Quantity of frazil transformed in anchor ice in reach	Variables				
AI _{grR}	m/h	Growth (or accretion) rate of anchor ice in reach	0.004	0.003	0.0035	0.0025	0.0015
AI _{meltR}	%	Time-dependent ratio of AI melt vs. Frazil jam (FJ)melt	Variables				
AI _{meltbias}	%	Bias towards preferential melt of AI compared with FJ	50				
AI _{cumul}	Tons	Cumulative mass of anchor ice in reach	Variables				
AI _{thickness}	m	Reach-averaged anchor ice thickness	Variables				
AI _p	-	Initial porosity of anchor ice in reach	0.4	0.3	0.3	0.3	0.3
AI _{settled}	m	Re-evaluation of AI thickness cons. Settlement (creep)	Variables				
AI _{settleRR}	m/day	Settlement rate of anchor ice during settlement episodes	0.04	0.02	0.02	0.02	0.02
AI _{volRR}	%	Ratio of AI volume loss caused by settlement	30				
AI _{melt}	Tons	Quantity of anchor ice melt per time step	Variables				
AI _{meltRR}	Tons	AI melt from other heat sources (when E _{net} = 0)	250	250	200	200	100
AI _{lifted}	Tons	Anchor ice lifted from the bed (rather than melted)	Variables				
AI _{lmR}	-	Ratio of AI lifted (released) from the bed vs. melted in situ	2				
AI _{icov}	%	Ice coverage (Cov _{corr}) above which AI cannot be lifted	30				
SF _{supply}	Tons	Available frazil that is not stored as SI or AI	Variables				
SF _{max}	Tons	Maximum amount of frazil that can be stored under SI	Variables				

Parameter			R1-2	R3	R4	R5	R6	
Symbol	Unit	Meaning	Values					
SF _{cov min}	%	Minimum ice coverage (Cov _{corr}) for SF to accumulate	15					
SF _P	-	Porosity of stored frazil in reach	0.3	0.3	0.4	0.4	0.4	
SF _{cov max}	%	Maximum ice coverage (Cov _{corr}) for SF to develop in reach	50	45	40	40	35	
SF _{cumul}	Tons	Balance of stored frazil in reach	Variables					
SF _{thickness}	m	Reach-averaged stored frazil thickness	Variables					
SF _{daily}	Tons	Daily flux of ice in stored frazil in reach	Variables					
SF _{melt}	Tons	Melting of stored frazil in reach	Variables					
SF _{breakup}	Tons	Amount of stored frazil that exits the reach as an ice run	Variables					
TF	Tons	Frazil not stored as SI, AI or SF and therefore transported	Variables					
FJ _{supply}	Tons	Available frazil that is not stored as SI, AI, or SF	Variables					
FJ _{E_{TR}}	W/m ²	Minimum heat flux (E _{net}) for FJ to form in reach	-220	-220	-220	-195	-190	
FJ _{cov min}	%	Minimum ice coverage (Cov _{corr}) for FJ to form in reach	30	40	40	40	50	
FJ _{RR1}	-	Rate of frazil interception into SF for Cov _{corr} > F _{Jcov min}	1	1	1	1	0.2	
FJ _{cov int}	%	Intermediate ice coverage for FJ to keep growing in reach	45	40	40	40	80	
FJ _{RR2}	-	Rate of frazil interception into SF for Cov _{corr} > F _{Jcov int}	0.6	0.3	0.35	0.3	0.25	
FJ _{cov max}	%	Ice coverage above which at TF is sent downstream	60	95	90	95	95	
FJ _{cov spring}	%	At breakup, frazil jam can no longer extend if Cov _{corr} is lower	5	5	5	20	20	
FJ _{thermal}	Tons	Ice forming in unfrozen water within TF at each time step	Variables					
FJ _P	-	Initial porosity of frazil jam in reach	0.3					
FJ _{E_{TR}}	W/m ²	Heat flux (E _{net}) above which all new FJ freezes entirely (FJ _P =0)	-305	-350	-300	-280	-280	
FJ _{cumul}	Tons	Balance of frazil jam in reach	Variables					
FJ _{daily}	Tons	Daily flux of ice in frazil jam in reach	Variables					
FJ _{cumul}	m ³	Balance of frazil jam in reach considering density	Variables					
FJ _{density}	-	Relative density of frazil jam as a verification (max = 0.92)	Variables					
FJ _{thickness}	m	Reach-averaged frazil jam thickness	Variables					
FJ _{thickmax}	m	Maximum FJ average thickness in reach	NA					0.6

Parameter			R1-2	R3	R4	R5	R6	
Symbol	Unit	Meaning	Values					
FJ _{mettbias}	%	Bias towards preferential melt of AI compared with FJ	Variables					
FJ _{melt}	Tons	Amount of frazil jam melted at any time step	Variables					
FJ _{mRR}	Tons	SF melt from other heat sources (when E _{net} = 0)	0	0	100	200	100	
FJ _{breakup}	Tons	Amount of frazil jam that exits the reach as an ice run	Variables					
BR _{cond1}	Binary	Breakup condition 1 based on warming air temperatures	Variables			NA		
BR _{Erise}	W/m ²	Rise in E _{net} for breakup to occur	250	290	290			
BR _{EriseD}	Days	Maximum number of days over which E _{net} must rise	7					
BR _{covEmin}	%	Minimum Cov _{corr} for BR _{cond1} to occur	10	5	5			
BR _{covEmax}	%	Maximum Cov _{corr} for BR _{cond1} to occur	80	50	50			
BR _{cond2}	Binary	Breakup condition 2 based on warm air temperatures	NA			Variable		
BR _{melt}	W/m ²	E _{net} for breakup to occur				0	-20	
BR _{meltD}	Days	Number of days over which breakup cannot be repeated				4		
BR _{covmmin}	%	Minimum Cov _{corr} for BR _{cond2} to occur				5		
BR _{covmmax}	%	Maximum Cov _{corr} for BR _{cond2} to occur				90	55	
BR _{cond3}	Binary	Breakup condition 3 based on new minimum flow	Variables					
BR _{Qmin}	m ³ /s	Drop in minimum flow (Q _{min}) for breakup to occur	5	4	4	6	6	
BR _{EQmin}	W/m ²	E _{net} below which condition does not apply	-305	-350	-300	-280	-190	
BR _{QminD}	Days	Number of days over which new minimum is established	5					
BR _{covQmint}	%	Minimum Cov _{corr} for BR _{cond3} to occur	10	5	10	10	10	
BR _{covQminh}	%	Maximum Cov _{corr} for BR _{cond3} to occur	40	45	50	99	55	
BR _{cond4}	Binary	Breakup condition 4 based on daily flow variations	Variables					
BR _{ΔQ}	m ³ /s	Minimum daily variation in flow (ΔQ) for breakup to occur	10	8	8.5	8.5	8.5	
BR _{EAQ}	W/m ²	E _{net} below which condition does not apply	-305	-350	-300	-195	-190	
BR _{ΔQmin}	%	Minimum Cov _{corr} for BR _{cond4} to occur	10	5	5	5	5	
BR _{ΔQmax}	%	Maximum Cov _{corr} for BR _{cond4} to occur	60	60	60	55	55	
BR _{cond5}	Binary	Breakup condition 5 based on massive anchor ice release	Variables					NA

Parameter			R1-2	R3	R4	R5	R6
Symbol	Unit	Meaning	Values				
BR _{AI%}	%	Minimum loss in AI for condition to apply	75				NA
BR _{AI}	tons	Minimum amount of AI released for condition to apply	15,000	15,000	15,000	12,000	
BR _{cond6}	Binary	Breakup condition 6 based on new maximum flow	NA				Variable
BR _{Qmax}	m ³ /s	Maximum flow (Q _{max}) threshold for breakup to occur					18.5
BR _{EQmax}	W/m ²	E _{net} below which condition does not apply					-190
BR _{QmaxD}	Days	Maximum number of days over which E _{net} must rise					5
BR _{covQmaxl}	%	Minimum Cov _{corr} for BR _{cond6} to occur					5
BR _{covQmaxh}	%	Maximum Cov _{corr} for BR _{cond6} to occur					40
BR _{cond7}	Binary	Breakup condition 7 based on new minimum spring flow	Variables				
BR _{QminS}	m ³ /s	Drop in minimum flow (Q _{min}) for spring breakup to occur	4				
BR _{EQminS}	W/m ²	E _{net} below which condition does not apply				-195	-190
BR _{QminDS}	Days	Number of days over which new minimum is established	4				
BR _{covQminS}	%	Minimum Cov _{corr} for BR _{cond7} to occur	5	3	3	3	2
BR _{covQminhS}	%	Maximum Cov _{corr} for BR _{cond7} to occur	80	80	90	99	99
BR _{covR}	%	Reduction in Cov _{corr} when breakup occurs (includes BR _{cond7})	5	3	3	3	2
BR _{DR}	Days	Number of days after which a new breakup event can occur	5	5	5	5	4
IR	Tons	Amount of broken ice leaving the reach as an ice run	Variables				
IR _{cov}	%	Maximum Cov _{corr} for ice runs to occur	35	50	40	40	40
IJ _{indicator}	-	Indicator of the occurrence of an ice jam	Variables				
IJ _{rubble}		Amount of ice in the spring melting front rubble (no impact)	5,000				
IJ _{cov spring}	%	Ice jam no longer occur below this Cov _{corr} = FJ _{cov spring}	5	5	5	20	20
IJ _{influence}	-	Days when ice jam influence water levels	Variables				
IJ _D	Days	Duration of recent ice jam influence	4				
IJ _{covh}	%	Breakup ice jam has a hydraulic influence above this Cov _{corr}	50	60	80	95	96
I _{cumul}	Tons	Cumulative amount of ice in reach	Variables				
F _{out}	Tons	Amount of frazil leaving reach	Variables				

