Yukon University

Developing new river ice breakup forecasting tools in the Yukon - Yukon River near Dawson

Phase I | Final | November 2024

This publication may be obtained from:

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Recommended Citation:

Turcotte, B., Dubnick, A., Saal, S., Girard, M., 2024. Developing new river ice breakup forecasting tools in the Yukon - Yukon River at Dawson. Presented to the Water Resources Branch, Department of Environment, Government of Yukon. YukonU Research Centre, Yukon University, p. 1-50.

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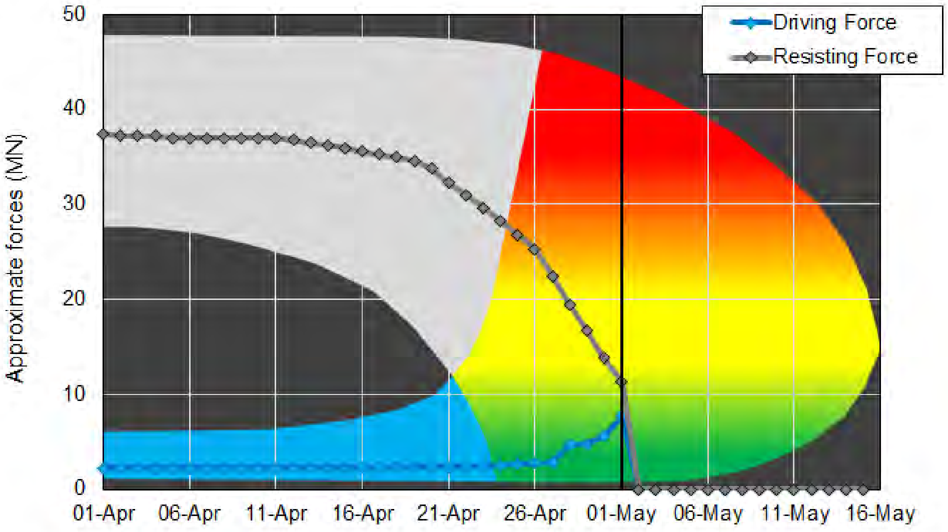
Executive Summary

The objective of this project is to develop knowledge about breakup patterns and controls as well as to present a prototype model to forecast breakup timing and intensity in the Yukon River at Dawson. In addition to information found in the literature, including reports and publications specifically about ice processes near Dawson, seven years (2018-2024) of observations were analysed to better understand breakup patterns and 55 years (1970-2024) of historical data were compiled to improve our understanding of river ice breakup dynamics along more than 200 km of the Yukon River.

Results of the analyses presented in Section 4 suggest that few dominant breakup ice jam locations exist along the Yukon River between the White River and the U.S. border (Figure 4.1.1). However, weaker and stronger ice cover segments have been identified (Figure 4.3.1), and these have a significant influence on breakup patterns. Moreover, it seems that ice processes taking place upstream of the Stewart River generally have limited impact on breakup scenarios at Dawson, but that several tributaries can affect breakup to varying degrees (Table 4.2.1). Finally, the backwater influence of an ice jam downstream of Dawson seems to vanish when its toe is more than 40 km away. Typical breakup patterns in the Yukon River near Dawson are explained in subsection 4.4.

In terms of parameters that affect river ice breakup intensity, Section 5 presents logical trends, however the generally poor correlation can be justified by the complexity of interacting controls influencing both breakup drive and resistance. Through a simple statistical analysis, several anomalous breakup events are identified and described. These outliers are as important as the identified trends in explaining typical and extreme breakup events in the Yukon River.

Section 6 describes the structure of the prototype breakup forecast model and presents an example of its use. This 0D, Excel-based model uses physical and empirical equations to evaluate breakup driving and resisting forces at a daily time step. Breakup intensity is proportional to the meeting point of those forces whereas breakup timing is indicated on the horizontal axis.



Section 7 ends with recommendations to improve our knowledge and the model.

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Acknowledgements

The authors would like to acknowledge the financial contribution of, and the comments provided by, the Water Resources Branch to this project. The project is also supported by ArcticNet’s North-by-North program. The authors would like to thank Avery Zammit and Brian Horton who provided significant support to this project.

This project is taking place on the Traditional Territory of the Tr’ondëk Hwëtch’in who have lived on these lands and by these rivers for time immemorial. It is the authors’ intention to continue improving our level of collaboration with TH. Our worldviews connect through respect for and admiration of, Chu kon’ dëk and Tr’ondëk.

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1 Introduction

The City of Dawson has been affected by significant ice jams from the Yukon River since its founding in the late 1890s up until the 1980s. At least two dikes were built around the city to protect its population and infrastructure against floods. The current dike dates from the mid-1980s and protects against 200-year flood events (Klohn Leonoff, 1986; Turcotte and Saal, 2022). Despite the absence of severe ice jams at or immediately downstream of Dawson since 1979, and warming winters as a result of climate change, ice jams still represent the most likely flooding process in the lower Yukon River. An example of this is the breakup event of May 2023, with flooding at Forty Mile that is probably unprecedented in recent history. This event alone justifies the maintenance and upgrading of the existing dike.

More generally, there is a need to minimize the risk of flooding for Dawson. Several flood risk-reduction measures were proposed by Turcotte and Saal (2022), and some are currently being undertaken. A flood mapping study is now underway for Dawson City and the Klondike Valley that will result in the development of official flood maps covering the combined hazards of ice-induced and open water floods. A statistics-based model, developed in the 1980s (Gerard and Stanley, 1986), still offers insight into the potential timing of spring breakup. Recent scientific progress, combined with the availability of valuable historical breakup-related information, now supports the development of diverse river ice breakup forecast tools.

The objective of Phase I of this project is to develop knowledge and a prototype model to support ice jam flood forecasting along the Yukon River near Dawson for the Water Resources Branch (WRB) of the Government of Yukon's Department of Environment.

2. Background

The most comprehensive publication about river ice breakup was edited and co-authored by Dr. Spyros Beltaos (2008). It covers several topics related to breakup, from thermal processes to the mechanical and hydrodynamic aspects of ice jam formation and release. It also includes a chapter by White (2008) about breakup forecasting, which mostly includes statistics-based approaches developed in the U.S. that either disregard or simplify physical processes. These models are generally robust but could under- or over-predict the probability of large ice jams when used in conditions that are outside of their calibration range. Interestingly, this chapter also includes a few words about the Yukon River (in Alaska only). Most importantly, the work presented by White is a great introduction to predictive models that rely on key parameters impacting river ice breakup intensity and the formation of ice jams (e.g., freeze-up levels, cumulative degree-days of freezing, discharge, air temperatures, precipitation).

The current work is inspired by the same textbook, specifically Figure 6.1, which shows a simplified diagram describing how river ice breakup driving and resisting forces evolve from pre-breakup onset to post-breakup conditions. There is no doubt that most existing river ice breakup forecast models take these forces into account, either indirectly through the use of easy-to-measure proxies (e.g., air temperature), or semi-directly through the use of estimated parameters (e.g., discharge). The current project builds on Figure 6.1 from Beltaos (2008) to develop a model interface, which is, as far as we are aware, a novel approach to forecasting breakup timing (on the x axis) and intensity (on the y axis).

One could assume that, since breakup on the Yukon River at Dawson has been documented for more than 125 years (www.yukonriverbreakup.ca; as it was the most important natural event of the year for Dawson citizens before the construction of the Klondike Highway), and because it has been studied in the past (e.g., Gerard and Stanley, 1986; Gerard et al., 1992; Jasek et al., 2001), it should be fairly straightforward to predict its occurrence several days in advance. However, the process appears to be relatively complex as is frequently the case in other cold region rivers. Moreover, it seems that the spatial aspect of breakup has not been thoroughly documented and that key parameters affecting breakup dynamics, namely the discharge and the ice thickness, are largely uncertain and poorly correlated with their common indicators, respectively. Therefore, the current report proposes to revisit the river ice breakup dynamics of the Yukon River near Dawson.

The most important aspect in the development of the proposed breakup model was to take the spatial aspect of breakup, or the breakup sequence, into consideration. More specifically, this work investigated where the ice cover is generally more resistant prior to breakup, and where ice jams form in the Yukon River near Dawson. A study by Turcotte (2020) proposed that freeze-up congestion (or lodgment; interception of frazil slush and pans), against which an ice cover forms by frontal progression over long distances (Beltaos, 2013), occurs 100 km and 2 km downstream of Dawson, as well as 2 km and 120 km upstream of Dawson. Freeze-up sequences vary depending on late-fall discharge and weather conditions (mainly air temperatures and snowfall-on-water events), and this impacts the location of consolidated (strong) and juxtaposed (weak) ice cover segments (or ice free-segments, such as near Moosehide).

In the spring, there are three types of locations where breakup ice jams can be observed:

- Downstream of weak ice cover areas. Small, juxtaposed types of ice jams can form immediately downstream of those sites at the onset of breakup. The resulting jams rarely cause flooding and are mobilized at a low discharge with timing that may be predictable.
- Dominant ice jam sites where ice runs stop relatively consistently year after year in a fairly predictable sequence. They are generally the last river ice segments to break up and, as a result, can cause a significant rise in water levels. The textbook example of such a site is where a river enters a lake or reservoir (e.g., the town of Hay River).
- Areas of generally high ice resistance that absorb the energy of small and large ice runs or river segments where the energy of ice runs is dissipated (e.g., presence of islands) to form ice jams. The exact location of the toe of these jams may be difficult to predict as it depends on the momentum of the ice run compared with the (heterogeneous) resistance of the ice cover over a relatively long distance (several tens of cross-section equivalents).

Ice observations made by the Water Resources Branch and reported on paper maps can be used to identify recurrent ice jam locations. In recent years, satellite products offer a complementary source of information to support similar assessments.

Does considering spatial aspects of breakup mean that the proposed model needs to be developed using a 1D or 2D hydrodynamic platform? The short answer is “no”, and this would require acquiring a significant quantity of information that is not easily available. From the perspective of the authors, through this first phase of the project, a complex ice-hydrodynamic approach would not yield more accurate results than a simple methodology as it would be data-limited. It may also be found in a later phase of the project that the risk of ice jam flooding at Dawson is sufficiently low that a more complex forecasting approach is not required or cost-effective.

Importantly, this project emphasizes a diversity of parameters that can support the estimation of breakup driving and resisting forces. As breakup progresses in a river system, breakup driving forces become highly variable in time and space (going from slowly varying conditions to unsteady conditions). Ice jams store a significant amount of ice rubble and water in the form of potential energy, and this weight increases the forces acting on the downstream ice cover. The high roughness of ice jams also impacts the shear stress at the ice-water interface, therefore increasing downward constraints. Ice jam release waves (referred to as javes, Jasek and Beltaos, 2008) may significantly increase the slope of the water surface for minutes to hours, and ice runs can carry a significant amount of kinetic energy - enough to plow through an intact ice cover over long distances, or to lift the toe of an ice jam and set it in motion. These instabilities are hard to predict in most river systems, and in turn affect our ability to forecast the timing of the local ice cover mobilization. Additionally, as a river breaks up, expanding areas of open water absorb more shortwave radiation, which increases the rate of downstream ice melt. This eventually weakens the ice cover, reducing its ability to withstand high driving forces.

These chicken-and-egg types of situations represent a serious challenge for anyone attempting to foresee the spatial evolution of thermal and dynamic ice processes during breakup. The authors are confident that the proposed breakup model will 1. Support breakup forecasting by providing insight into the influence of forces impacting the timing and severity of breakup for the Yukon River at Dawson, 2. Pave the way for the development of diverse and user-friendly breakup models for the Yukon River at Dawson, and 3. Receive some attention from the river ice community in Canada and abroad.

3. Study area

Figure 3.1 presents the segment of the Yukon River that is relevant to this project. The km points correspond to those used by the Water Resources Branch in the last few decades to characterize ice conditions during breakup observation flights (they differ from those used by Gerard et al., 1992). Km 0 is situated at the White River confluence with the Yukon River and kilometres increase in the downstream direction. This figure also presents the main tributaries of the Yukon River: Some of them have a direct (either small or strong) impact on spring breakup sequences in some years. The information provided in Figure 3.1 will be used in subsequent sections of the report, mainly in Section 4, to describe the spatial aspects of breakup.