Parameter			R1-2	R3	R4	R5	R6
Symbol	Unit	Meaning	Values				
IR _{out}	Tons	Amount of ice rubble (ice runs) leaving reach	Variables				
n _{rise}	-	Manning's n (channel roughness) for ice cover forming	Variables				
n _{open}	-	Manning's n (channel roughness) for open water conditions	0.025	0.025	0.022	0.022	0.023
n _{icemax}	-	Maximum intact ice Manning's n (channel roughness)	0.035	0.032	0.030	0.028	0.030
Mn _{covrise}	%	Cov _{corr} at which maximum Manning's n is reached	20	70	70	70	70
n _{smooth}	-	Manning's n (channel roughness) for mid-winter conditions	Variables				
n _{full}	-	Manning's n (channel roughness) for full ice coverage	0.032	0.030	0.026	0.026	0.027
n _{jam}	-	Manning's n (channel roughness) for ice jams, if applicable	Variables				
n _{jamC}	-	Manning's n (channel roughness) for ice jams	0.040	0.035	0.033	0.032	0.032
S	-	Water surface slope	Variables				
S _{open}	%	Open water surface slope	0.35	0.34	0.22	0.25	0.20
S _{IJ}	%	Ice jam surface slope	0.32	0.32	0.20	0.23	0.18
Y _{va}	m	Vertical adjustment of water depth to consider ice forms	Variables				
a _{SI}	-	Multiplicator for surface ice	1.0	1.0	1.0	1.0	1.0
b _{SI}	-	Exponent for surface ice	1.0	1.1	1.1	1.1	1.1
a _{AI}	-	Multiplicator for anchor ice	1.0	0.9	1.0	0.9	0.9
b _{AI}	-	Exponent for anchor ice	1.0	1.1	1.0	1.1	1.1
a _{SF}	-	Multiplicator for stored frazil	1.0	1.0	0.9	1.0	0.9
b _{SF}	-	Exponent for stored frazil	1.0	1.1	1.1	1.1	0.9
a _{FJ}	-	Multiplicator for frazil jam	0.9	0.9	0.9	0.9	0.9
b _{FJ}	-	Exponent for frazil jam	1.0	1.1	1.1	1.1	1.1
Y _{simKpX}	m	Simulated water depth at a Kp using modified Manning Eq.	Variables				
Y _{max}	m	Maximum water level over the course of winter	Variables				
OF	m	Overflow caused by a rise in Y _{sim}	Variables				
OF _{covmin}	%	Minimum Cov _{corr} for overflow to occur	20				
OF _{rise min}	m	Minimum rise in Y _{sim} in one time step for significant overflow	0.02				

Parameter			R1-2	R3	R4	R5	R6
Symbol	Unit	Meaning	Values				
AU	m	Freezing of overflow to form aufeis	Variables				
AU _{Tair}	°C	T _{air} threshold for overflow to freeze	-5				
AU _{overbank}	m	Aufeis thickness above the top of bank	Variables				
Y _{bank}	m	Elevation of bank (to be adjusted by the user)	Input variable				
IJ	-	Occurrence of ice jam for visualization purposes	Variables				
IJ2	-	Occurrence of ice jam for visualization purposes	Variables				
Y _{sim adj}	m	Adjusted water elevation for visualization purposes	Variables				

Appendix C - Manning Equations for ice-covered conditions in a triangular channel



$$A = \frac{YW}{2} - \frac{YW \cos^2}{2}$$

$$A = \frac{YW(1-\cos^2)}{2}$$

$$P = Y + W + \cos Y - \cos W$$

$$P = W(1-\cos)$$

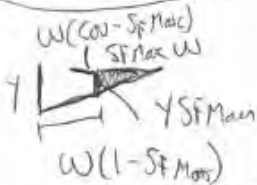
$$R_h = \frac{Y(1-\cos^2)}{2(1-\cos)}$$

$$Q = \frac{YW(1-\cos^2)}{2} \cdot \frac{Y^{2/3}}{2^{2/3}} \frac{(1-\cos^2)^{2/3}}{(1-\cos)^{2/3}} \cdot \frac{S^{1/2}}{n}$$

$$\frac{Qn}{S^{1/2}} = \frac{Y^{5/3} W (1-\cos^2)^{5/3}}{2^{5/3} (1-\cos)^{2/3}}$$

$$\frac{Qn 2^{5/3} (1-\cos)^{2/3}}{S^{1/2} W (1-\cos^2)^{5/3}} = Y^{5/3}$$

$$\left[\frac{Qn 2^{5/3} (1-\cos)^{2/3}}{S^{1/2} W (1-\cos^2)^{5/3}} \right]^{3/5} = Y$$



$$A = \frac{YW(1-SF_{max}^2)}{2}$$

$$P = Y + W(1-SF_{max}) + Y SF_{max} + W(\cos - SF_{max})$$

$$P = Y + W - W SF_{max} + Y SF_{max} + W \cos - W SF_{max}$$

$$P = Y + W - 2W SF_{max} + Y SF_{max} + W \cos$$

$$P = W(1 - 2SF_{max} + \cos)$$

$$R_h = \frac{Y(1-SF_{max}^2)}{2(1-2SF_{max}+\cos)}$$

$$Q = \frac{YW(1-SF_{max}^2)}{2} \cdot \frac{Y^{2/3}}{2^{2/3}} \frac{(1-SF_{max}^2)^{2/3}}{(1-2SF_{max}+\cos)^{2/3}} \cdot \frac{S^{1/2}}{n}$$

$$\left[\frac{Qn 2^{5/3} (1-2SF_{max}+\cos)^{2/3}}{S^{1/2} W (1-SF_{max}^2)^{5/3}} \right]^{3/5} = Y$$

Appendix D - Project Charter

“The Äshèyi Chu/Aishihik River - River Ice Model”

[DRAFT] Project Charter

Prepared by Yukon University; for review by Core team and supporting contributors
April 28, 2022

Introduction

The following provides a basis for guiding the project entitled “The Äshèyi Chu/Aishihik River - River Ice Model”. This collaborative project includes Yukon University as the grant holder, Champagne and Aishihik First Nations (CAFN), Yukon Energy Corporation (YEC), and Yukon Government (YG) as contributors. This project is funded by Crown and Indigenous Relations and Northern Affairs Canada’s (CIRNAC’s) Climate Change Preparedness in the North (CCPN) program.

This charter provides the framework for representatives from YukonU, CAFN, YEC, and YG to jointly and equally oversee and provide guidance to YukonU based on guiding principles and shared values.

Project Outline

<p>SUMMARY OF PROJECT</p>	<p>The purpose of this project is to develop a numerical river ice model to simulate winter hydraulic thermal and ice related processes on the Äshèyi Chu/Aishihik River downstream from Aishihik Generating Station (AGS). The model is intended to inform strategic flow management on both short term and help understand long term management that may reduce the occurrence of overbank icing and winter flooding that impacts the Aishihik River floodplain, including both public and CAFN settlement land, infrastructure and related ecological conditions, in a context of changing winter climate conditions.</p> <p>Additional goals of this project will be to provide training to interested partners (e.g. CAFN via the Land Guardians program) in river hydrology, data gathering and monitoring methods, as well as</p>
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	<p>usage of the model and to exchange knowledge of the river and its change over time.</p> <p>The project will be completed by YukonU Research Centre (YRC) and supported by guidance from a core team that includes representation from CAFN, YEC, and YG.</p>
START & END DATES	<p>Start: July 2021 End: March 2024</p>
FUNDING	<p>This project is funded by Crown Indigenous Relations and Northern Affairs Canada’s Climate Change Preparedness in the North (CCPN) program. Funding was awarded based on the proposal provided to CCPN in Winter 2021 (Annex 1). Funds are held by Yukon University (YukonU), with in-kind contributions from YukonU, CAFN, YEC, and YG.</p> <p>Project Total: \$358,791.30</p> <p>Yearly Budget</p> <ul style="list-style-type: none"> • Year 1 (2021-22): \$128,030.00 • Year 2 (2022-23): \$124,415.05 • Year 3 (2023-24): \$106,346.25

Shared Values

We recognize that this project takes place in a context where practices by governments, private companies and researchers have disempowered and negatively impacted Yukon First Nations, generally, and Champagne and Aishihik First Nations, specifically. In support of reconciliation, we will:

- Include CAFN as an equal voice in this project.
- Ensure that the project is planned and carried out in ways that are consistent with and informed by Dän K’e (“Our way”).
- Ensure research activities are carried out in a manner that respects the land and people using it.
- Ensure that research results are shared with CAFN citizens in an accessible format that invites conversation.

A value outside of the context of reconciliation that is important to this project is the recognition that everyone in Yukon shares an interest in access to sustainable energy resources for the territory.

Expected Project Outcomes

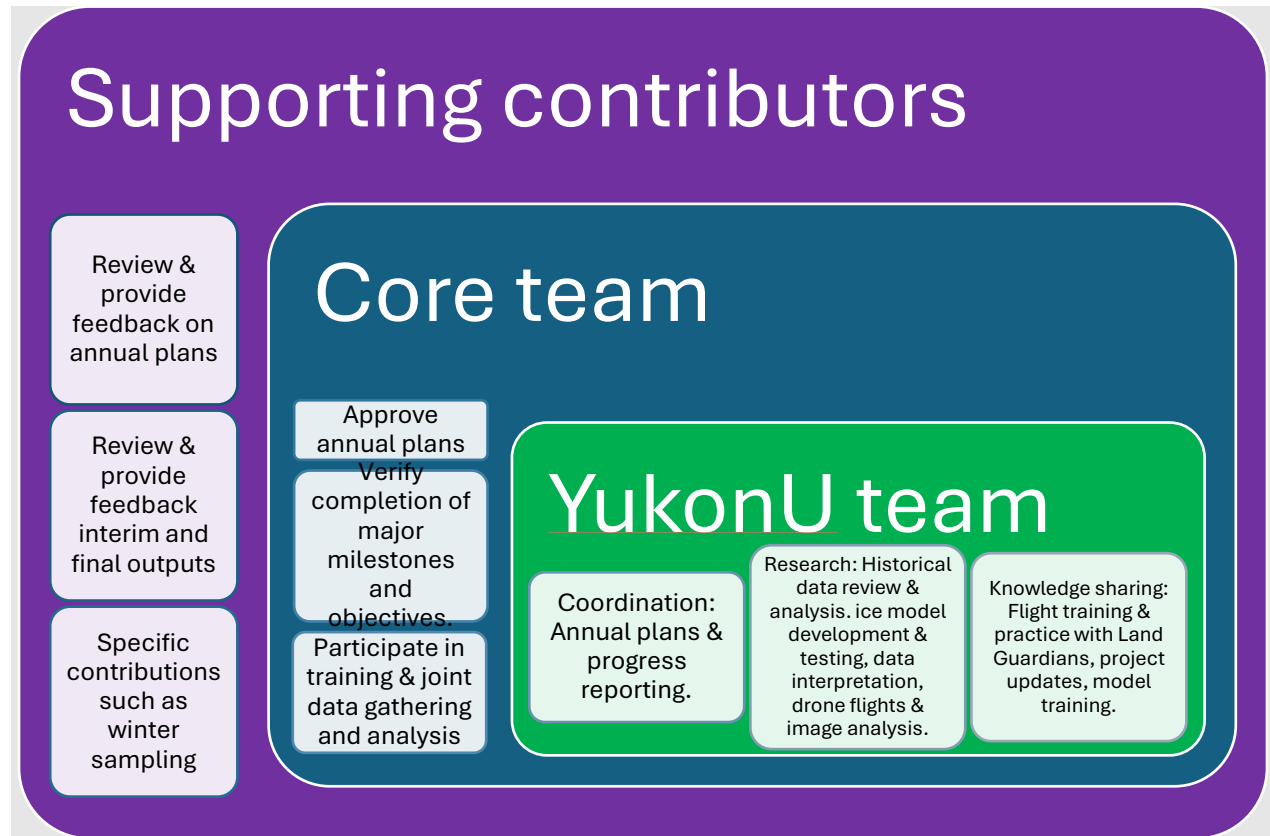
The primary deliverable of this project will be a rigorous numerical river ice model that will quantify ice conditions that can then feed into YEC's management systems. In doing so, it will help inform strategic flow management on both short term and help understand long term management of AGS by helping to define flow management that may reduce overbank icing and flooding that affects CAFN settlement land, infrastructure and ecological conditions, in a context of changing winter climate conditions. Additional outcomes associated with the primary deliverable include:

- Training sessions delivered by YukonU to core team or other representatives of the organizations on spatial data gathering (via drone), spatial data processing and spatial data interpretation, to produce high quality drone operators within the CAFN guardians.
- Knowledge sharing sessions hosted by YukonU with core team on river hydrology and river ice processes.
- Training sessions delivered by YukonU to core team or other representatives of the organizations on model usage and interpretation of results.

Team structure, roles and membership

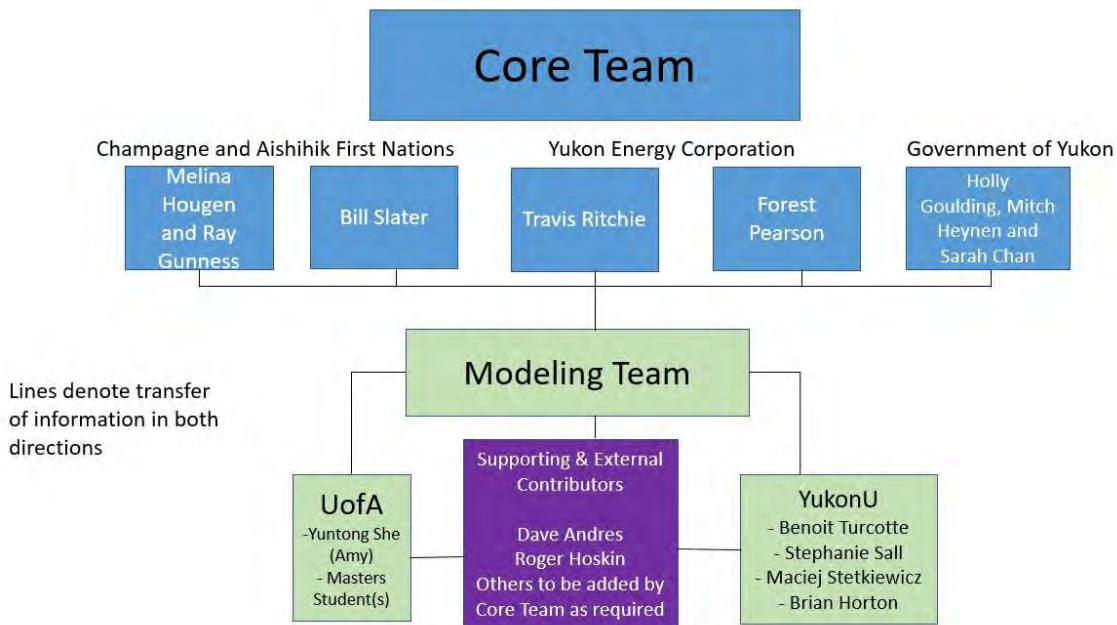
All project contributors attest that they value honesty, transparency, collaboration, and fairness and acknowledge their commitments to supporting reconciliation with First Nations people and governments. We share the objective of wanting to ensure that good quality science is respectfully conducted; inclusive of, consistent with and informed by different knowledge systems; broadly shared; and can inform solutions to challenges that have been jointly voiced. To help ensure that all contributors are able to make efficient use of their time and contribute meaningfully, the following graphic outlines the expected roles and team structure for the project.

General roles:



Members

Individual members may change during the project; however, the institutions and organizations will remain constant.



Core team

In order to ensure transparency and quality of the research project, the researchers report to and seek guidance from the Core team. The three organizations represented on the Core Team include CAFN – whose Knowledge and Traditional Territory we acknowledge and are grateful include in this research; YEC – the public utility that operates the AGS and is considered a main end-user of the ice model; and YG – with expertise in northern hydrology and Yukon water governance.

The Core Team will:

- Monitor progress of the project and ensure that it is remaining in scope and on track. The initial scope for the project is described in the proposal that was approved by CCPN (Annex 1). Changes in scope would need to be unanimously supported by the core team and approved by CIRNAC;
- After seeking and considering input from Supporting Contributors as appropriate, provide guidance and strategic recommendations that are rooted in Dän K'e and/or technical in nature, during project planning and implementation, and review of findings as key milestones are achieved (see Workplan), and
- Assist in ensuring that the needs of their respective organizations are being met by the project.

Guiding Principles and Accountability

YukonU is accountable to the members of The Core team as well as to the Funder. CIRNAC.

The Core Team is constituted as a collaborative forum with the intent of supporting YukonU in delivering on its commitment to develop an ice model that has shared benefits for core team members.

The Core Team will strive for consensus-based decisions. Where consensus may not be achieved, key points of disagreement will be summarized and put to the Funder for resolution. The Funder will be asked to gather independent expert input in order to advise on a resolution.

Meetings of The Core Team may only occur if all parties are represented by at least one designated representative, or unless a Party confirms in writing that the meeting may proceed as a sub-group meeting in the absence of that party.

All meetings, including Sub-group communications, will be transparent with records of any sub-group meetings circulated to at least one designated representative of all Parties.

Supporting Contributors

Parties on the Core Team may engage experts (e.g. technical, *Dān K'e*) to support their informed and equitable participation. These experts should have relevant expertise and may include Elders, contractors, partners from other organizations (such as a non-profit), or informed members of the broader community. Parties may seek input from supporting contributors at their own discretion. In addition, Parties may, at their own discretion, invite supporting contributors that are listed in this Charter to participate at Core Team meetings or provide written input and/or recommendations. Parties may also request to have unlisted supporting contributors participate at Core Team meetings, or provide written input and/or recommendations. In the case of unlisted supporting contributors, the party being represented must provide a clear statement describing the relevant expertise and role of the supporting contributors.

To support the participation of supporting contributors, the Core Team expects the following:

- Recommendations from supporting contributors will serve as technical guidance and should not be understood to be the official stance of the party that they represent.
- The supporting contributors is fully informed and agrees to the content of the Project Charter.
- The project funds managed by YukonU cannot be used to compensate these supporting contributors.
- The Core Team will consider and where possible accommodate input and recommendations from supporting contributors as they support overall improvements to the research project. Yukon U will require funder approval if there are significant changes in scope for technical aspects of the project.
- As an academic institution, YukonU and U of A are required to preserve standards of academic freedom. In the extremely unlikely event that YukonU and/or U of A feel that there

is risk of losing academic freedom, the Core Team will meet to determine potential resolutions. YukonU's Academic Freedom policy is attached in Annex 3.