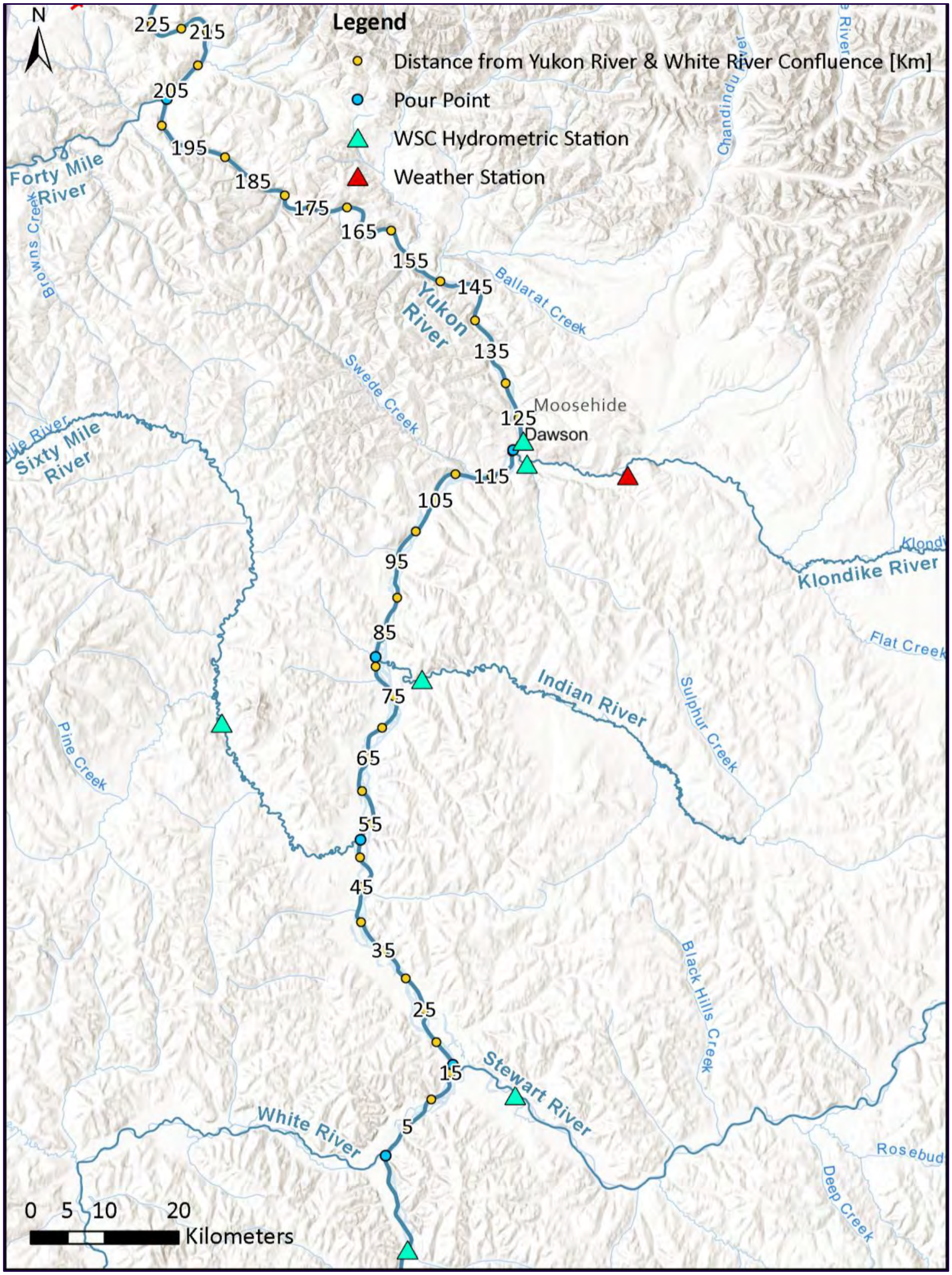


FIGURE 3.1. STUDY REACH OF THE YUKON RIVER BETWEEN THE WHITE RIVER CONFLUENCE (KM 0) AND THE FORTY MILE AREA (KM 225).

4. Spatial aspects of breakup

The authors of this report believe that developing river ice breakup forecast tools for a specific site or community should always involve documenting the upstream to downstream sequence of ice movements, from intact ice cover conditions until the last ice jam has been mobilized. Indeed, hydrometeorological factors (explored in Section 5) and local hydromechanical aspects (considered in the hydrotechnical approach; Kovachis et al., 2017) only represent partial perspectives of the river ice breakup regime.

4.1. Ice jam locations

Ice jam floods rarely happen during the first stages of breakup. They can be caused by a pause in the progression of an impeded ice run (e.g., Jasek and Beltaos, 2008), but, in the Yukon River near Dawson, they mostly result from the release of an upstream ice jam and the local or downstream interception of the ensuing (unimpeded or sporadically impeded) ice run against a largely intact ice cover. Therefore, there is a need to identify dominant ice jam locations upstream and downstream of Dawson.

This assessment was done by analyzing several sources of information, mainly Sentinel-2 and Landsat-8 visible imagery (EO Browser, 2024), but also aerial photos. Two ice jam types were distinguished:

- Minor ice jams: These are associated with limited backwater (or stage rise) because they happen during an early breakup phase (when driving forces are still low), they are relatively short (e.g., less than 3 km in length), and/or they only affect one of multiple channels.
- Major ice jams: These jams occur later at breakup and can cause floods because they involve a complete (in terms of total width) channel blockage and higher driving forces. They can be more than 20 km long.

Minor ice jams are very common in the 120 km-long Yukon River reach upstream of Dawson because 1. There are very few single channel segments along that reach and 2. There are several opportunities for small hydrological instabilities to occur (either from tributaries that break up first or from weaker ice cover sections that are set free). In addition to a channel gradient that is apparently relatively constant (about 0.04%), this explains why ice jams may form anywhere along this reach with very few confirmed, recurrent ice jam locations. In turn, small ice jams are less frequent downstream of Dawson and near the Forty Mile River because there are few islands or secondary channels, and ice runs either cause a single major ice jam or move further downstream past the Alaska border. The gradient of that single-channel reach is apparently similar to the reach upstream of Dawson, about 0.035%.

The most important point from this analysis is that dominant ice jam locations that can affect Dawson cannot be established with confidence. Such locations may simply not exist because 1. The channel gradient and width are relatively constant and 2. The momentum of ice runs as well as the resistance of the ice cover (a legacy of freeze-up patterns) largely vary from year to year. It is interesting to note that Dawson is located at the transition between two different river ice breakup regimes, and this certainly has something to do with the morphology of the Yukon River.

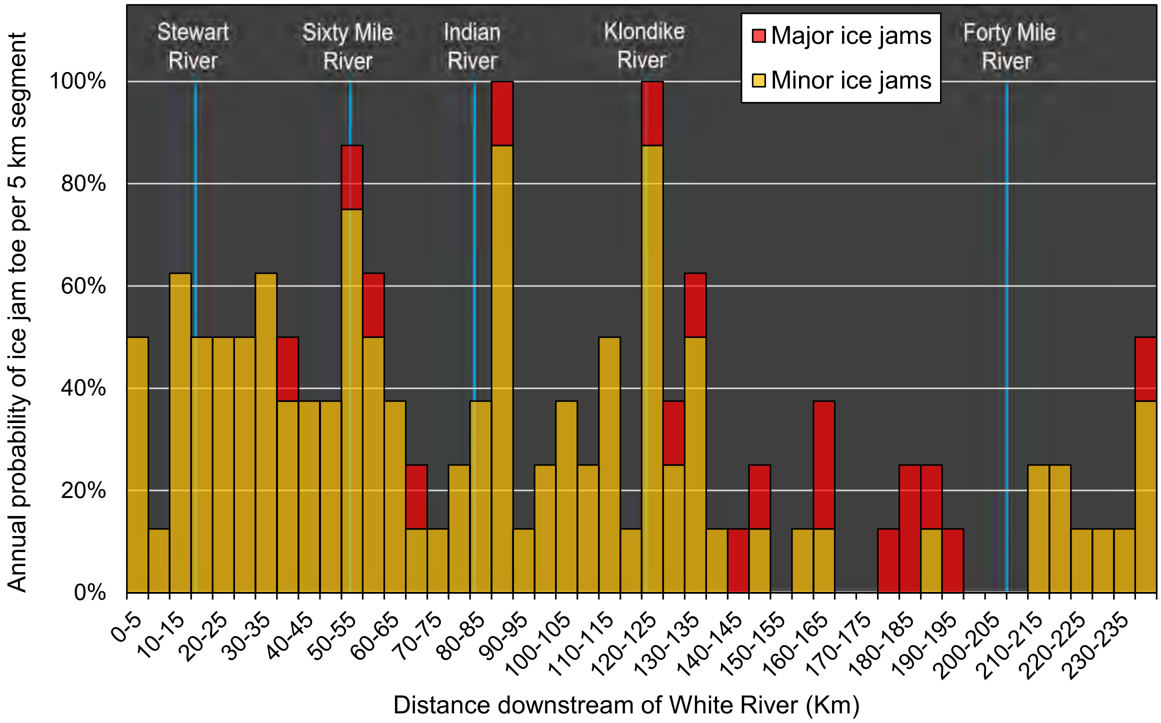


FIGURE 4.1.1. ANNUAL PROBABILITY OF MINOR AND MAJOR ICE JAMS OVER 240 KM OF THE YUKON RIVER WITH KM 0 LOCATED AT THE WHITE RIVER OUTLET. THIS ASSESSMENT IS BASED ON VISIBLE SATELLITE IMAGERY AS WELL AS AERIAL PHOTOS AND INCLUDES DATA FROM 2017 TO 2024.

This spatial breakup regime translates into a relatively narrow set of possible peak breakup water level scenarios at Dawson:

- Scenario 1: Water levels remain low (in the range of 314.5 m to 315.5 m above sea level at Water Survey of Canada station 09EB001, CGVD 2013) common during thermal breakups.
- Scenario 2: Water levels are low to moderately high (in the range of 315.5 m to 316.5 m) during dynamic breakup years as ice runs mostly flow through Dawson and only stop at locations where their backwater (i.e., hydraulic) influence is minimal, if any.
- Scenario 3: In rare occasions (e.g., once every 20 years, on average), peak water levels may reach an elevation of 317.0 m or more, when a major ice run is stopped between Km 123 and 160.

4.2. Role of tributaries

Figure 4.1.1 revealed that ice jams often form at, or immediately downstream of, Yukon River tributaries (e.g., Sixty Mile River, Klondike River). This deserves an explanation as it is quite common to consider ice conditions in, or ice supplies from, tributaries in breakup forecast models (e.g., Smoky River for the Peace River breakup, Clearwater River for the Athabasca River at Fort McMurray). Are there any tributaries that play a major role in the timing and intensity of breakup on the Yukon River at Dawson? Based on observations from recent years (up to 12 breakup events), Table 4.2.1 provides a summary of the influence of several tributaries on the river ice breakup sequence of the Yukon River.

Table 4.2.1. Role of several tributaries in the breakup sequence and intensity of the Yukon River in the Dawson reach and at Dawson.

Tributary	Breakup timing and intensity	Potential impact on the Yukon River	Potential impact at Dawson
Yukon River above White River (km 0)	One day before to several days after breakup at Dawson / Moderate to high intensity (dominant ice jam location at Km -2).	Low to major: The release of the quasi-annual ice jam upstream of the White River will contribute to clearing the Yukon River of its residual ice down to the Alaska border.	Limited: The Upper Yukon rarely plays a role in breakup at Dawson. It actually reduces and delays the supply of ice moving towards Dawson.
White River (km 0)	Consistently several days before breakup at Dawson / Mostly a thermal breakup with weak ice runs, if any.	Moderate: Mostly causing minor ice jams down to Km 15 (above Stewart River outlet).	Low: Generally causing a steady rise in water supply (see assessment by Gerard et al., 1992).
Stewart River (km 16)	A few days before to a few days after breakup at Dawson / Thermal to very dynamic breakup (dominant ice jam location at the outlet).	Low to major: Mostly causes a local river ice breakup and a minor ice jam a few km downstream, but it can also send a powerful ice run down the Yukon River.	Low to major: Beyond a rise in water supply, ice runs and flow instabilities from the Stewart River can trigger ice movements at Dawson.
Sixty Mile River (km 52)	A few to several days before breakup at Dawson / Generally dynamic breakup with an ice jam forming against the ice cover of the Yukon River or slightly downstream.	Low: Generally, causes thermal degradation of the ice cover below the outlet and promotes the formation of an ice jam a few km downstream, but can partially block the Yukon River and directly contribute to a Yukon River ice jam.	Low: It mostly plays an indirect role by partially breaking the ice cover of the Yukon River and creating an opportunity for a subsequent (minor) ice jam release.
Indian River (km 81)	A few to several days before breakup at Dawson / Generally dynamic breakup with an ice jam forming in a secondary channel of the Yukon River.	Low: Similar to the Sixty Mile River, but with a lower potential to interfere with the Yukon River.	Low: Same as Sixty Mile River.
Klondike River (km 121)	A few days to a few hours before breakup of the Yukon River at Dawson / Generally dynamic breakup with two or more ice runs (including a local run and another from the C-4 subdivision).	Low to major: It generally blocks part of the Yukon River channel, and it can extend to the opposite bank of the Yukon River. It either indirectly contributes to breakup timing and intensity at Dawson by promoting the formation of a local ice jam, or it can play a more direct, dynamic role. However, it has not been seen to immediately trigger a complete breakup of the Yukon River at Dawson.	
Chandindu River (km 152)	A few days before to several days after breakup at Dawson / Generally thermal breakup.	Limited: Generally, a minor, local thermal impact.	Negligeable.
Forty Mile River (km 205)	A few days before to a few days after breakup at Dawson / Generally dynamic breakup, with an ice jam forming at the mouth.	Low to major: The ice jam generally blocks part of the Yukon River channel, and it can extend to the opposite bank of the Yukon River. It can influence breakup dynamics over several km downstream.	None: Too far downstream to have a hydraulic influence on Dawson water levels.

The information presented in Table 4.2.1 suggests that:

- The White River is the first large tributary to cause a rise in spring flows in the Yukon River.
- Breakup in the Stewart River and, to a lower extent, breakup in the Klondike River can directly impact ice conditions and water levels in the Yukon River at Dawson, especially during dynamic breakup years when snowmelt runoff occurs suddenly.
- The Sixty Mile River and Indian River can influence local (close to their outlet) ice conditions in the Yukon River, enough to promote the formation of an ice jam, the release of which could influence ice conditions and water levels at Dawson.
- Generally, ice conditions between Km 15 and 160 can affect water levels at Dawson.