Core Team Meetings

A Core Team meeting will occur based on the completion of milestones as indicated in the Work Plan. Additionally, once work on the project has started, the Core Team will be updated monthly by way of written report from YukonU. Core team members may request a meeting at any time.

YukonU will be secretariat for meetings (coordinating times, making and circulating agenda, taking notes and minutes, hosting.) Chair of meetings will either be YukonU.

Specific Roles or Dependencies:

- CAFN
 - Contributing to knowledge and data sharing to ensure that a full perspective of historical and current flow and icing conditions is incorporated into the model.
 - Coordinating the participation of the Land Guardians in the project (e.g. Coordinating with YukonU to meet at field sites and participate in training activities.);
 - Helping coordinate community visits for result dissemination (e.g. organizing community meetings, or putting YukonU on the agenda for existing meetings etc.);
 - Supporting understanding and application of *Dän K'e*.
- YEC
 - Continuing to support the provision of historical and ongoing winter monitoring data and results.
- Yukon Government
 - Continuing to contribute data from existing instrumentation, if available.
- Modelling Team
 - University of Alberta
 - (Yuntong She; Masters student(s) yet to be determined.)
 - Manage River 1D modelling efforts that relate to this project.
 - Supervisor any U of A student that contributes to this project.
 - When possible, participate in technical discussions to help advance project objectives, especially as they related to River 1 D.
 - When possible, share results and data for interested members of project team.
 - Yukon U; (Benoit Turcotte, Stephanie Saal, Maciej Stetkiewicz and Brian Horton)
 - Manage empirical modelling efforts that relate to this project.
 - Participate in technical discussions to help advance project objectives.
 - Provide updates to project team.
- Supporting Contributors
 - Dave Andres, independent contractor [invited by CAFN]

- Providing expert advice on modelling and hydrothermal processes.
- Participate in technical discussions to help advance project objectives.
- CAFN Dän K'e experts [invited by CAFN] including CAFN staff (e.g., heritage) and/or elders,
 - providing expertise on how to conduct the project in ways that are consistent with and informed by Dän K'e.
- Morrison Hershfield [invited by YEC]
 - Forest Pearson – Senior technical expert with extensive local experience and knowledge of the Aishihik River system
 - Roger Hosking – Field program and data analysis lead.
 - Supporting Contributors may be invited to provide additional information and expertise as needed by the Core Team. Rational for participation shall be provided to the Core Team prior to participation of External Contributors.

Workplan

Color coding	YukonU Team	Supporting Contributors	Core Team
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ID	Project Milestone	Date of Completion	Groups Involved		
1	Meet to discuss and draft project Charter	2021-08-27			
2	Progress update on Classification of historical data; and Approval of winter monitoring plan	2021-09-17			
3	Meeting to plan 2021/2022 winter modelling project activities	2021-09-30			
4	Classification of historical data into inclusive spreadsheets	2021-09-30			
5	Purchase and installation of winter modelling project monitoring equipment for 2021-22	2021-10-15			MH
6	Purchase of Drone	2021-10-15			

7	Re-analysis of historical photos, maps, and satellite images for ice coverage quantification and ice process identification	2021-12-30			
8	Winter modelling project monitoring 2021/2022	2021-11-05 to 2022-04-30		CAFN Guardians	MH
9	Drone training for partners [2021/2022 Act as visual observers YukonU team; 2022/2023 Flight planning and creation of Ortho images; 2023/2024 relating to satellite imagery]	2021-11-05 to 2024-03-30		CAFN Guardians	
10	Development of ice, flow, water level and heat parameter correlations	2021-12-01			
11	Initial selection of physical river ice and heat budget equations	2021-12-01			UAlberta, Dave Andres
12	Progress update and gathering feedback on physical river ice and heat budget equations	2021-02-15			
13	Validation of Re-analysis of historical photos, maps, and satellite images for ice coverage quantification and ice process identification	2022-03-31			
14	Finalizing and signing of Project Charter	2021-06-01			
15	Finalizing and signing of data sharing agreement	2021-06-01			
16	Development of multi-year historical spreadsheets	2021-06-15			
17	Progress update on 2021/2022 winter modelling project monitoring; Model development and gathering of feedback	2022-06-15			

18	Activity and Expenditure Report to funder	2022-06-15			
19	Literature review about existing models and physical ice formation equations	2022-07-01			
20	Programming of the model structure	2022-07-01			
21	Approval of 2022/2023 winter modelling project monitoring plan	2022-10-17			
22	Winter modelling project monitoring 2022/2023	2022-11-05 to 2023-04-30			
23	Iterative development and finalizing pilot model version	2022-11-15			
24	Progress update on 2022/2023 winter modelling project monitoring; pilot model version; and gathering feedback	2022-11-30			
25	Programming of automatic ingestion of input parameters	2023-01-01			
26	Progress update and gathering feedback on input parameters	2023-01-01			
27	Refinement and completion of the model	2023-04-01			
28	Progress update on Model and gathering feedback	2023-04-15			
29	Activity and Expenditure Report to funder	2023-06-15			
30	Approval of 2023/2024 winter modelling project monitoring plan	2023-10-15			
31	Winter modelling project monitoring 2023/2024	2023-11-05 to 2024-04-30			
32	Progress update on 2023/2024 winter modelling project monitoring	2024-04-30			

33	Knowledge sharing on River Hydrology and Ice Processes	[Discuss with group]			
34	Training on Spatial data analysis [Relate satellite imagery to ortho images]	[Discuss with group]			
35	Training on Model usage	2023-04-01 to 2024-03-30			
36	Written communications and production of interim one-pagers	2023-04-01 to 2024-03-30			
37	Preparation of two scientific papers	[Discuss with group]			
38	Preparation of final report	[Discuss with group]			
39	Final Activity and Expenditure Report to Funder	2024-06-15			

Risks and Risk Management Approach

External Risks

- COVID 19: Possible constraints to travel, field work, and knowledge dissemination.
 - o Constraint will be mitigated by abiding by any restrictions in place, following guidelines of Chief Medical Officer and those of communities visited. Knowledge dissemination will occur via remote presentation and other engagement methods that do not require in person attendance.
- Restriction of field visits or drone usage due to weather conditions.
 - o Constraint will be mitigated by planning redundancy into number of site visits to ensure ample opportunity to collect necessary data and allow for training opportunities.
 - o Purchase of drone capable of flying in colder conditions.
- Impossibility to calibrate the model because of the complexity of interacting processes
 - o Although the ice regime of the river system appears to be somewhat predictable, there is a small chance that it will simply be impossible to develop and calibrate a model that will be useful to reduce the probability of overbank icing. In any case, the development of the model will certainly improve our understanding of ice processes in the Aishihik River and other model structures (e.g., decision tree) could be prepared as a worst-case situation.

Internal Risks

- Changes to project teams (e.g. member of project team cannot continue participation in project or in tripartite committee).
 - o The organization in which the individual that leaves the project belongs to will ensure their roles are filled by other current project team members within their organization or by instituting a replacement.
 - o If a party is unable to participate in the project the Core Team will come together to find a solution.
- Unavailability of some monitored data used for calibration of the model
 - o This could be related to a range of reasons for instrument malfunction or loss to absence of sharing agreement
- Improper file management
 - o YukonU's enterprise license for Microsoft SharePoint will be used as the collaborative platform for all project activities.
 - o YukonU will maintain records for the project and provide "edit" level access to Core Team and selected Supporting Team members (upon request from the Core Team). All users are expected to only edit documents where they have a specific role

assigned by the Core Team and to advise YukonU if changes were made to a document unintentionally. This will allow YukonU to restore a backup.

- All data are stored on servers located in Canada.
- If CAFN Traditional Knowledge is collected and electronically stored, it will be done according to CAFN rules and expectations. These expectations can be documented independently, or as an addendum to this charter.

Limitations of Scope

This project will not include

- Specific tasks related to the relicensing process and water use license requirements of the AGS;
- Modelling water quality parameters besides water temperature (e.g. turbidity);
- The deployment and operation of permanent aquatic or riparian instruments by YukonU;
- Specific recommendations regarding long-term operation of AGS (although short-term recommendations in order to test the model may be offered, pending core team approval);
or
- Forecasting inflows to simulated reach (Aishihik River below tailrace) and hydrological (including ice and water level conditions) downstream of the Aishihik River.

Intellectual Property

- YukonU Researchers involved in the project remain owners of the copyright over all presentations concerning work, including those given at seminars, meetings, symposia, and over all publications concerning the project, including text and articles submitted for publication in magazines or over other works. Such researchers dispose of the foregoing as they see fit, subject to confidentiality obligations and to submit proposed disclosures in advance to the core group.
- All project intellectual property developed solely by one institution and all intellectual property rights relating thereto shall belong to said institution. However, for the purpose of the project, the other parties who are not owners of such project intellectual property shall have a non-exclusive right to use such solely owned project intellectual property.
- All parties will have access to the model as they deem appropriate, once different model versions will become available.
- If there is a new application of the data for a subsequent or related project, the Research team will seek authorization from CAFN.
- CAFN is recognized as having intellectual property rights for the collective of CAFN traditional and local knowledge contributed to the research team through this project.
- The Research team is recognized as having intellectual property rights including copyright to academic publishing, including theses, and will acknowledge the role of the project partners in the research.