4.3. Breakup sequences

The spatial aspect of spring breakup can also be explored through the quantification of the ice coverage expressed over a length of river over time (cryographs from 2018 to 2024 are presented in Appendix A). Figure 4.3.1 presents the average ice coverage of the Yukon River for 5 km-long segments between the White River (Km 0) and the large meander bends carved in the mountains upstream of the Alaska Border (Km 240) during the 5 to 7 days preceding peak breakup water levels at Dawson. This analysis reveals a different perspective of breakup, including the presence of several areas where ice clearance occurs well before others. Weaker ice segments (green), mostly occur upstream of the Klondike River outlet and just downstream of Dawson. The resistance of the ice cover is moderate (yellow) at Dawson, which correlates with the more frequent occurrence of minor ice jams between Km 120 and 125 (Figure 4.1.1). The highest resistance (red) occurs between Km 140 and 205. This partially explains why most of the reported major jams in recent years occurred in that northwest-oriented stretch of the Yukon River past the Klondike River outlet (Figure 4.1.1).

Figure 4.3.1 demonstrates how the probabilities of a major ice jam at Dawson are influenced by opposing ice resistance factors:

- The ice cover resistance is moderately high downstream of the Sixty Mile River (Km 55 to 70) and Indian River (Km 90 to 105). In these segments, ice rubble and water (i.e., potential energy) can be stored while the ice cover at Dawson remains in place.
- The moderately resistant ice cover at Dawson (Km 120 to 125) is generally associated with the formation of a short ice jam (composed of ice originating from Km 105 to 120). It is unclear whether the ice bridge (Km 123) is responsible for that higher resistance, but the ice bridge itself has not been seen to impede large ice runs in recent years (when it was in place).
- The low resistance of the ice cover downstream of Dawson, near Moosehide (Km 125 to 130), generally offers an opportunity for major ice runs to gain momentum and move away from Dawson. It is possible that sediment entrainment from the seasonal ferry ramps over the years influences hydraulic and ice conditions immediately downstream of Dawson.
- However, the presence of a highly resistant ice cover beyond Km 140 can cause the formation of a major ice jam (intercepting ice originating from Km 0 to 140), and this has the potential to generate high water levels at Dawson.

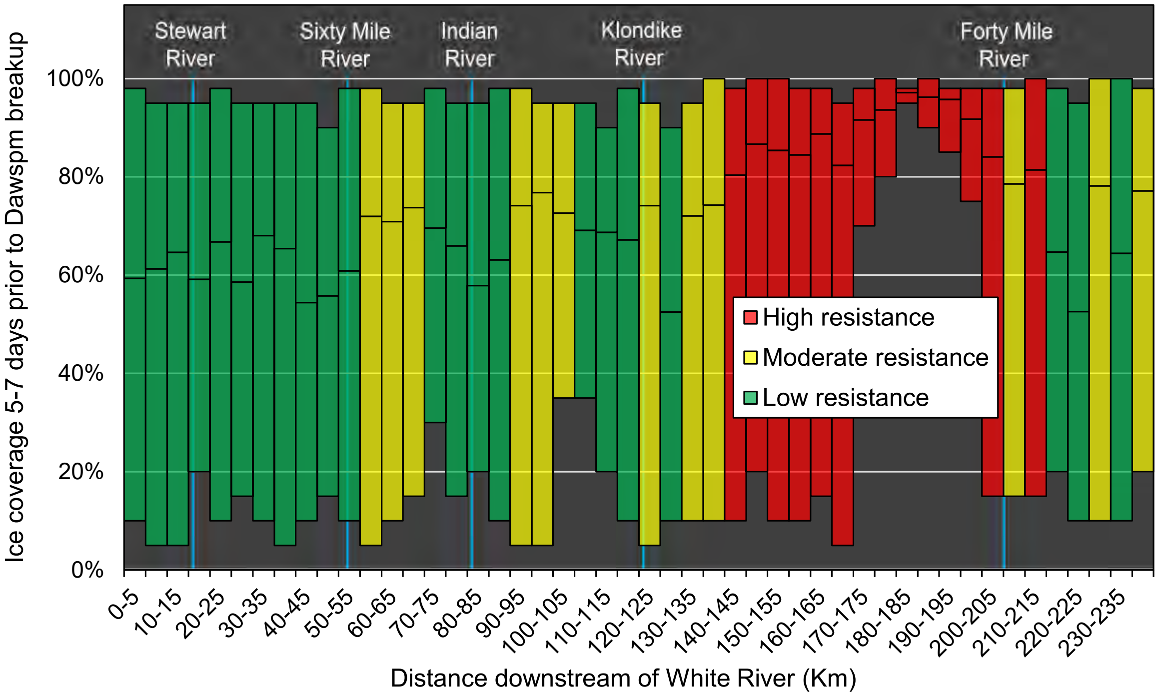


FIGURE 4.3.1. AVERAGE ICE-COVERAGE OVER 5 KM-LONG SEGMENTS OF THE YUKON RIVER OVER 240 KM DOWNSTREAM OF THE WHITE RIVER OUTLET DURING THE 5 TO 7 DAYS PRECEDING BREAKUP AT DAWSON (BASED ON DATA FROM 2018 TO 2024). HORIZONTAL LINES NEAR THE MIDDLE OF EACH COLUMN ARE MEDIAN VALUES.

4.4. Typical and extreme breakup patterns

Based on what has been presented in previous subsections, it becomes obvious that there are virtually unlimited river ice breakup sequences in the Yukon River near Dawson. However, based on the analysis of photos, radar products, and water level data from 2013 to 2023, the authors suggest that a typical breakup sequence in the Yukon River near Dawson, following a partially dynamic breakup scenario, would correspond to what is described in Table 4.4.1. This would result in peak breakup water levels ranging from 315.5 m to 316.5 m at the Water Survey of Canada station 09EB001 located at the downstream end of Dawson.

The breakup sequence leading to an ice jam flood at Dawson is not obvious. Indeed, major ice runs between Km 16 and 120 tend to lose power and momentum through secondary channels whereas the ice cover immediately downstream of Dawson (e.g., in front of Moosehide) seems to be consistently weak from year to year, a common result of the freeze-up pattern (Turcotte, 2020). Therefore, based on observations from 2018 to 2024, it is possible that the White River and the Stewart River play a direct role in this critical scenario: First, the White River sees its flow increasing significantly without causing much damage to the ice cover. In the 24 to 36 hours prior to breakup at Dawson, a major ice run is released by the Stewart River and a major ice jam first forms at Km 55, then at Km 82. This allows potential energy to be stored not too far upstream of Dawson while still allowing the resulting ice run to recruit more ice floes along the way. The ice run comes with enough power to mobilize the ice cover through Dawson (including the narrower section in front of Queen Street and the ice bridge, both of which probably represent cross-sections of slightly higher resistance), but not enough to mobilize the resistant, intact ice cover past Km 140. A subsequent (early) ice run from the upper Yukon River (i.e. above the White River) could cause the head of this jam to extend closer to, or even through Dawson. This dynamic scenario, associated with a flow above 3000 m^3/s, probably corresponds to what occurred in 1998 and, more importantly, in 1979. Freeze-up patterns could also play a role, and the absence of open water near Moosehide (near Km 125) during the winter period could represent a factor leading to major breakup ice jams forming immediately downstream of Dawson.

TABLE 4.4.1. COMMON BREAKUP SEQUENCE IN THE YUKON RIVER NEAR DAWSON.

Days prior to local breakup at Dawson	Ice conditions and dynamic events
- 5 days	Opening of the White River. Ice cover relatively intact elsewhere (this was also identified in previous studies from the 1980s, e.g., Gerard et al., 1984).
- 3 days	Breakup in the Sixty Mile River and Indian River. Minor ice jams forming near Km 11, 24, 28, 32, 46, 54, 87, 121, with a one to two km open water segment upstream of each site. Minor ice run from the lower Klondike River (below C-4). Gradual opening of the Yukon River at Moosehide.
- 2 days	Breakup of the Stewart River (it seems that its role was not mentioned in studies from the 1980s). Ice jams consolidating near Km 52 and 87. New ice jams forming near Km 100 and 110. Thermal expansion of open water areas downstream of Dawson. Breakup of the Forty Mile River with ice jam formation against the Yukon River ice cover. Ice movements downstream of Km 220.
- 1 day	Stewart River fully open. Clearing of long stretches of the Yukon River upstream of Km 50 and between Km 65 and 80. Opening of the Yukon River between Km 110 and 120. Ice jam consolidation at Dawson. Significant ice run from Klondike River (above C-4). Open water between Km 124 and 130. Only minor ice degradation and movements between Km 130 and 205. Consolidation of the Forty Mile River ice jam. Open water between Km 205 and 210 as well as between Km 220 and 225.
0 day	Clearing of ice jams from the Stewart River outlet to Dawson. Ice running through Dawson. Ice jam formation between Km 150 and 190. Ice clearing below Km 220.
+ 1 day	Open water from White River to Alaska Border. Release of ice cover upstream of White River.
+ 2 days	Unimpeded ice run from above the White River passing through Dawson.

During thermal breakup years, like in 2019 or 2016, breakup extends over a much longer period than what is described in Table 4.4.1. In this type of scenario (imposed by a low snowpack and/or cool and dry conditions), most open water areas extend by melting rather than by ice cover fracturing and mobilization, and tributaries that normally behave dynamically only cause minor flow instabilities in the Yukon River. Several short ice jams form in the system, most of which melt in place before their toe gets mobilized. This gives enough time for the ice cover downstream of Dawson to significantly degrade before weak ice runs flow past Dawson. Throughout this breakup sequence, the discharge in the Yukon River would remain well below 2000 m^3/s.

4.5. Ice indicators to forecast breakup at Dawson

The following section of the report will describe hydrometeorological factors that control or influence the timing and intensity of river ice breakup in the Yukon River near and at Dawson. If, for any reason (i.e., a major breakup event affecting hydrometric stations or a website malfunction) hydrometeorological conditions would not be known between the White River, Stewart Crossing, and Dawson, specific ice conditions could be used to forecast the timing and intensity of breakup at Dawson. The following list is by no means exhaustive, but can be used to forecast breakup at Dawson some days in advance:

- 2-3 days before breakup at Dawson: Minor ice jamming at the outlet of the Stewart River, Sixty Mile River, Indian River, and Klondike River.
- 48 hours before breakup at Dawson: Significant ice run from the Sixty Mile River and Indian River.
- <24 hours before breakup at Dawson:
    - (Dynamic scenario) Significant ice run from the Stewart River and/or Klondike River,
    - (Dynamic scenario) Major ice jam near Km 30, 55 or 87,
    - (Thermal scenario) Ice coverage upstream of Dawson below 60% and including several minor ice jams,
    - (Thermal or dynamic scenario) Moderately intense ice jam in front of Queen Street.

If the ice coverage is higher than 60% while major ice runs are moving past Km 55, breakup intensity could be higher than average at Dawson. Comparably, if the ice cover downstream of Moosehide is largely intact and highly reflective (high albedo) while major ice runs are moving towards Dawson, high ice-induced water levels should be expected at the community.

5. Hydrometeorological aspects of breakup

5.1 Hydrometeorological envelope

From a physical point of view, the timing and intensity of river ice breakup on the Yukon River at Dawson City is controlled by hydrodynamic and mechanical forces. Once breakup driving forces (those oriented downstream) rise above breakup resisting forces (those oriented upstream), ice movements will occur. This may lead to a consolidation process, which means that the ice rubble will thicken or get anchored to the banks, resulting in a higher, local resisting force. On the other hand, the sun may also be shining on the rubble and the upstream water to a point where the ice becomes structurally weaker, making the jam less resistant over time. Eventually, a new rise in the driving force, often associated with a surge that precedes or carries an ice run, will manage to mobilize the ice jam and move it to a downstream location of higher resistance. Unfortunately, this physical context cannot be quantified with certainty, and the forces involved in the breakup process cannot be accurately measured or monitored. Therefore, they need to be estimated and/or the entire breakup process needs to be simplified before being translated into equations using variables corresponding to measurable input parameters.

Parameters that influence breakup forces can be divided into hydrological (including ice-related) and meteorological parameters. It is of interest to appreciate, at an early stage of forecast model development, when and under what range of hydrological and weather conditions breakup occurs in the Yukon River near Dawson. Table 5.1.1 presents a summary of key variables.

TABLE 5.1.1. HYDROLOGICAL OR METEOROLOGICAL VARIABLES, OR PARAMETERS, THAT INFLUENCE BREAKUP TIMING AND INTENSITY AT DAWSON.

Parameters	Historical range	Historical average	Years of record
Estimated peak breakup level at station 09EB001 (CGVD2013)	314.2 to 320.6 m	315.9 m	55 (1970-2024)
Date of local breakup	April 23 to May 15	May 5	55 (1970-2024)
Date of breakup peak level	April 23 to May 18	May 5	38 (1979-2024)
Estimated peak flow at peak breakup level at station 09EB001	1000 to 7000 m^3/s	3000 m^3/s	38 (1979; 1985-2024)
Effective cumulative degree-days of thaw* at breakup at Dawson	150 to 310 °C-days	215 °C-days	38 (1979-2024)
Average April 1 snowpack at 5 snow courses (water equivalent)	70 to 260 mm	140 mm	50 (1975-2024)
Maximum cumulative degree-days of freezing at Dawson	2100 to 4600 °C-days	3350 °C-days	55 (1970-2024)
Estimated peak freeze-up water level at station 09EB001	313.0 to 315.0 m	313.8 m	16 (1994-2024)
Date of local freeze-up**	Oct 31 to Nov 30	Nov 10	10 (1975-2023)
Cumulative degree-days of freezing at local freeze-up**	150 to 250 °C-days	180 °C-days	10 (1975-2023)

* This uses corrected air temperatures to take sun radiation into account

** Local freeze-up may occur gradually with no obvious stage rise

5.2 Correlations between breakup indicators

The timing of spring breakup in the Yukon River at Dawson is influenced by a number of factors, all of which also play a role in controlling the breakup intensity. Using the data from 1970 onward, there is no correlation and no clear trend between effective degree-days of thaw at breakup (an indicator of ice strength, or resistance) or the estimated discharge at breakup (an indicator of driving forces) and the breakup date. A similar result is obtained between the maximum ice-induced water level at the end of winter (an indicator of local breakup intensity) and the breakup date. This means that, based on our analysis, thermal to mechanical breakup events can happen between late-April to mid-May in any given year, and that the sun angle and the number of sunlight hours per day seem to represent poor indicators of breakup timing and unreliable proxies for breakup intensity. Interestingly, when analyzing the data presented by Gerard and Stanley (1986), a comparable scatter is obtained, but ice jam floods prior to the 1980s seem to occur earlier in the range of possible breakup dates, which aligns with the river ice breakup theory: when breakup happens later in the spring, there has been more cumulated energy from shortwave radiation (the sun), and this contributes to weakening the ice cover, therefore promoting a thermal breakup scenario.