- CAFN may request co-authorship within academic publishing, excluding theses, if time and capacity allow.
- The parties agree that any economic benefits or opportunities that arise as a result of this work shall default to CAFN unless otherwise specified.
- All photos and videos (including drone footage) resulting from the project will be reviewed by CAFN and authorized before being published in a public setting, including captions.

Reporting plan

YukonU will report project progress and spending to the Funder on a yearly basis. Non-confidential elements of these reports will be prepared by representatives of YukonU's YRC team and shared with the Core Team.

YukonU will call a meeting of the Core Group to report on project milestones. The standing agenda will be to review work done since last meeting and approve the plan until next meeting.

Once the work commences, YukonU will provide written updates to the Core Team on a monthly basis or as necessary.

Frequent informal meetings and discussions will occur between YukonU and Supporting Contributors. Formal meetings and discussions will occur during the following dates:

- September 17, 2021: Progress update on Classification of historical data;
- February, 2022: Progress update and gathering feedback on physical river ice and heat budget equations
- April 1, 2022: Progress update on 2021/2022 winter monitoring; Model development and gathering of feedback
- November 30, 2022: Progress update on 2022/2023 winter monitoring; pilot model version; and gathering feedback
- April 15, 2023: Progress update on Model and gathering feedback
- April 30, 2024: Progress update on 2023/2024 winter monitoring

Project budget

The total budget for the project is \$757,004.30. It includes salaries for part-time YRC staff to assist with research, coordination of activities and communication between parties (\$161,935), FN Guardians (\$50,000), and a University of Alberta Master's student (\$50,000), travel to the Aishihik River for two YRC researchers for instrument maintenance and site observations in the Fall and Winter (\$9,492), trips to meetings and workshops for two YRC researchers (\$10,000), purchase of scientific instruments to support the current monitoring effort (\$26,000), administrative costs (\$46,114.20), in-kind contribution from YukonU for research and additional project coordination, as well as in-kind contribution from partner organizations for monitoring and participation in tripartite oversight group (\$398,213, which represents 54% of the total budget).

The funder must provide final approval of any changes to the budget; however, any proposed changes that arise during the project will first be proposed to the core team prior to being proposed to the funder.

Acknowledgement:

We, the undersigned, have collaboratively developed this Project Charter and agree that it represents our expectations for the Äshèyi Chu/Aishihik River - River Ice Model project. We will follow the plans outlined in this Charter and rely on its guiding principles and shared values as a basis to make decisions in the event that there are errors, omissions, or other unforeseen circumstances when completing the project.

Champagne and Aishihik First Nations

Name: _____

Signature: _____

Government of Yukon

Name: _____

Signature: _____

Yukon Energy Corporation

Name: _____

Signature: _____

Yukon University

Name: _____



Signature:

Annex 1 – Proposal Approved by CIRNAC

Proposal Template

Climate Change Preparedness in the North Program

AND

Climate Change and Health Adaptation Program

For more information on these funding programs, visit these websites:

CCPN <https://www.rcaanc-cirnac.gc.ca/eng/1481305554936/1594738066665>

CCHAP <https://www.sac-isc.gc.ca/eng/1536238477403/1536780059794>

This Proposal Template is a guide to show what information should be included in your application. You may use this form directly OR another format that is best for you.

Your proposal should tell us:

- | | |
|------------------------------------|---------------------------|
| 1. Who is applying (Cover page) | 5. Who you will work with |
| 2. What you want to do | 6. Budget |
| 3. Why you want to do it | 7. Letters of support |
| 4. How you will achieve your goals | |

The Climate Change Community Liaison or Research Coordinator for your region is ready to help!

Your regional Liaison or Coordinator can tell you about the funding programs, the application process, and the next review date in your region. They can check if your proposal is eligible for funding and help you develop or improve it. Please contact them at the phone number or email below.

GET IN TOUCH WITH THE LIAISON or COORDINATOR FOR YOUR REGION		
Yukon – Merran Smith 867-393-9200 ext 9244 Merran.Smith@cyfn.net	Yukon – Merran Smith 867-393-9200 ext 9244 Merran.Smith@cyfn.net	Yukon – Merran Smith 867-393-9200 ext 9244 Merran.Smith@cyfn.net
Nunavik – Adam Gardner 819-491-7227 agardner@krg.ca	Nunavik – Adam Gardner 819-491-7227 agardner@krg.ca	Nunavik – Adam Gardner 819-491-7227 agardner@krg.ca

1. Cover page: Who is applying?

<p>PROJECT TITLE:</p>	<p>The Äshèyi Chu/Aishihik River - River Ice Model</p>
<p>MAIN CONTACT or PROJECT LEAD</p>	<p>Name and title: Benoit Turcotte Ph.D., P.Eng., Senior Research Professional - Hydrology Organization: Yukon University, YukonU Research Centre, Climate Change Research Group Mailing address: 500 University Drive, PO Box 2799, Whitehorse, Yukon, Y1A 5K4, Canada Phone and email: 867-456-6969</p>
<p>PROPOSAL WRITER (if different than project lead)</p>	<p>Name and title: Organization: Phone and email:</p>
<p>COMMUNITY/ COMMUNITIES INVOLVED</p>	<p>Champagne and Aishihik First Nations Canyon Subdivision</p>
<p>BRIEF SUMMARY OF PROJECT (up to 4 sentences)</p>	<p>Under guidance from a tripartite oversight group (Champagne and Aishihik First Nations, Government of Yukon and Yukon Energy Corporation), a numerical river ice model will be developed to simulate winter hydrological processes on the Äshèyi Chu/Ashihik River downstream from AGS. The objective of the model will be to inform strategic flow management that will reduce the occurrence of overbank icing and flooding that impacts important Champagne and Aishihik First Nations (CAFN) cultural and infrastructure values and related ecological conditions, in a context of changing winter climate conditions.</p>
<p>START & END DATES</p>	<p>Start: July 2021 End: March 2024</p>

AMOUNT OF FUNDING REQUESTED	Project Total: \$358,791.30
	Yearly Budget (for multi-year projects):
	Year 1 (2021-22): \$128,030.00 •
	Year 2 (2022-23): \$124,415.05 Year 3 (2023-24): \$106,346.25

In the following sections please tell us about your project. Please keep it brief and write in plain language. The more complete your proposal is, the easier it will be for the regional review committees to understand and assess it. We suggest a maximum of 10 pages (not including the cover page, budget/workplan, and appendices).

Before you write, read through the whole template first. If a question does not apply, write “not applicable”. If a question seems repetitive, tell us where in the proposal you have already given the answer. Contact your Liaison or Coordinator with any questions you have about this template or what should be included in your proposal.

2. What do you want to do?

Goals and objectives

2.1 In one or two sentences, tell us the main goal or goals of your project.

The objective of the project is to develop a numerical river ice model that will inform sustainable management of the Aishihik hydropower Generating Station (AGS) in the future by helping to define flow management that will reduce overbank icing and flooding that affects Champagne and Aishihik First Nations (CAFN) cultural and infrastructure values and associated ecological conditions, taking into account winter weather conditions in a changing climate.

3. Why do you want to do it?

Project rationale

3.1 Why is this project needed?

Water levels in the Aishihik River are significantly higher and much more variable than under natural conditions during winter months because of hydropower demand. The AGS related flow regime generates overbank icing that affects private properties and infrastructure, impacts riparian and floodplain vegetation, modifies the river channel morphology and fish habitat, and creates hazardous conditions for people and wildlife. Increasing demand for electrical energy, in part arising from efforts to reduce carbon emitting energy sources, is likely to exacerbate the adverse effects of the AGS on the Aishihik River unless the effects can be managed through a

better understanding of the relationship between the flow conditions and adverse effects. The model will be used to identify optimal flow conditions and other potential mitigation measures in order to reduce the adverse impacts. “Our Clean Future: A Yukon strategy for climate change, energy, and green economy” (OCF), a strategy prepared by the Government of Yukon with input from Yukon First Nations and other Yukoners, emphasizes the importance of clean and reliable energy production as one of several avenues to adapt to a changing climate. The proposed project specifically relates to actions E1, E13 and E14 of OCF (relating to lowcarbon energy objectives), and also includes attenuation of downstream impacts through modelling. Finally, the project represents a component of the water relicensing process that improves the toolkit available to Yukon Energy Corporation (YEC) and others to sustainably operate the AGS. What we learn in terms of modelling approaches may be transferrable to other hydropower plants in other cold regions.

3.2 Have you, or another group, taken steps in the past to understand or address these needs or concerns identified in the previous question? If so, what steps were taken, and were they effective? Why or why not?

Since 2017, YEC, has been monitoring the Aishihik River in winter to improve the general understanding of the ice formation processes. Both Government of Yukon and CAFN have also conducted some monitoring activities to improve the understanding of ice conditions and effects on water levels. However, the complexity of winter hydrological processes combined with highly variable weather conditions has prevented the development of protocols that would inform sustainable flow management. As a result, the adoption of mitigative measures that would reduce the severity of the adverse outcomes currently being observed. Development of effective flow management approaches purely through prototype-scale experimental processes would be costly, time consuming, and potentially increase icerelated risks. Additional variability in weather conditions from climate change will exacerbate sustainable flow management. A model, developed and calibrated using past and current monitored data, can provide a mechanism to evaluate water management measures and predict potential outcomes in a much more timely way while minimizing the risks associated with direct experimental approaches. Recent steps taken towards this objective have included monitoring at additional locations along the Aishihik River during Winter 2020-2021 and the development of a model framework during Fall 2020.