In this subsection, peak breakup water levels (or intensity) are expressed as a function of varying factors or parameters influencing the forces involved in the breakup process as an attempt to confirm their influence on local breakup conditions at Dawson, independently of ice conditions far upstream to far downstream of the community. These trends and correlations will support the development of the river ice breakup forecast model (Section 6).

5.2.1 Discharge at breakup

The first parameter that is known to control breakup intensity through a direct influence on hydrodynamic conditions is the discharge. The discharge cannot be measured or calculated when ice conditions are unstable, which is the fundamental characteristic of the channel during peak ice-induced water level conditions. However, given the experience of the authors at estimating ice-affected streamflow (e.g., Turcotte and Rainville, 2022), the breakup discharge was evaluated for 38 breakup events (accuracy is expected to be in the range of 30%). Results are presented in Figure 5.2.1. The trend is positive, which was expected, but the correlation is low (R^2 of 0.25), which is not surprising, given that several ice-related factors influence water levels and could therefore create significant “noise” in the results:

- Occurrence of an unimpeded or impeded ice run through Dawson
- Formation, or not, of an ice jam
- Location of the ice jam toe and extent of the jam relative to Dawson

Outliers are identified in red (above trend) and in green (below trend) in Figure 5.2.1. Possible explanations for the occurrence of these outliers are:

- 1987, 2010, 2015: Breakup followed a relatively warm winter (in terms of freezing, respectively) and occurred somewhat late (in terms of effective degree-days of thaw), both conditions promoting low ice cover resistance and smaller ice volumes.
- 1979, 1998, 2021: These are all confirmed ice jam scenarios affecting Dawson.

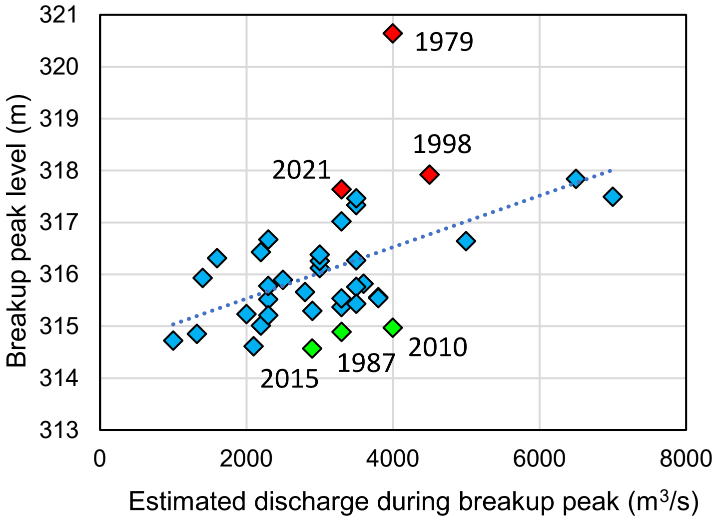


Figure 5.2.1. Breakup peak levels (water surface elevations) expressed as a function of estimated discharge during corresponding peaks at station 09EB001 (data from 1979 and 1985 to 2024 with gaps).

Flow is difficult to estimate in real time, especially since post-breakup (e.g., open water) conditions are not known (the rating curve applies as soon as the ice-backwater is negligeable, and this is when it becomes easier to understand hydrological conditions during the previous ice-affected period). Yukon River tributaries are either ice-covered, too small, or simply ungauged to be used as discharge proxies during breakup at Dawson. However, existing hydrometric stations upstream of Dawson could still be used to estimate flow trends during the days prior to breakup. Even then, there is certainly also a need to identify indirect flow indicators that can be easily measured or estimated.

5.2.2 Snowpack prior to breakup

In some snowmelt-dominated regimes, an indicator of "potential" flow in a watershed is the amount of snow on the ground at the end of winter. Gerard and Stanley (1986) had hypothesized that the snowpack in the Yukon watershed would not represent a limitation to breakup intensity. However, observations from 2019 would have convinced these authors that a thin snowpack year in Yukon can force a thermal breakup scenario. Ideally, the maximum, distributed seasonal snow water equivalent (or SWE, in mm), or at least its anomaly, would be known in most of the watersheds that contribute to breakup at Dawson (i.e., from the White River to the Klondike River, as described in Table 4.2.1). While such products are being developed (e.g., by Environment and Climate Change Canada), the authors tested a simpler relationship between breakup intensity and the accessible April 1 SWE averaged from five snow courses in the Yukon.

The trend between maximum ice-induced water levels and SWE, presented in Figure 5.2.2 and informed by 50 years of data, does not defy the laws of physics: A higher potential for snowmelt runoff does result in higher breakup water levels, on average. However, the relationship is very noisy, in part because this refers to a rather indirect control with several other influencing factors in between.

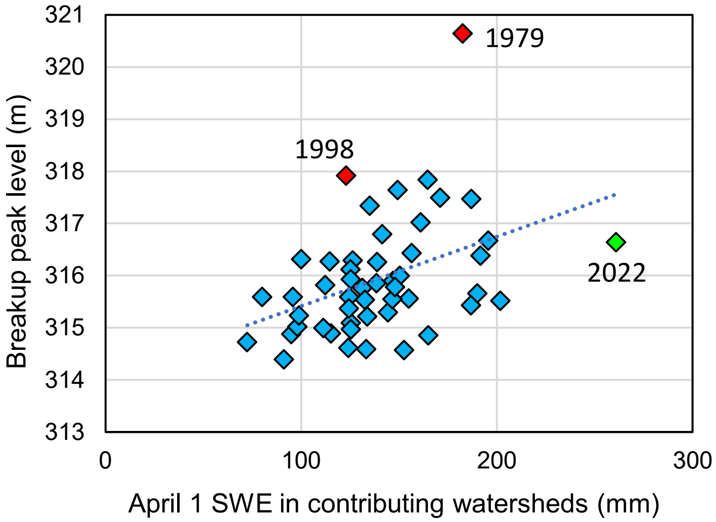


Figure 5.2.2. Breakup peak levels (water surface elevations) expressed as a function of April 1 Snow Water Equivalents (SWE) at five Government of Yukon snow courses (Beaver Creek, 09CB-SC01; Mayo Airport A, 09DC-SC01A; King Solomon dome, 09EA-SC01; Grizzly Creek, 09EA-SC02, Midnight Dome, 09EB-SC01). Data from 1975 to 2024 is used.

Outliers can be explained as follows:

- 1979: This is the most significant ice jam event documented in the history of Dawson. It was preceded by a very cold winter (4050 degree-days of freezing) and it occurred when the ice cover was still largely competent at Dawson (only 150 effective degree-days of thaw).
- 1998: Winter and spring weather conditions were not necessarily conducive to an intense breakup. However, Jasek (1998) confirms the presence of an ice jam downstream of Dawson in early May. This could be the result of an uncommon freeze-up pattern associated with a cold month of October 1997.
- 2022: Conditions were favorable for an intense breakup, but breakup at Dawson occurred before the ice run came from Km 55 and 87. The ice run, with its high ice concentration, caused the peak ice-induced water level.

Despite the weak correlation between SWE and breakup peak water level, it can be argued that the late-winter snowpack does influence hydrological conditions leading to breakup. However, from a hydrological forecast point of view, it cannot be stated that a significant (positive) SWE anomaly in upstream watersheds controls the potential (maximum possible) breakup intensity at Dawson. If the snow melts suddenly at the onset of breakup, the probability of the maximum possible breakup intensity to materialize is higher. The average peak breakup water level for 25 breakup events where the April SWE anomaly was positive is 316.4 m, compared with the 55-year average of 315.9 m (Table 5.1.1).

Snow can play another important role during breakup through its impact on the resistance side of the force balance equation: late-season snow that protects the ice cover against short-wave radiation does contribute to maintaining a strong ice cover as breakup driving forces rise, therefore increasing the probability of an intense breakup event. Of the 25 years with a positive

April 1 SWE anomaly, there are 8 springs in which there is a SWE gain or minimal loss over the proceeding month. This indicates new snow likely fell during April (or a cold month), keeping the albedo high and protecting the ice cover from solar degradation. The average peak water level of these 8 years is 316.7 m, not significantly higher than the 25 year data set, but it does exclude the major ice jam of 1979. It can be summarized that physical reasons and statistics, to some extent, support the inclusion of late-season snowfalls (or snow presence on the ice cover) as a breakup-influencing factor in the river ice breakup forecast model.

5.2.3 Degree-days of thaw

An obvious factor that influences breakup intensity is the state of degradation of the ice cover prior to its mobilization. As indicated earlier in this subsection, documenting the evolution of the ice cover resistance over time, especially during the breakup period, is difficult and dangerous, and has been achieved by very few researchers. An accepted proxy to determine the structural integrity of the ice cover over large areas is the cumulative degree-days of thaw, which corresponds to the energy absorbed by the ice cover, first to warm it to 0°C (which usually happens quickly), then to degrade (or melt) it.

Figure 5.2.3 presents the relationship between breakup peak water levels on the Yukon River at Dawson and effective (cumulative) degree-days of thaw at Dawson for 38 breakup events. The linear trend interpolated through is consistent with the physical process, especially since it considers the effect of the sun, to some extent, with a temperature correction (i.e., effective degree-days of thaw). The lack of correlation can be explained, again, by the existence of several other factors controlling breakup intensity. Note that Gerard and Stanley (1986) had obtained a similar trend and scatter using data prior to 1979, and their analysis did not consider any air temperature correction to take the date (or sun angle and hours of sunlight) into account.

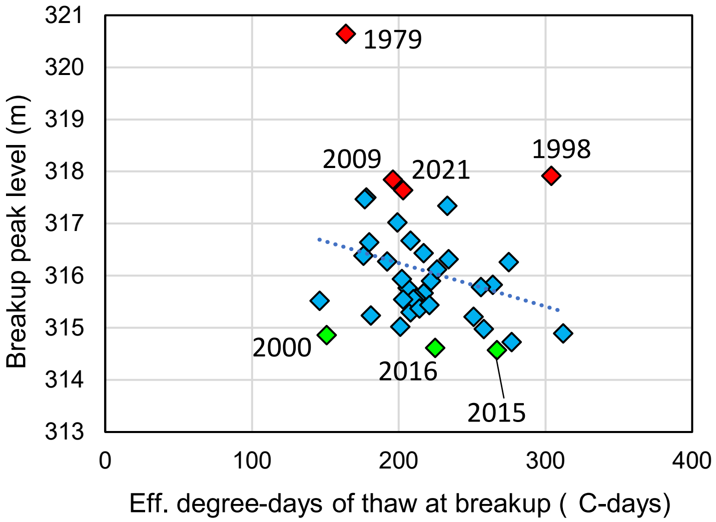


Figure 5.2.3. Breakup peak levels (water surface elevations) expressed as a function of effective (cumulative) degree-days of thaw at Dawson on the date of peak breakup. Data from 1979 and 1985 to 2024 is used.

Outliers in Figure 5.2.3 are associated with other dominant breakup controlling parameters.

- 1979, 1998, and 2021: As described above, these are not real anomalies as they correspond to ice jams at, or just downstream of Dawson.
- 2009: Given the high flows during the preceding fall (and potential dynamic freeze-up scenario), the coldness of the preceding winter (3750 degree-days of freezing), the positive snowpack anomaly (130% on April 1), and the relatively quick rise in air temperatures at the end of April, multiple factors supported water levels at Dawson above the average trend.
- 2000: The preceding winter was milder than average, especially during its second half, which suggests a low ice cover resistance during breakup.
- 2016: This is the warmest winter on record at Dawson, and the snowpack was below average, both conditions promoting a thermal breakup.
- 2015: This breakup event also followed a relatively mild winter (2,700 degree-days of freezing) and air temperatures prior to breakup were largely unstable, alternating between cold and warm. This later condition usually favors a thermal breakup scenario.

As noted by Gerard and Stanley (1986), degree-days of thaw represent a kind of paradox to forecast breakup timing and intensity: a fast rise in warm temperatures usually favours snowmelt (and a high runoff) whereas slowly rising temperatures support ice cover deterioration. However, when considered at a single location (weather station), degree-days of thaw are more representative of the local ice cover degradation than the watershed-scale snowmelt rate.

5.2.4 Degree-days of freezing

As indicated in preceding paragraphs, and from a river ice thickness (and therefore resistance) point of view, there should be a positive relationship between breakup intensity and cumulative degree-days of freezing during the preceding winter. The results presented in Figure 5.2.4 do agree with this, but again, with a significant scatter. Years that strongly depart from the identified trend are associated with the dominance of other breakup controlling parameters:

- 1979: This is not really an anomaly as Dawson could have been relatively lucky to be affected by only one major ice jam in the last 50 years (an event of similar magnitude occurred at Forty Mile, some 85 km downstream of Dawson, in 2023).
- 1998: This ice jam event is also not an anomaly, and this has been described above.
- 2023: Freeze-up was particularly dynamic during the fall of 2022 and late-season snow seemed to significantly delay ice degradation in the Yukon River at several locations.
- 1971, 1974, and 1976: There is limited data about these breakup events. However, it is possible that large variations in air temperatures during the breakup period resulted in atypical breakup sequences in the Yukon River and low water levels at Dawson.
- 1983: Limited data is available to analyze this event, but it appears that breakup took place during a cooling period.

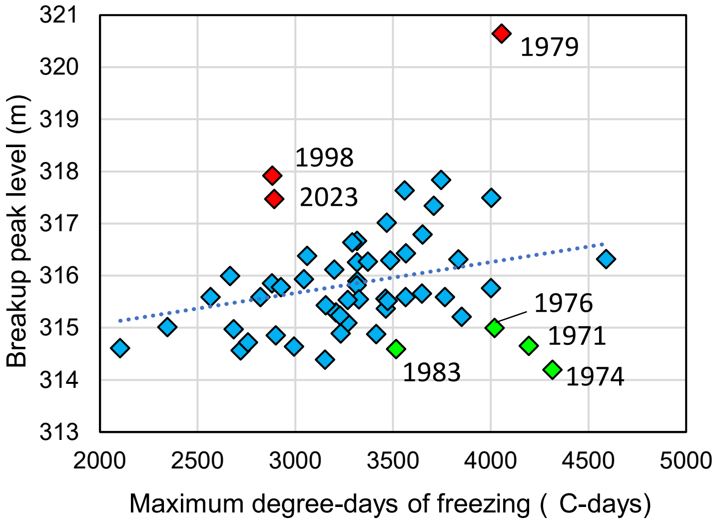


FIGURE 5.2.4. BREAKUP PEAK LEVELS (WATER SURFACE ELEVATIONS) EXPRESSED AS A FUNCTION OF THE MAXIMUM (CUMULATIVE) DEGREE-DAYS OF FREEZING AT DAWSON DURING THE PRECEDING WINTER. DATA FROM 1970 TO 2024 IS USED.

5.2.5 Freeze-up intensity

The intensity of the freeze-up process, even if it occurs several months before breakup, can still have a significant impact on spring water levels, as described for some identified anomalies in previous subsections. Indeed, freeze-up intensity can affect the resistance of the ice cover, a condition that would persist through the entire winter period. For instance, the flood of April 30, 2003, along the lower Klondike River was influenced by the freeze-up jam of mid-December 2002 (Janowicz, 2010, Turcotte et al., 2024).

Freeze-up intensity and freeze-up patterns are often overlooked as factors impacting breakup water levels. There is often a lack of data (e.g., satellite imagery, measured water levels) to support the documentation freeze-up intensity and patterns, possibly due to the darkness and cold conditions at that time of year, the difficulty of safely collecting discharge measurements after an atypical freeze-up process, or simply the lack of historical emphasis (some hydrometric stations would not operate during winter months). Data scarcity also represents a limitation to understanding freeze-up in the Yukon River at Dawson. Gerard and Stanley (1986) used the mean estimated discharge during the month of November to investigate how freeze-up impacts breakup, with no result. Clearly, the estimated flow during an entire month represents a poor indicator of freeze-up intensity as a start, but this was one of the only options available back then. In the current study, freeze-up intensity was linked with the peak water level during or after freeze-up. Even the limited data points presented in Figure 5.2.5 reveal that a relationship exists (note that the axes ranges were kept to 313 m to 321 m for consistency with preceding figures). The identified trend does not mean that water levels in the fall of 1978 could or would have been as high as 317 m in preparation for the 1979 ice jam flood (320.6 m), but it does indicate that the ice cover resistance at Dawson is not only the result of a cold winter or a limited state of degradation in the spring.

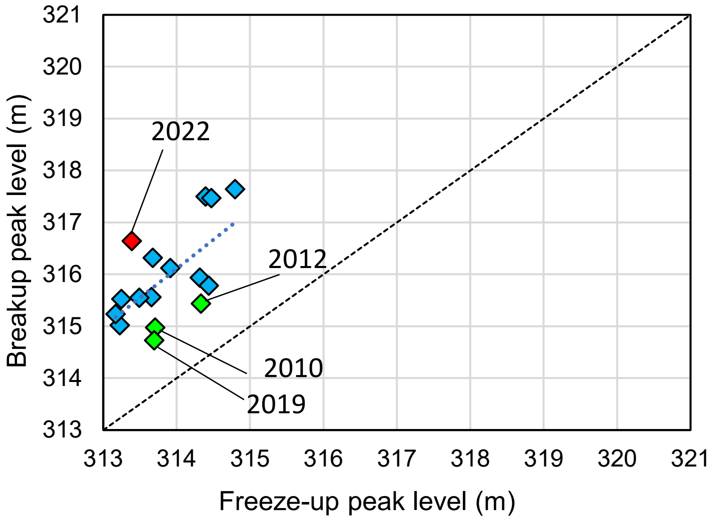


FIGURE 5.2.5. BREAKUP PEAK LEVELS (WATER SURFACE ELEVATION) EXPRESSED AS A FUNCTION OF THE MEASURED FREEZE-UP PEAK LEVEL DURING THE PRECEDING FALL (OR EARLY WINTER) ON THE YUKON RIVER AT DAWSON (STATION 09EB001). ONLY 16 DATA POINTS BETWEEN 1994 AND 2024 WERE AVAILABLE.

Four outliers departing from the identified trend are:

- 2022: This peak breakup water level is higher than what would have been expected from the trend presented in Figure 5.2.5. It is probably influenced by a combination of an average-cold winter and an associated strong ice cover, an early breakup (from an effective degree-days of thaw perspective) with limited potential for ice degradation, a significantly positive SWE anomaly with a high snowmelt potential, a cold month of April, and a relatively sudden and consistent rise in air temperatures prior to breakup.
- 2019: This breakup event followed a very mild winter and a record low snowpack in most tributaries of the Yukon River. There was simply no rise in breakup driving forces, and this represents an excellent example of how the snowpack can restrain breakup intensity in relatively dry areas of Canada.
- 2010: This breakup was thermal, following a very mild month of April with large variations in air temperatures that could have contributed to breaking the momentum of snowmelt.
- 2012: It is difficult to identify the exact reason why water levels remained so low during this breakup event. Melting conditions started relatively early in April (around the 13th), but it is possible that overcast conditions kept snowmelt rates under a critical threshold. The early breakup of the Klondike River seems to also have played a role.

The authors made an attempt to link freeze-up intensity, or associated peak water levels, with late fall or early winter flow at Dawson as well as in tributaries such as the Stewart River (09DD003) and the upper Yukon River (station 09CD001). However, the occurrence of flow instabilities in the fall, and the varying delay between the last reliable flow estimates and the formation of a solid ice cover by ice interception and consolidation (and subsequent peak freeze-up level) at Dawson prevented identification of any meaningful statistical link. Although this disappointing result compares with what Gerard and Stanley (1986) obtained, it could be further explored.

5.3 Breakup indicators at Dawson

The anomalies identified in Figures 5.2.1 to 5.2.5 and discussed in their respective subsections are as important as the trends themselves. They contribute to our understanding of spring breakup on the Yukon River at Dawson and pave the way for the development of a breakup forecast model that relies on accessible and simple but diverse input parameters. The way these parameters are considered in the model can vary. For example, a distinction needs to be made between snowpack in the watersheds upstream of Dawson (a potential driving force indicator) and recent snowfalls that contribute to reducing the albedo of the ice cover surface (a resisting force indicator). Also, there is a distinction to make between a given number of effective degree-days of thaw (for instance, 150) and the stability of air temperatures during the period over which these degree-days have accumulated.

Intense breakup events associated with high water levels at Dawson (above a water surface elevation of 318.0 m at station 09EB001) depend on the occurrence of these conditions:

- A resistant ice cover:
  - ➢ A high freeze-up level (generally above 314 m),
  - ➢ A cold winter (generally characterized by more than 3300°C-days of freezing),
  - ➢ A largely intact ice cover at the onset of breakup resulting from few effective degree-days of thaw (less than 200°C-days) and late-winter snow (a growing snowpack, in terms of SWE, until two weeks prior to breakup).
- A sudden, consistent rise in driving forces:
  - ➢ A positive snowpack anomaly (120% or higher) to maximize the potential for high snowmelt rates, and
  - ➢ A sudden and consistent rise in air temperatures (more than 12°C during the day, often involving sunny conditions, and limited freezing at night) in upstream watersheds, with a consequent consistent rise in runoff rates.

The role of overcast conditions on breakup intensity is two-fold. As described above for 2012, overcast conditions could have contributed to a thermal breakup scenario. This is because overcast conditions, in addition to limiting the rise in air temperatures during the day, tend to reduce snowmelt rates and consequent runoff. However, overcast conditions can also contribute to maintaining an intact ice cover for a longer period in the spring until sunny conditions return. In this case, the snowpack would already be isothermal and ready to melt whereas the ice cover, although also isothermal, would still be resistant (shortwave radiation has a significant effect on the structural integrity of an ice cover). This means that if overcast conditions are followed by sunny conditions, they can actually promote a dynamic (or intense) breakup scenario. This could explain the dynamic breakup of 1998 (Jasek, 1998).

Rain on snow events have not been investigated yet as a potential factor to account for during the breakup period in central Yukon (this possibility is mentioned in a report by Gerard, 1984, while Jasek, 1998, proposed that an unusual rainfall played a role in the 1998 breakup event). Given the lack of historical weather data, this analysis would probably need to be completed using climate reanalysis products and is beyond the scope of this project.

6 Prototype breakup model

6.1. Existing models for Dawson

The model developed by the University of Alberta in the 1980s (Gerard and Stanley, 1986) continues to be used by the Water Resources Branch (WRB) to support forecasting of the timing of breakup at Dawson. It relies on the availability of very accessible hydrometeorological parameters:

- Current rise in local water levels (or stage) at station 09EB001, automatically converted to a dimensionless discharge and corresponding to a breakup drive indicator,
- Current air temperatures, automatically converted to absolute degree-days of thaw and mostly representing a breakup resistance indicator,
- Winter air temperatures, converted to freezing degree-days by the user, and corresponding to a second breakup resistance indicator.

The performance of the model is, on average, adequate, in part because it is largely influenced by the local stage rise during dynamic breakup years. This means that the forecasting role of this model seems to be converted into a detection role when the risk of flooding is above average. “This does not allow much warning”, to quote Gerard and Stanley (1986). Since the stage measured at station 09EB001 remains the main available breakup drive parameter in the Dawson reach of the Yukon River, very few simple alternatives exist.

The main limitation of this model, beyond its small forecast horizon when it is the most needed, is that it overlooks key breakup resistance indicators that prevent it from offering insight about potential breakup intensity (and associated likelihood of ice jam flooding). As stated by Gerard and Stanley (1986), referring to the intensity of winter, “there is surprisingly little difference in ice thickness from year to year”. This, in addition to unconsidered parameters affecting ice deterioration, may explain in part why the model underperformed during the breakup events of 1998 (Jasek, 1998), 2007, 2008, 2010, 2012, 2015, 2016, and 2021 (based on a comparison of forecasted and actual breakup dates). The authors of this report believe that the University of Alberta model should remain part of the set of tools used for breakup forecasting by the WRB, but that it could be recalibrated using breakup data from the last 35 years.

Another prototype, Microsoft Excel-based model was developed in 2019 by the WRB. However, this model is not calibrated yet (for breakup intensity), and it was based on an estimation of the Yukon River discharge using station 09CD001 (Yukon River above White River). The use of this station presents two limitations: 1. This station is too far upstream of Dawson (it overlooks the dominant hydrological and ice contribution of the White River and the Stewart River), and 2. This station is often still affected by the presence of stationary ice when breakup occurs at Dawson (the discharge remains largely uncertain when its estimation is the most needed). The rationale behind this model is defendable (it uses proxies of driving and resisting forces) and it can be improved by considering additional hydrological inputs from tributaries (e.g., the Indian River).

The remaining portion of this section explains the physics behind the newly developed breakup forecast model.

6.2. Breakup indicators

6.2.1 Driving force

Theoretical considerations combined with results presented in Sections 4 and 5 of this report suggest that key breakup drive indicators for the Yukon River upstream of and at Dawson are:

- Late winter and pre-breakup water supply-related indicators:
  - Snowpack at low elevation in upstream watersheds (Lower White River, Lower Stewart River, Sixty Mile River, Indian River, Klondike River)
  - The swiftness or intensity of the onset of spring conditions in upstream watersheds (with above freezing night temperatures, at least at low elevations)
  - Toe occurrence or not of widespread rain-on-snow events in upstream watersheds
- Short-term, dynamic, ice condition-related indicators:
  - Estimated or calculated flows during breakup (higher flows generally produce higher water levels)
  - The occurrence or not of a major ice run from the Stewart River (Km 16)
  - The formation or not of a major ice jam near Km 55, 87, or 110
  - The occurrence or not of a significant ice run from the Klondike River (Km 120)
  - The formation or not of a moderate to intense ice jam at Dawson (Kms 120 to 122)

Note that a temporary return to colder-than-average air temperatures (including freezing at night) can impose a transition from a potentially dynamic breakup scenario to a thermal breakup scenario.