3.3 Does this build on an existing project? If so, describe the previous work completed and how this proposal builds on and compliments it.

This project builds on three past and current research initiatives: 1. The Aishihik River has been monitored with scientific instruments for four winters (in a water relicensing context) and observations have been made in the Aishihik River valley since before the AGS began operating, including observations by CAFN citizens. Information from that data set has been collected and digitized into maps, but needs to be interpreted in a systematic way to refine the conceptual framework upon which to develop a river ice model. 2. Based on a review of the

existing information, the YukonU Research Center (YRC) has proposed a preliminary river ice model structure that has been shared with a tripartite working group (including YEC, CAFN and Yukon Government). However, analyzing fully the historical data and building the model requires substantially more work, which represents a significant research effort over a longer time period. The three parties in the working group have agreed to jointly provide oversight to the research project. 3. YRC has worked with YEC and another academic group based in Quebec (INRS-ETE) between 2017 and 2020 to develop an inflow forecast model to Aishihik Lake. This upstream hydrological model will be used simultaneously with the proposed downstream river ice model to support informed decisionmaking to achieve an effective balance of interests including environmental/cultural protection and energy production. This project has been developed with a view to assisting in an area where there are still knowledge gaps, and in coordination with other research efforts led by CAFN and YEC relating to other environmental and Traditional Knowledge values affected by the operation of the AGS.

Link to climate change

3.4 Briefly and in plain language, describe how your project is linked to climate change.

Hydrological and ice processes are directly dictated by weather conditions, which are in turn influenced by climate change. A model that can simulate complex hydrological processes along the Aishihik River is needed for several reasons. First, sound decision making for hydroelectric production cannot only rely on experience based on past climate conditions but needs to take the impact of increased weather variability and systematic changes to the climate. Moreover, hydroelectric demand, and therefore flow conditions in the Aishihik River, are also intimately linked to weather conditions (e.g., through home heating). AGS needs to be sustainably operated in a context of future energy demand uncertainty, which involves a reduction of downstream negative impacts through a responsible operation of AGS.

Hydroelectricity is the most important source of non-carbon emitting energy in Yukon. Increased use of AGS aligns with the objectives of OCF. However, increased use of the AGS is likely to further worsen conditions in the river as they relate to cultural and environmental values. The increased use is, to some extent, caused by climate change because there is and will be more pressure on non-carbon based sources of energy. This model is needed to address the increased effects that are an indirect result of our planned response to climate change.

3.5 How will your project help your community adapt to the impacts of climate change and build resilience?

The project will contribute to the development of operating protocols that will ultimately reduce overbank flooding and/or mitigate its negative impacts during winter months. Beyond flood hazard reduction, the project will also make flooding predictable, which will directly improve the resilience of downstream residents and facilitate the understanding of complementary river science topics such as water turbidity and fish habitat. Despite not being specifically included in the project, the model will significantly facilitate future studies on these important topics. Also, the proposed model will also provide a framework to inform maximum allowable hydropower production rates during high demand periods, based on the ice-related, system tolerances. Finally, the model will represent an accessible neutral scientific tool that will contribute in building a trust relationship between the different stake and right holders.

4. How will you achieve your goals?

Activities and results

4.1 Prepare a workplan that lists the key activities you plan to carry out each year. For each activity provide details on:

- estimated timelines,
- expected results or outcomes, and
- estimated cost.

The detailed workplan is presented in Tab #1 of the excel workbook. The first group of activities involves working with project partners to establish a co-governance model for decision making and coordination of the project for its entire duration. The co-governance model will provide for representatives from CAFN, YEC, YG to jointly and equally oversee and provide guidance to the project based on principles that include shared objectives, collective values, consensus decision-making, transparency, fairness, acknowledgement of past history, and collaboration. The parties have previously engaged relevant technical experts to support their oversight and input, a practice that is expected to continue. The project team will embrace a collaborative approach with the intent of developing shared outcomes and deliverables and maintaining transparent communication with all members.

The second group of activities, taking place from July 2021 to June 2023, involves the compilation, assessment, and analysis of both historical and new data, which includes the interpretation of photos and satellite images from sources not yet consulted, as well as analysis of digitized traditional knowledge mapping (provided consent is granted).

The third set of activities relates to the development of a process-based, numerical model to simulate ice conditions (coverage, volume, production, breakup and redistribution over time) and corresponding water levels (considering the ice volume and flow from AGS) at salient

locations along the Aishihik River. This will take place between December 2021 and Dec 2023 and will culminate with the testing and approval of the model. Figure 1 below presents the preliminary model structure as presented to the YEC, CAFN and Yukon Government tripartite oversight group during the Fall of 2020.

The fourth group of activities includes the purchase, and operation of a drone and additional instrumentation that can be installed in remote locations, as well as field trips, which will take place on the Traditional Territory of CAFN. This effort will complement the monitoring achieved by YEC during winters 2021-21 and 2022-23. YEC will continue to conduct this monitoring as an in-kind contribution to the project. CAFN Guardians will participate in this element of the project, gaining practical experience flying drones in order to collect data. The Guardians will also be trained in the use of the model once it has been completed.

The fifth and final group of activities is about communication and dissemination of project results, and includes meetings with the oversight group as well as the preparation of workshop presentations and scientific journal publications, in collaboration with the different stake and right holders. Finally, the last activity, taking place between October and December 2023, is the preparation of the final report and the transfer of the final model to the oversight group. This report will also include information related to the need for permanent real-time monitoring to support optimal model results over time.

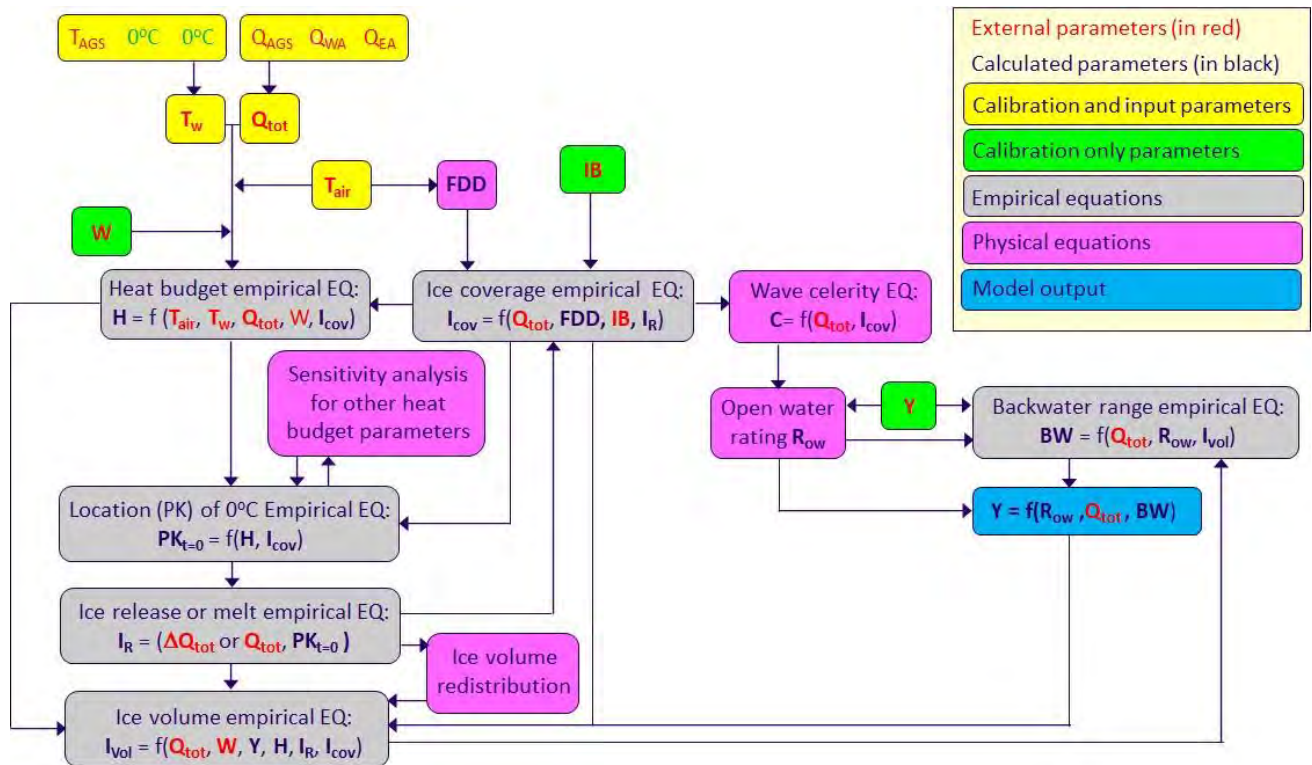


Figure 1. Proposed structure of the river ice model including different parameters and equations.

4.2 What are the expected deliverables and outcomes of your project (for example: training, workshop, action plan)?

The main deliverable is the proposed river ice model that will improve how decision-makers to predict ice conditions and subsequent water levels along the Aishihik River for expected weather and flow conditions.

A report will be produced by the YukonU Research Center (YRC) to characterize the river, explain ice processes, describe the model and how to operate it, recommend necessary permanent instrumentation for optimal model performance, and discuss possible future work.