6.2.2 Resisting force

Theoretical considerations combined with results derived from the analyses presented in Sections 4 and 5 of this report suggest that key Yukon River breakup resistance indicators from Dawson and down to 40 km downstream of Dawson are:

- Fall to pre-breakup, ice-related indicators:
  - Maximum water level elevation at freeze-up
  - The existence, or not, of a single or several freeze-up jams (related to flows in the fall or to variations in weather conditions during freeze-up, generally from late October to late November, including intense snowfall events)
  - Late winter average ice cover thickness (associated with winter coldness and dryness)
  - Presence and extent of open water leads after freeze-up (mainly associated with freeze-up patterns) and prior to breakup (maximum ice extent)
- Short-term ice and snow condition-related indicators:
  - Air temperatures during breakup (freeze-thaw cycles, consistent warm conditions, or consistent, local cold conditions)
  - Sky conditions during breakup (i.e., cloud coverage)
  - Ice cover albedo throughout the breakup period (e.g., presence of a thick snowpack, new snow, highly reflective crystals at the ice cover surface, or water on ice)
  - Evolution of open water areas during breakup (e.g., early ice movements)

Unlike driving forces, which generally rise but can also stabilize and even decrease during the breakup period, resisting forces can only decline as breakup progresses (unless an ice jam, which toe would be anchored against the riverbanks or an island, forms downstream of Dawson). Once the ice coverage of the Yukon River has started to decrease (as a result of ice melt, ice movements, and the formation of weak, juxtaposed types of ice jams), the breakup resistance is probably irremediably declining, regardless of weather conditions.

6.3. New model development

The objective of the model is to forecast both the timing and the intensity of river ice breakup in the reach of the Yukon River along which ice conditions can affect water levels in the downtown area of Dawson (Km 123 to 160, approximately, with Dawson located between Km 121 and 123). The prototype version of the model was developed in Microsoft Excel and is based on a diagram presented by Turcotte (2023). It was developed mainly from equations found in the literature (predominantly in Beltaos, 2008). The model ultimately calculates approximate, daily breakup drive and resistance forces using indicators that available to model users. When both forces meet, breakup will occur. The timing of breakup is indicated on the X axis (daily time step) whereas the intensity of breakup is proportional to the forces at play (on the Y axis) through a color index ranging from green (thermal breakup, no flooding) to red (dynamic breakup, flooding possible). The breakup forecast horizon is limited by the accuracy of the weather forecast. Table 6.3.1 presents model inputs and their role or impact for the calculation of the forces (these parameters appear in yellow cells in the model spreadsheet).

The model takes into account several processes (Table 6.3.1) that influence river ice breakup timing and intensity:

- Freeze-up intensity (any value between 0 and 1) and ice cover thickness (cm)
- Ice cover degradation (using shortwave radiation and considering cloud coverage and ice surface albedo, in Watt-days per cubic meter, W d/m^3)
- Ice cover melting (using air temperature indicators, reduction calculated in m)
- Weight of the ice cover in the downstream direction (in kilo Pascals, kPa)
- Shear stress associated with varying flow velocities (kPa)
- Modification of the shear stress (Manning's n, surface slope and ice thickness) caused by the presence of local ice jams and the release of upstream ice jams (occurrence of javes)

The ice cover resistance is expressed in mega Newtons (MN) whereas the shear stress and downstream component of the ice cover and ice jam is expressed in kPa. The conversion of the driving shear stress into a driving force (MN) is completed using the Boundary Constraint Criterion (Beltaos, 2008, equation 6.10, which takes into account the channel curvature) and then multiplied by the area of the intact ice cover (including at the toe of an ice jam that would form at or downstream of Dawson).

TABLE 6.3.1. PARAMETERS USED IN THE BREAKUP MODEL WITH THEIR CORRESPONDING ROLE

Parameter	Source	Physical role/impact
Freeze-up intensity (e.g., stage rise, freeze-up jams) **(optional)**	WSC station 09EB001, reported observations	Affecting ice thickness t_{ice} calculation if ice thickness is not measured
Late winter ice thickness t_{ice} **(optional)**	WSC, reported observations	Used to calculate resisting forces
Maximum cumulative degree-days of freezing $CDDF_{max}$ **(optional)**	ECCC station 2100407	Used to calculate ice thickness using CDDF if ice thickness s not measured
Maximum daily air temperature $T_{air\ max}$	ECCC station 2100407	Used to calculate effective cumulative degree-days of thaw (ECDDT) and the ice cover thickness reduction (melt; $t_{ice\ red}$). It also impacts an ice degradation threshold.
Minimum daily air temperature $\mathrm{T}_{\mathrm{air\ min}}$		
Observed cloud coverage $Cloud_{obs}$ **(optional)**	Sentinel-2, Km 120 to 160	Reduces shortwave radiation (SW_{net}) affecting ice cover integrity, or strength.
Observed open water ratio *OW*	Sentinel-2, Km 120 to 160	Affects shortwave (*SW*) absorption
Observed, spatially averaged, ice cover surface albedo $Albedo_{ice}$	Sentinel-2, Km 120 to 160	Controls shortwave radiation (SW_{net}) absorption by the ice cover, affecting its integrity, or strength.
Water level at Dawson Y	WSC station 09EB001	Used to estimate the discharge (*Q*) and the backwater (*BW*). This ultimately impacts the calculation of the flow velocity (*U*), and shear stress.
Ice-induced water level variations at Dawson Y_{rises} **(when occurring)**		
Last winter discharge (*Q*) measurement in the Yukon River near Dawson	WSC station 09EB001 or NHS Hydrological North (contact at ECCC for historical WSC data)	Used to estimate the April 1 ice-induced backwater (*BW*)
Water level (*Y*) during the last winter flow measurement		
Confirmed or anticipated presence and intensity of ice jams at Dawson *Loc. Jam* **(when occurring)**	WSC station 09EB001, Sentinel-2, local observations, informed anticipation	Used to correct the water column (Y_{wcol}) and weight of the ice and impacting the Manning's *n* for the calculation of the shear stress and driving force (F_d).
Occurrence and potential intensity of waves induced by upstream ice movements *Jave* **(when occurring)**		Used to alter the channel surface slope and average flow velocity, impacting the shear stress and the driving force (F_d).

The model relies on several physics-based empirical equations and calibration parameters or values. These parameters and equations include:

- An air temperature correction ($T_{air\ corr}$) to calculate effective cumulative degree-days of thaw (*ECDDT*), which varies with the date (sun angle and day duration)
- An approximate ice thickness (if measurements or estimates are not available), using the Stefan equation and a parameter α calibrated at 0.018
- An estimated cloud coverage ($Cloud_{emp}$) based on daily air temperature variations and calibrated using Sentinel-2 imagery (cloud coverage observations, to be used when $Cloud_{obs}$ are not available). Clouds had been outlined by Jasek (1998) as an important factor controlling breakup.

- Absorption of shortwave radiation by the snow at the ice cover surface for highly reflective cover values (high $Albedo_{ice}$)
- An initial value of ice cover resistance to degradation (MJ/m^3) and a rate of degradation based on Bulatov (1970), with modifications.
- An approximate open water rating curve for Dawson in the form of $Y = a\ Q^b + c$ where Y is the water level, Q is the estimated discharge and a,b,c, are empirical parameters.
- The backwater (*BW*) induced by the presence of an ice cover or an ice jam with an initial value estimated using a measured discharge and stage (generally at the end of winter).
- An estimated, average flow velocity U under the ice cover (or under an ice jam).
- An ice cover Manning's n roughness that considers the freeze-up intensity, the presence of an ice jam, as well as the ice cover melt at the ice-water interface.
- A channel gradient (*Slope*, initially estimated to 0.05%) that takes into account the occurrence of ice jam release waves (javes) of varying intensities (this proportionally increases the driving force).

As currently calibrated, the most sensitive parameters affecting the breakup resisting force are the pre-breakup ice thickness (either measured, estimated, or empirically calculated) and the surface albedo (evolving over time and determined by the user, refer to Appendix B for examples from the Yukon River). On the other hand, the most impactful parameters affecting the breakup driving force are the presence (or expected formation) of a local ice jam and the occurrence (and expected occurrence) of ice jam release waves (javes, unsteady aspect of the model), both of which are also defined by the user based on judgment and experience. Table 6.3.2 presents a guide for determining the values of these parameters for current and future, short-term conditions.

TABLE 6.3.2. RANGE OF VALUES AND ASSOCIATED INDICATORS FOR LOCAL ICE JAMS AND JAVES

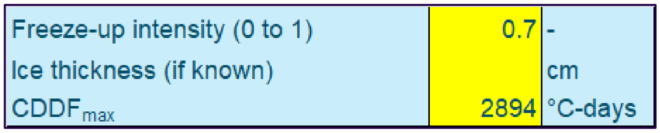
Parameter	Indicator/observations	Value range
Local ice jam (Loc. Jam)	Intact ice cover or no ice movement (only in-situ melting)	0, default
	Juxtaposed ice jam at the Klondike River delta, limited stage rise	0.1 – 0.2
	Weak ice jam in front of Dawson, ice floes not significantly impacting the vegetation along the dike, backwater in the order of 1 to 2 m	0.3 - 0.4
	Moderate ice jam in front or downstream of Dawson, damage to vegetation along the dike, backwater in the order of 2 to 3 m near the jam toe	0.5. – 0.7
	Major ice jam in front or downstream of Dawson, possible flooding, backwater above 3 m near the jam toe	0.8 – 1.0
Jave	No ice movements upstream of Dawson, stage signal is smooth	0, default
	Some ice movements upstream of Dawson, ice run from Indian River, open water sections shorter than 5 km, ice coverage generally above 80%, water level fluctuations in the order of 0.1 m	0.1 – 0.2
	Presence of small to moderate ice jams in the Yukon River above Dawson, open water segments extending beyond 5 km, ice coverage above 70% in most segments downstream of Stewart River, water level fluctuations in the order of 0.2 to 0.5 m	0.3 - 0.4
	Presence of large ice jams between Km 55 and 120, full concentration ice runs in the system, stage fluctuations in the order of 0.5 to 1.0 m	0.5 – 0.7
	Major, impeded ice run travelling towards Dawson, worst scenario	0.8 – 1.0

6.4. Example of model use – Spring 2023

The prototype of the model was developed using data from spring 2020. Several parameters were then adjusted and calibrated using breakup data from spring 2019, 2021, and 2022. A final test was performed on the model using data from 2023. This section presents an example of the use of the model for spring 2023.

6.4.1 Setting the model on April 1

It was known that freeze-up (fall of 2022) had been relatively dynamic with several freeze-up jams reported downstream of Dawson. A value of 0.7 was proposed for freeze-up intensity (this value could have been 0.6 or 0.8, and this would not have had a great impact on the model results). The maximum cumulative degree-days of freezing at Dawson airport ($CDDF_{max}$) ended up reaching 2894°C-days.



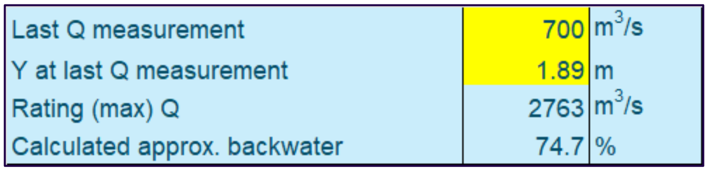
Freeze-up intensity (0 to 1)	0.7	-
Ice thickness (if known)		cm
$CDDF_{max}$	2894	°C-days

This combination led to an initial, average ice cover thickness (t_{ice}) estimated to 1.17 m.

The winter period ended with an ice cover albedo ($Albedo_{ice}$) of 0.9 (white cover with fresh snow) as well as an open water ratio (OW_{ratio}) of 2% (Figure 6.4.1 shows a Sentinel-2 image with about 1% open water near Dawson and about 3% open water downstream of town). The exact value for OW_{ratio} is not critical, as long as open water areas are assessed as accurately as possible.

FIGURE 6.4.1. COPERNICUS SENTINEL-2 IMAGE (HIGHLIGHT OPTIMIZED NATURAL COLORS) FOR APRIL 2, 2023, WITH MINOR OPEN WATER AT THE KLONDIKE RIVER DELTA AND NEAR MOOSEHIDE.

The initial water level was 1.55 m at station 09EB001 (elevation of 313.47 m), and the initial ice cover backwater effect (*BW*) was set to 75% based on a discharge (Q) measurement of about 700 m^3/s at a stage of 1.89 m (313.81 m) completed by the Water Survey of Canada in March 2023 (it was assumed that this value did not change significantly over the month of March, which is generally the case based on a study performed by Turcotte (2022)).



Last Q measurement	700	m^3/s
Y at last Q measurement	1.89	m
Rating (max) Q	2763	m^3/s
Calculated approx. backwater	74.7	%

This gave an approximate April 1 discharge of 584 m^3/s. The driving force (F_d) on the ice cover near Dawson was calculated to be 3.3 MN compared with a resisting force (F_r) of 41 MN.

6.4.2 Conditions on May 5

River conditions started to change faster near May 5, 2023. Based on remote and local observations (sample shown in Figure 6.4.2), the cloud coverage ($Cloud_{obs}$) was set to 20% to account for the high-level cloud visible in the area. The value for OW_{ratio} was set to 4% (combining some 5% downstream of Dawson and 3% in front of Dawson). The $Albedo_{ice}$ was set to 0.8 (some grey ice, but still mostly snow covered).

FIGURE 6.4.2. COPERNICUS SENTINEL-2 IMAGE (HIGHLIGHT OPTIMIZED NATURAL COLORS) FOR MAY 5, 2023, WITH GROWING OPEN WATER AREAS AT THE KLONDIKE RIVER DELTA AND BELOW MOOSEHIDE.

Between May 4 and May 6, the ice cover was losing about 10% of its strength every day, and the residual F_r was evaluated to 31 MN on May 5. In turn, the stage at station 09EB001 was 2.1 m (314.02 m, with no correction yet to account for local ice movements and BW adjustments), and this translated into a discharge estimated to 980 m^3/s. No significant water level variations caused by upstream ice movements were reported and the values for local ice jams (Loc. Jam) and ice jam-release waves (Jave) were still 0. Therefore, the value of F_d remained low, at 4.3 MN.

6.4.3 Conditions on May 9 (breakup day)

On May 9, 2023, $Albedo_{ice}$ at and downstream (over 40 km) of Dawson was estimated to 0.65, given its darkness and the absence of residual snowpack on the ice cover in most river segments (Figure 6.4.3). OW_{ratio} had risen to 9% (8% in front of Dawson and 10% downstream of Dawson) and the $Cloud_{obs}$ was set to 60% as an average for the day (generally overcast, but mostly-high and mid-level clouds). The residual resistance (F_r) of the ice cover was 21 MN (from a combined 20% reduction in ice thickness and 63% reduction in ice cover strength).

FIGURE 6.4.3. ICE COVER (WITH MINOR ICE JAM) NEAR KM 134 OF THE YUKON RIVER ON MAY 9, 2023. THE PRESENCE OF WATER ON ICE, DARK-DRY ICE, AND SOME SNOW-COVERED ICE COVER SECTIONS TRANSLATE INTO A REDUCED ICE COVER ALBEDO ESTABLISHED OF 0.65.

In terms of breakup drive, the flow was now estimated (Q_{est}) at near 3000 m^3/s (stage of 3.78 m – 315.70 m – with a -0.16 m cumulative correction to account for the downstream (Moosehide) release of the ice cover). This alone would not lead to breakup as F_d would still be at about 10.8 MN. However, the presence of a small ice jam at the Klondike River delta (*Loc. Jam* = 0.2, Figure 6.4.4) combined with an advancing ice front located at Km 90 (location of the ice jam toe near mid-day, Figure 6.4.5, *Jave* potential set to 0.3) translated into a F_d of 24.1 MN, just enough to cause breakup at and past Dawson if that ice run would materialize (rather than causing a jam upstream of Dawson).

FIGURE 6.4.4. TOE OF A COMBINED KLONDIKE RIVER (DARKER) AND YUKON RIVER (LARGER ICE SLABS) ICE JAM AT DAWSON ON MAY 9, 2023, AROUND 2 PM.

FIGURE 6.4.5. TOE OF AN ICE JAM NEAR KM 90 OF THE YUKON RIVER AT 2 PM ON MAY 9, 2023 (LOOKING DOWNSTREAM).

The value for Jave was not set higher on that day because ice jams were relatively short, which means that they would not carry a significant amount of energy if/when they reached Dawson.

Breakup occurred at 5:30 pm on that day and was largely caused by the release of a large ice run from the Stewart River several hours earlier. It took two more days for the breakup front to move past the Forty Mile River, where a major flood was reported. By then, the flow was probably in the order of 4000 m^3/s. Based on Gerard et al. (1992), if an ice jam had still been in place near Dawson, flooding could have resulted.

6.4.4 2023 model results

Figure 6.4.6 presents the results of the model, based on information acquired after the event (the model was created in 2024). It seems to successfully predict the timing (May 9) and intensity (yellow to orange background) of the breakup event on the Yukon River. Model users will understand that most input parameters used to feed the model cannot be known in advance with great certainty. For instance, on May 5, only the weather forecast ($T_{air\ max}$, $T_{air\ min}$, Cloud$_{\text{obs}}$) is available for the next five days. However, values for other key parameters can be proposed:

- There was no snow in the forecast, therefore $Albedo_{ice}$ could only drop (a rate of -0.05 every 24 to 48 hours is generally reasonable under sunny conditions once most of the ice cover is no longer protected by a snow layer).
- The rise in stage can be anticipated by foreseeing the flow rise, both of which often follow an exponential trend under consistently warm conditions. Flows from tributaries that have already been affected by breakup can also be used to determine flow trends at Dawson.
- Values for *Loc. Jam* and *Jave* can be tested for sensitivity. Once the ice coverage in upstream reaches starts to decline and ice jams occur in the system, values greater than 0 should occur. Table 6.3.2 can be used to test reasonable or conservative values for those parameters.

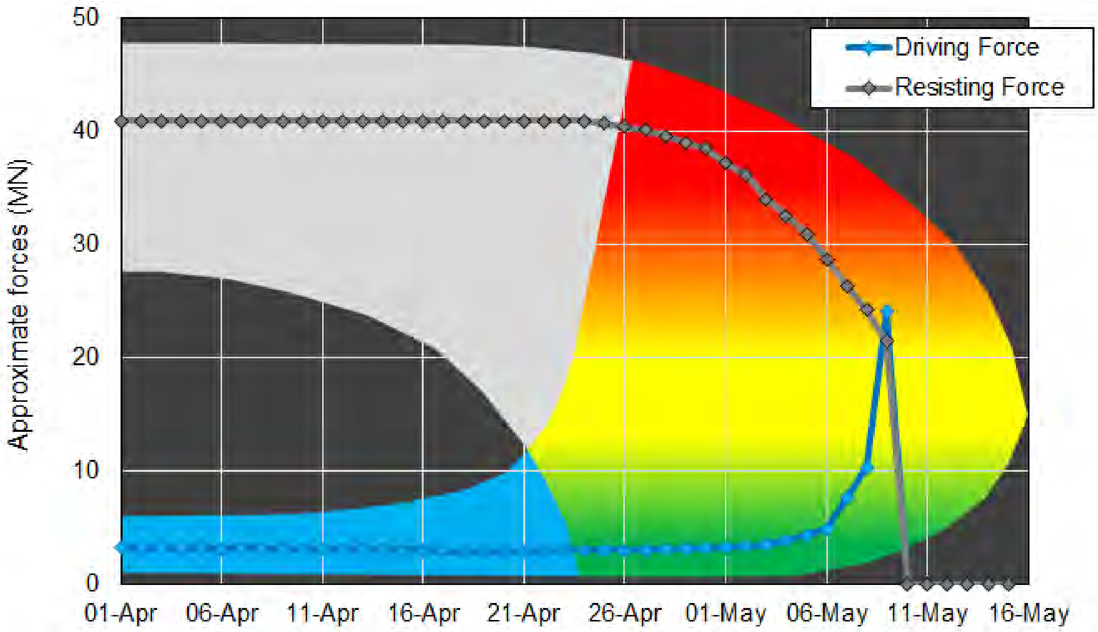


FIGURE 6.4.6. MODEL RESULTS FOR THE 2023 BREAKUP EVENT. THE COLORED AREA REPRESENTS POSSIBLE BREAKUP TIMING AND INTENSITY, BASED ON DOCUMENTED HISTORICAL EVENTS AND THEORETICAL CONSIDERATIONS.

In summary, the resisting force (F_r) in the model is probably more predictable than the driving force (F_d) because it generally declines gradually. F_d, through *Loc. Jam* and *Jave*, is more volatile, but this is exactly how nature behaves: No model can predict the exact timing of breakup many days in advance on the Yukon River at Dawson (or any other unregulated river) because it depends on the sum of multiple, compounding upstream hydrological processes (taking place in a multi-channel context).

The model was tested during the thermal breakup event of 2024 and performed adequately. However, the persistence of the ice front below Dawson (between Km 125 and 160) represented a challenge for the model. The accuracy and user friendliness of this prototype could still be improved. This is discussed next.

7 Summary and recommendations

Historical data and observations were analyzed to understand the spatial and temporal aspects of river ice breakup on the Yukon River near Dawson. Sections 4 and 5 of this report introduced important interpretations and concepts that can support strategic breakup monitoring and forecasting activities, including identifying if and when Government of Yukon breakup flight surveys should begin. Section 6 presented the first version (prototype) of a semi-empirical model to forecast the timing and intensity of river ice breakup on the Yukon River at Dawson.

The following list of recommendations will help improve current knowledge and future model upgrade phases:

- Continue (post-2024) analyzing freeze-up, mid-winter and breakup related information, emphasizing the position of freeze-up consolidations, the origin of ice runs, and the location and extent of spring breakup ice jams between Km 15 and Km 220,
- Building relationships with Tr’ondëk Hwëtch’in citizens to enhance knowledge sharing about the fall freeze-up and spring breakup dynamics along the Chu kon’ dëk, ultimately improving our shared understanding of breakup patterns and processes,
- Produce a high-accuracy river profile of the Yukon River from Km -20 (upstream of the White River) to Eagle, Alaska, using the SWOT (now fully operational) in order to identify steeper and flatter segments of the Yukon River, which would help explain the location and resilience of breakup ice jams,
- Improve the reliability of station 09EB001 during the freeze-up and breakup period. This could be done by protecting air lines from river ice impacts (freezing, ice movements, and ice runs) as well as by testing and adopting complementary monitoring equipment. Historical notes about freeze-up levels could also be consulted.
- Measure the late winter ice thickness at several locations along the Yukon River between Km 120 and Km 160 to investigate the link with winter meteorological conditions with the goal of improving the empirical approach adopted in this version of the model.
- Measure the under-ice flow of the Yukon River prior to breakup, generally in early April (when the ice bridge is in place, it can probably safely be used, and this could be organized through communications with the Department of Highways and Public Works),
- Investigate the role of rain-on-snow events during the breakup period using different sources of information, including climate reanalysis products,
- Reconstruct breakup hydrographs and compare the combined stage and discharge with the theoretical, hydrodynamic, steady-state approach developed by Gerard et al. (1992),
- Improve RCM and Sentinel-1 ice maps by adjusting the backscatter classification to clearly differentiate the presence of ice jams and open water (these products are probably not reliable until some ice jams have formed in the river system),
- Fly the Yukon River during years where breakup is expected to be moderately to highly dynamic between Km 15 and 160, at least. This especially applies to overcast days and when Sentinel-2 is not collecting visible imagery over the region (interestingly, this was also recommended by Gerard et al. back in 1992).

Possible improvements of the prototype model would include:

- Using a representative (as opposed to synthetic) river cross section to obtain a more accurate estimation of the under-ice velocity during the breakup period (i.e., using the recent work completed to create flood maps for Dawson),
- Including the length of local ice jams in the calculation of the average Manning's n and average ice cover thickness (downstream component of the weight of the ice),
- Shifting from a backwater approach to a Manning approach to determine the rise in discharge during the breakup period,
- Adding a module that enables users to directly impose a discharge forecast into the model as a complement to a projected stage combined with an ice-affected rating curve (assuming that a hydrological model will eventually be tested during the breakup period),
- Developing an empirical equation that would complement or replace the Boundary Constrain Criterion (Beltaos, 2008) that is currently considering meander bends as a limitation to breakup, but that is ignoring variations in channel width or the presence of islands as factors influencing breakup sequences.
- Developing an equation that accounts for a rise in breakup resistance at the toe of an ice jam that would be partially supported by the channel banks (or grounded on a sill).
- Introducing conservative (i.e., overpredicting) and less aggressive (e.g., underpredicting) trends that could be defined by the user to develop a reasonable range of breakup forecasts.
- From a hydrodynamic and theoretical perspective, testing the applicability of Figure 7.6 in Beltaos (2008) to evaluate the accuracy of predicting a water depth in the presence of an ice jam as a function of the estimated discharge in the Dawson reach of the Yukon River.

These changes should not greatly increase the complexity the model, nor should they impose an additional dimension to its structure (it can currently be considered a 0D model or a single location 1D model). The model will still require the judgement and experience of users, who will in turn benefit from it as a learning tool.

As stated in Section 6.1, it would also be reasonable to dedicate resources to recalibrating the University of Alberta model (Gerard and Stanley, 1986) that has been used by the Water Resources Branch for decades. Other, complementary empirical or physics-based models could also be developed in a later phase of the project (refer to conditions defined in Section 6.2).

8 References

Beltaos, S., 2013. River Ice Formation. Committee on River Ice Processes and the Environment CGU-HS, Edmonton, AB, Canada.

Beltaos, S., 2009. River Ice Breakup. Highlands Ranch, Colorado: Water Resources Publications, LLC.

Bulatov, S.N., 1970. Calculating the strength of ice cover at the beginning of wind activated ice drift. Trudy Vypysk 74, Gidrometeorologisheskoye Izdatel'stvo, Leningrad. Translated by US Army CRREL, IR 799, 120 p.

EO Browser (2024). Sentinel Hub by Planet Labs. Accessed Aug 2023 to Nov 2024. https://www.sentinel-hub.com/explore/eobrowser/

Gerard, R., Stanley, S., 1986. A Preliminary Appraisal of Meteorological and Streamflow Effects on Break-up, Yukon River at Dawson. Report prepared for Indian and Northern Affairs Canada. University of Alberta, Edmonton, Alberta.

Gerard, R., Jasek, M., Hicks, F., 1992. Ice Jam Flood Assessment – Yukon River at Dawson. Report prepared for Indian and Northern Affairs Canada. University of Alberta, Edmonton, Alberta. 171 p (including addendum from 2022).

Janowicz, J. R., 2010. Observed trends in the river ice regimes of northwest Canada. Hydrology Research, 41(6), 462–470.

Jasek, M., 1998. 1998 Break-up and Flood on the Yukon River at Dawson - Did El Nino and Climate Change Play a Role? 14th International Symposium on Ice, Potsdam, New York. July 27-31.

Jasek, M., Muste, M., Ettema, R., 2001. Estimation of Yukon River discharge during an ice jam near Dawson City. Can. J. Civ. Eng. 28: 856-864.