Other deliverables will include capacity building for CAFN citizens and staff (e.g., training on the use of drones for environmental monitoring and surveillance, and on how to use the model) as well as community outreach.

4.3 After this project is done, what would your community or organization like to do next? How will the results of this project support these next steps?

It is expected that transitional support from the YRC to YEC and CAFN can be completed before the end of the project. However, the YRC will remain available to perform improvements to the model, and provide advice and support about application of the model, if needed, after March 2024.

The type of ice conditions on the Aishihik River, caused by high and highly variable winter flows (adjusted to meet electricity demand), are not unique to the Aishihik River, but occur elsewhere in Canada, including at YEC's two other hydro facilities. However, there is not much knowledge about the downstream impact of power plants located in relatively small and morphologically mobile rivers. The structure of the model developed through this project will be adaptable and transferable to other coldregion rivers that are regulated for hydropower production in Yukon as well as in other provinces and territories.

In a broader context, this type of numerical model can potentially be used to predict and reduce hazards associated with similar ice-related river flooding in natural (unregulated) environments. The YRC has an interest to explore how this type of predictive tool can answer the needs of Governments and

Communities in the North, especially in a context of climate change that may lead to changes in ice and flooding conditions on northern rivers.

4.4 What contingencies or back-up plans will you have in place to ensure that your project is a success despite potential impacts from COVID-19?

The vulnerability of the project as it refers to COVID19, or any natural or anthropogenic hazard, is relatively limited. Indeed, a significant amount of data has already been collected, additional monitoring currently relies on robust and reliable automated sensors or remote technologies, and any future monitoring and observations will not depend on a regular presence in the field (the Traditional Territory of CAFN).

As during the Fall 2020 and Winter 2021, all safety protocols, including the safe 6 +1 are part of the YukonU policy and CAFN guidelines for visitors, and will be applied to greatly reduce the probability of spreading any disease within and outside of the research team. Right and stake holders will be consulted prior to any in-person meeting and virtual meetings will represent adequate compromise to share knowledge and to communicate. CAFN has significant experience in conducting consultation and engagement activities, including in relation to the AGS, using virtual fora. Otherwise, most activities will be completed in YukonU or at our home offices.

Details on approach (where applicable)

4.5 Will you collect and/or use Indigenous Knowledge/Inuit Qaujimagatuqangit during the project? If yes, describe the approach that will be used for collecting and using it.

The model will heavily rely on western science, and quantitative data, such as water level and air temperature measurements. However, complementary data and observations made by CAFN will provide valuable supporting information and context. On previous projects, YRC has established protocols with CAFN to access and use CAFN data and information, including Dän K'e (Our Way, Traditional Indigenous Knowledge.). YRC has initiated discussions with CAFN about establishing similar protocols for this project and CAFN has confirmed that it recognizes the benefits of such information sharing that Dän K'e can bring to the project, and it is interested in getting appropriate information sharing protocols in place. Such protocols would allow access to relevant CAFN knowledge Dän K'e and related data either using reports or during meetings. Existing reports prepared by or for CAFN in the context of the AGS Water License, will also be consulted and this knowledge will be included in the project.

4.6 Will you use funds to purchase equipment, or collect and store information in a database?

- If yes, explain the ownership and who will be responsible for proper storage, maintenance, and management.
- If these items form a significant part of the budget, provide detail such as type, how they will be used, and their importance to the project work.

Both YEC and CAFN have performed monitoring using their own equipment along the Aishihik River and are independently storing the information, a situation that is not expected to change for the next three winters (including the current 2020-21 winter). These data belong to each organization, but the project will work to establish data sharing agreements to make use of all available information during the project.

In parallel, as a complementary effort, the YRC will purchase and operate a drone adapted to collecting observations under cold weather conditions, a critical need at this point to perform key river ice observations at remote river locations. The YRC will also purchase, install and operate 5 remote water level loggers and 5 remote cameras to support short-term monitoring efforts, based on identified gaps and needs after the end of winter 2020-21. These instruments, which represent about 20% of the project budget, will be owned, stored and maintained by the YRC.

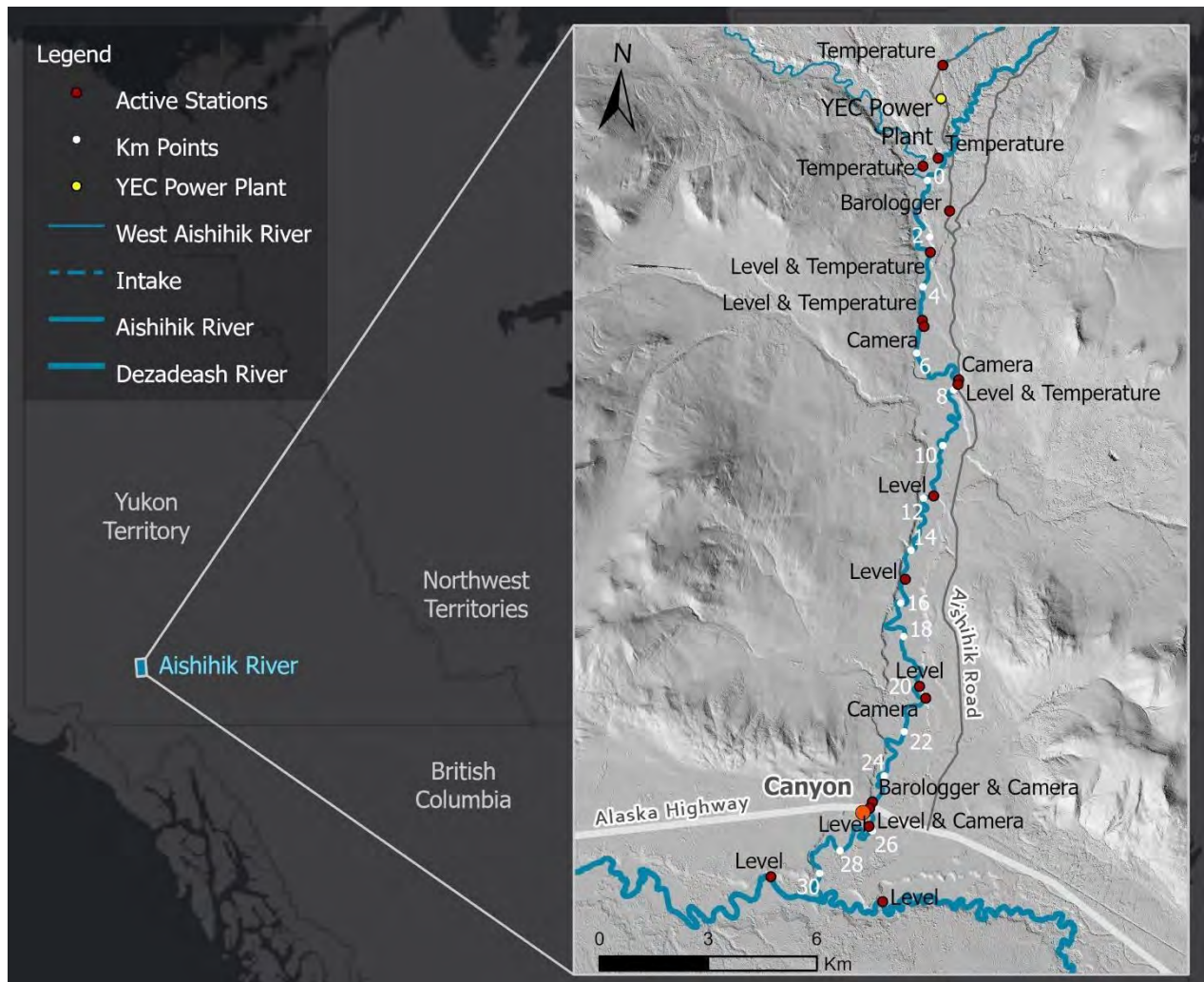
The data from this monitoring program will be shared with the tripartite oversight group and will only be used for the project or for scientific publication with the approval of all parties. All the data collected by the YRC as well as visualization files will be shared with all parties of the tripartite oversight group. These will not be shared with other parties, unless all members of the oversight group formally agree. The equipment that will be used for real-time monitoring at selected sites along the Aishihik River (to support optimal model performance) after the end of the project may be purchased and maintained by YEC.

4.7 Does your project include land or infrastructure that will be assessed or studied (for example, a slope stability assessment)?

- If yes, identify land ownership or management for any areas that will be involved.
- Describe your efforts to engage landowners or managers and ensure they are supportive of the project.

n/a

4.8 Include a map of the project area, if applicable.



Communication Plan

4.9 Describe what information you will share, when you will share it, and how it will be shared for each of the following groups:

- your community or region
- decision-makers (for example: municipal council, leadership)
- other communities or groups that might be interested

The YRC will coordinate a communication plan with the tripartite oversight group (with membership from CAFN, YG and YEC). The data obtained and model developed by the YRC will be available to all parties once completed and reviewed by the tripartite oversight group. There will be seasonal onepage reports, updates provided in newsletters, as well as meetings to outline the progress of the project for decision makers. The YRC will participate to Community meetings and is will participate in events such as the CAFN Culture Camp, as invited. Finally, two scientific papers will be submitted to peer-reviewed journals; one

about the current conditions of the Aishihik River and explaining hydrological processes, and another one about the model and the outcomes of the project. These publications will be reviewed by tripartite oversight group members, all of whom could join as coauthors should they wish.

5. Who will you work with?

Project team and partners

5.1 Please provide the information requested in the table below, identifying the project manager, team members and external partners. Descriptions of related experience and roles in the project should be brief. If partnerships or staff positions are planned, include these, and explain how they will be developed. The table below is a suggested format for this information.

Project Team and External Partners Table			
Team and partner contact information	Community or organization	Related experience	Role in the project
Benoit Turcotte Senior Research Professional bturcotte@yukonu.ca	YRC, Climate Change Research Group	Dr. Turcotte has worked on complex river ice projects since 2010, including river ice models	Technical lead – modeler Expert in hydrological processes
Stephanie Saal Research Assistant ssaal@yukonu.ca		Has worked on remote sensing and hydrological processes mapping and modeling since 2016	Expert in Geographic Information Systems (GIS), remote sensing, drone operations, and programmers
Maciej Stetkiewicz Project Coordinator mstetkiewicz@yukonu.ca		Has participated in various research project about climate change and rivers since 2016	Project coordinator and expert in hydrological processes
Yuntong She Professor yuntong.she@ualberta.ca	University of Alberta, Department of Civil and Environment Engineering	Dr. She has been doing research in river ice for more than 10 years. She has strong river modeling skills	External expert in river ice processes and modelling

Forest Pearson Consultant, Morrison-Hershfield	YEC Consultant	Forest Pearson, P.Eng, has been leading most of the	YEC lead on the tripartite oversight
FPearson@morrisonhershfield.com		river data analysis and has been working on many AGS topics for several years. He is overseeing all technical matters as they relate to the Aishihik River system for the Water Relicensing process.	group, technical expert in river processes.
Bill Slater, Consultant, Slater Environmental Consulting, bslater@bslater.ca	CAFN consultant	Bill Slater B.Sc.(Eng.) is a consultant and strategic advisor for CAFN. He has more than 25 years of experience in water management in Yukon, including involvement related to the impacts of the AGS beginning in 1993.	CAFN lead on the tripartite oversight group.
Holly Goulding, Acting Senior Scientist – Hydrology, Water Resources Branch, Department of Environment, Yukon Government Holly.Goulding@yukon.ca	Yukon Government	Holly (P.Eng., Msc) has been working on supporting research into northern river processes for over 10 years.	YG advisor on the triparty oversight group

We may request more details on the qualifications of the project manager and team members. Contact your Liaison or Coordinator if you need clarification on the level of detail needed in your application.

Community Engagement and Capacity Building

5.2 Who is your target audience? How do you plan to get them involved in the project?

Our central audience is the tripartite oversight group. We will work with members of the oversight group to develop outreach materials that target other audiences, including the constituents of the oversight group members (e.g., CAFN Citizens, youth, rate payers, the public), but the central audience will remain the intended users of the model. The YRC has been working with the three parties since August 2020. The project is intended to have a positive impact on the Water Relicensing process for AGS. Refer to activity

4.9.

5.3 Provide details on any plans to get youth engaged or involved in the project. Will youth contribute to project goals? If so, what skills, experience or knowledge will they gain?

The project team will work with CAFN to explore how youth can participate through the Guardian Program in the monitoring program. In this case, youth could learn about hydrological process at play, how to install and operate scientific river monitoring instruments in a cold environment as well as to perform targeted observations to inform scientific projects.

5.4 Will your project help build local capacity? If it will, tell us how. For example, briefly describe any training, mentorship, employment or other forms of learning or skills building.

The YRC will develop a significant expertise in understanding and modeling rivers during the winter period, which will have a positive impact on a broad range of future applied research projects in hydrology.

In addition, YRC will provide training to appropriate representatives of the three parties on how to use the Aishihik River Ice Model. Capacity building related to installing and operating permanent river instruments, as well as drone training represents a positive outcome of the project and could involve other parties, such as CAFN Guardians and youth.

5.5 What steps have you already taken to engage partners and community members in the development of this proposal?

The YRC has been working on this project with representatives of the three parties since August 2020. The community of Canyon (subdivision) and CAFN are informed of, and have been participating in, the monitoring taking place along the Aishihik River since 2017. Support letters from all project partners have been received. The participation of the University of Alberta (professor Yuntong She) in the project as an external technical expert has been confirmed. Dr. She's role will be to participate in technical discussions with the YRC (model structure, specific equations) as well as with any other party, and to suggest alternate approaches to simulate specific river processes. If the funding is awarded, Dr. She will hire and train a graduate student who will work on this project by testing an alternate modelling

approach (referred to as hydrodynamic modelling). This approach has been suggested as an alternative to the numerical modelling approach.

Last thoughts

5.6 Is there anything else that you would like the review committee to know about your project?

This project is scientifically ambitious. To the knowledge of the technical lead of the project, this type of model has not been developed in the past in a small regulated river with daily flow fluctuations. Nonetheless, YRC is confident to complete the project on time while meeting the objectives.

Budget

The detailed budget is presented in Tab #2. The total budget for the project is \$757,004.30. It includes salaries for part-time YRC staff to assist with research, coordination of activities and communication between parties (\$161,935), FN Guardians (\$50,000), and a University of Alberta Master's student (\$50,000), travel to the Aishihik River for two YRC researchers for instrument maintenance and site observations in the Fall and Winter (\$9,492), trips to meetings and workshops for two YRC researchers (\$10,000), purchase of scientific instruments to support the current monitoring effort (\$26,000), administrative costs (\$46,114.20), in-kind contribution from YukonU for research and additional project coordination, as well as in-kind contribution from partner organizations for monitoring and participation in tripartite oversight group (\$398,213, which represents 54% of the total budget).

6.1 Briefly outline what you are including under the "Professional Services" expense category (if applicable). Include funding amounts you are requesting.

The CAFN Guardians will be part of this project, but because funds are held by YukonU, they will be hired as a professional service to work on the project. An alternative could be to split the funding and each have agreements with CIRNAC (as per other projects). CAFN Guardians will be participants in field work, will be invited to participate in the training for how to operate the model, and will be provided practical training for drone operation. The project also budgets for the registration costs for Guardians to receive formal drone license training (as opposed to the practice they will have with YukonU).

In addition, a Master's student, located at UAlberta will participate in the project. His role will be to provide field work assistance as well as to explore the feasibility of developing a 1D river icehydrodynamic model in such a complex river environment. If successful, the results will be

compared with those of the model developed by YRC. This will give us a means to test a more complete range of technical options for a low cost.

Letters of support and additional information

Letters of support strengthen your proposal. You are strongly encouraged to submit support letters from project partners. We recognize that it may take extra time to get these letters. If the support letters are not ready when you submit your application, please let us know when you expect them.

We may ask for more information on a part of your proposal. Contact your Liaison or Coordinator for clarification on what information to include.

Permission to Share

Check here if you grant permission for us to share your application with other federal funding programs.

How to submit your proposal

Please email your proposal to the Climate Change Community Liaison / Research Coordinator for your region (see contacts on first page) and aadnc.adaptnord-northernadapt.aandc@canada.ca. We will send you an email confirming that we received your proposal.

Annex 2 Yukon University Academic Freedom and Responsibility

ARTICLE 58 – ACADEMIC FREEDOMS AND RESPONSIBILITIES

For the purpose of this Article, faculty shall mean Bargaining Unit members engaged in research and scholarly activity on behalf of the University.

58.01 The purpose of academic freedom is to allow Yukon University to fulfill its mandate to pursue truth, educate students, and to advance and communicate knowledge. Academic freedom is a core value of Yukon University. It protects the right of the faculty to teach and of Yukon University students to learn. It promotes the open exchange of ideas, which is an essential function of the University.

58.02 Academic freedom allows the faculty to take intellectual risks and explore challenging and controversial topics in their teaching, research, and scholarship. The free and open pursuit of truth can result in different judgements with respect to that truth.

58.03 Academic freedom is available to the faculty of the University and must be grounded in reasoned discourse and rigorous and extensive research and scholarship, as guided by peer review and constrained by the professional standards of the faculty member's discipline.

58.04 The commitments, rights and responsibilities of faculty members include three major interrelated

roles: to participate in search for truth and to communicate openly the results of this search; to develop scholarship and research in specific disciplines, within which the students participate in the process of rational enquiry; and to ground their teaching, research and scholarship in the best available evidence.

58.05 The parties agree to respect the right of all faculty members to exercise their academic freedom. This means the faculty members have the freedom to teach, to design and develop curriculum and pedagogy; to engage in scholarly activity including but not limited to research and creative work; and to publish or otherwise present the products of that scholarly activity.

58.06 Academic freedom carries with it high standards of academic responsibility. These include adherence to the professional standards of the faculty member's discipline, and acknowledgement of the need to base teaching, research, and scholarship on rigorous and extensive research, scholarship, and peer review.

58.07 Academic freedom must be exercised in a reasonable and responsible manner. It does not require neutrality; rather it carries with it the duty to use that freedom in a manner consistent with the Yukon University Code of Ethics and the scholarly obligation to base research, teaching, publication, and other forms of scholarly expression on an honest search for knowledge and rigorous enquiry.

58.08 Academic freedom does not confer legal immunity; nor does it diminish the obligation of members to meet their responsibilities to the University. In the exercise of academic freedom, members shall respect the academic freedom of others, and shall ensure that the human rights of students are respected and that students are encouraged to pursue their education according to the principles of academic freedom.

58.09 Faculty members shall, in their published professional or scholarly work, undertaken as an employee of Yukon University, indicate their affiliation with Yukon University and properly attribute significant contributions of others.