Jasek, M., Beltaos, M., 2008. Ice-Jam Release: Javes, Ice Runs and Breaking Fronts. In: S. Beltaos (ed.): River ice Breakup. Water resources publications, Highland Ranch, Colorado.

Klohn Leonoff Consulting Engineers, 1986. Dawson City Dyke Improvements. Report on Preliminary Design and Economic Analysis. 87 p.

Kovachis, N., Burrell, B., Huokuna M., Beltaos S., Turcotte B., and Jasek, M., 2017. Ice-jam flood delineation: challenges and research needs. Canadian Water Resources Journal, 42(3):258–268.

Turcotte, B., 2023. Defining design ice jam water levels in rivers of northwestern Canada: limitations and recommendations. 22nd CGU-HS CRIPE Workshop on the Hydraulics of Ice-Covered Rivers. Canmore, Alberta, Canada, July-9-12.

Turcotte, B., 2022. Improving winter discharge estimates, Phase II – proposed new procedure and proof of concept. Presented to the National Hydrological Services, Meteorological Services Canada. Prepared by the YukonU Research Centre, Yukon University, 57 p.

Turcotte, B., 2020. Will there be an ice bridge this winter? Predicting spatio-temporal freeze-up patterns along the Yukon River, Canada. 25th IAHR International Symposium on Ice. Trondheim, Norway. Nov 23-25.

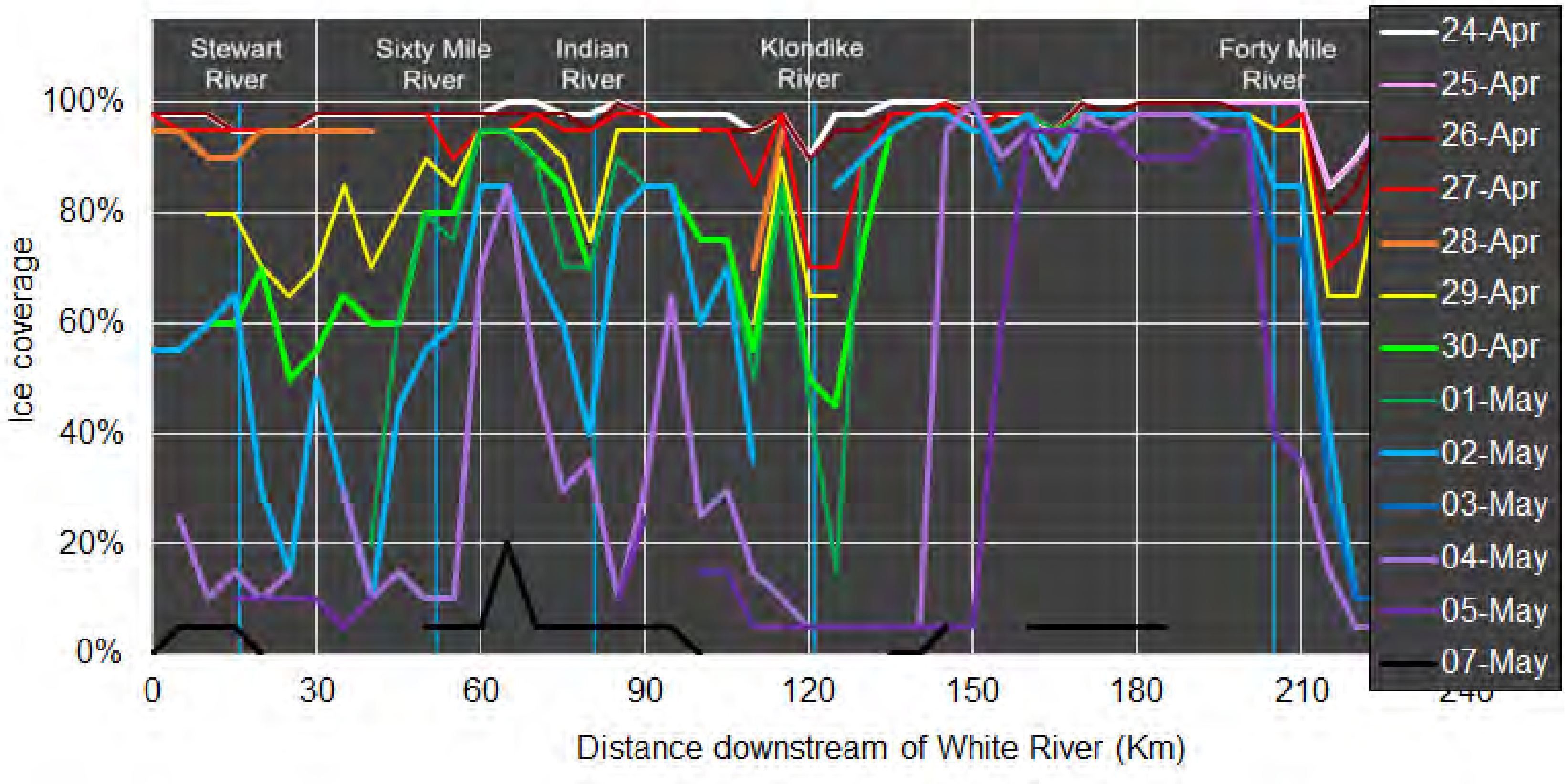
Turcotte, B., Rainville, F., 2022. A new winter discharge estimation procedure: Yukon proof of concept. 26th IAHR International Symposium on Ice. Montréal, Canada. June 19-23.

Turcotte, B., Saals S., 2022. Flooding in Dawson City: exposure analysis and risk reduction recommendations. Whitehorse: Presented to the Infrastructure Branch of the Department of Community Services, Government of Yukon. Prepared by YukonU Research Centre – Climate Change Research, 90 p.

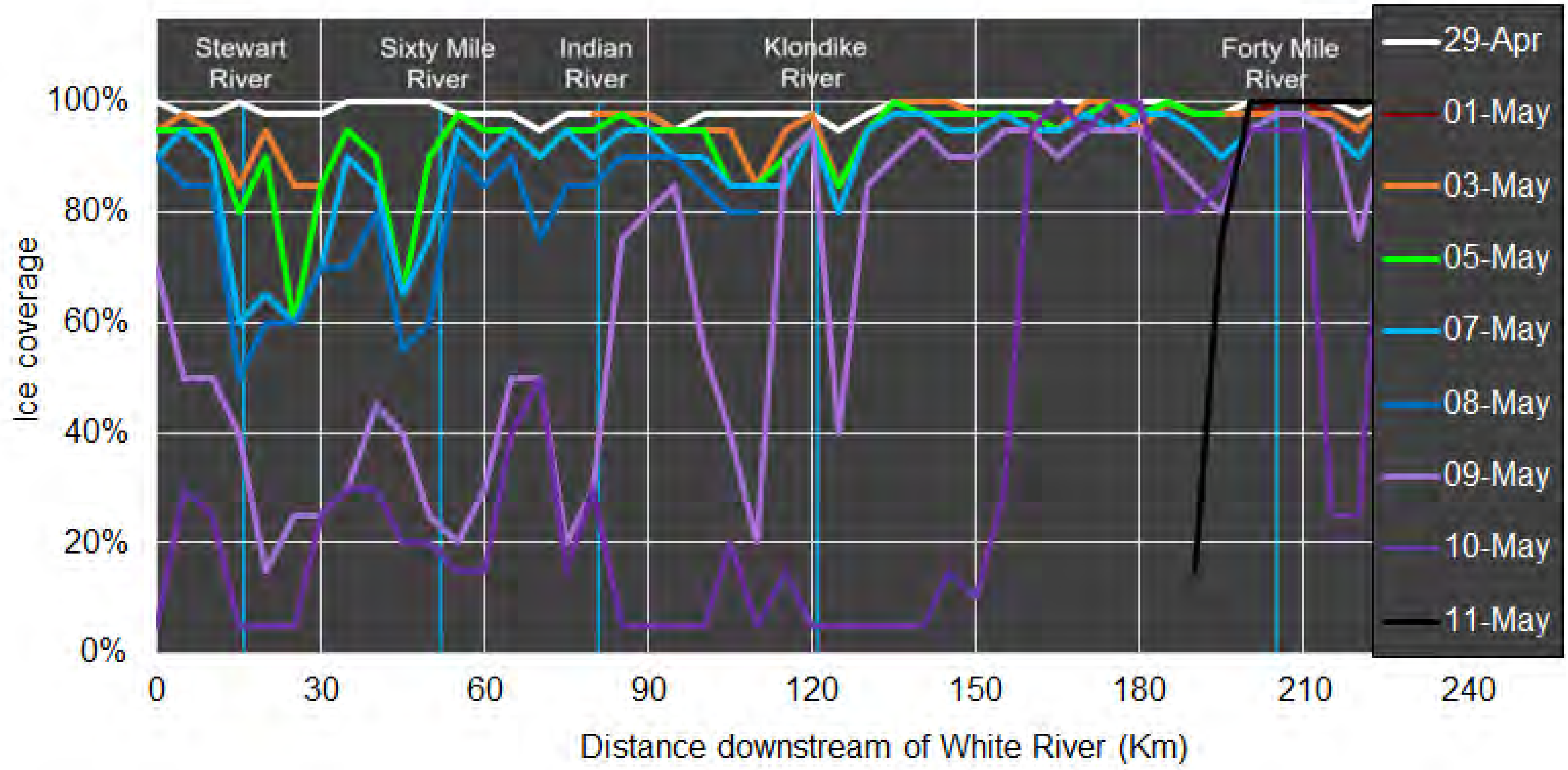
White, K.D., 2008. Breakup Ice Jam Forecasting. In S. Beltaos (ed.): River ice Breakup. Water resources publications, Highland Ranch, Colorado.

Appendix A:

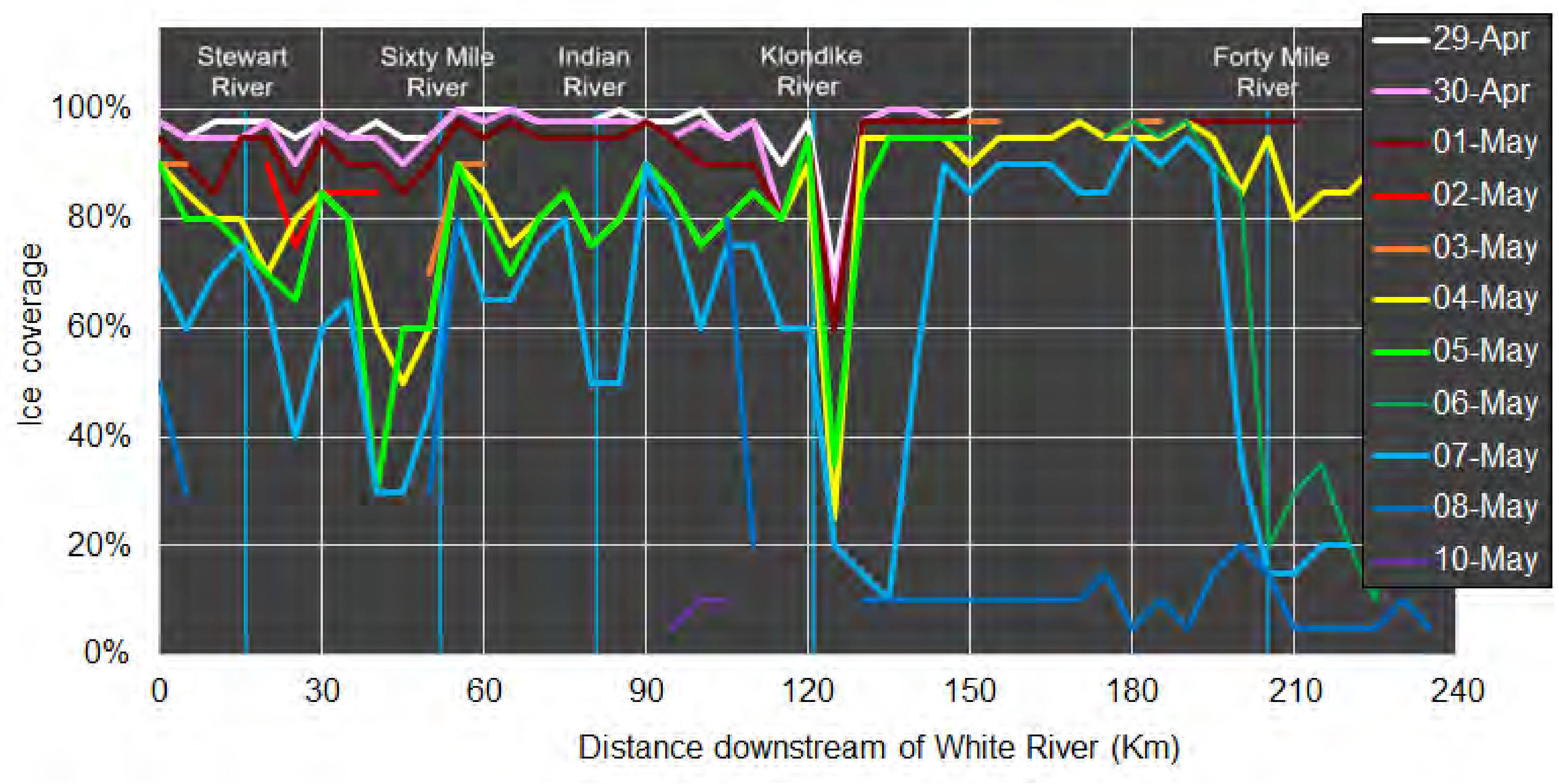
Cryograph from spring 2024.



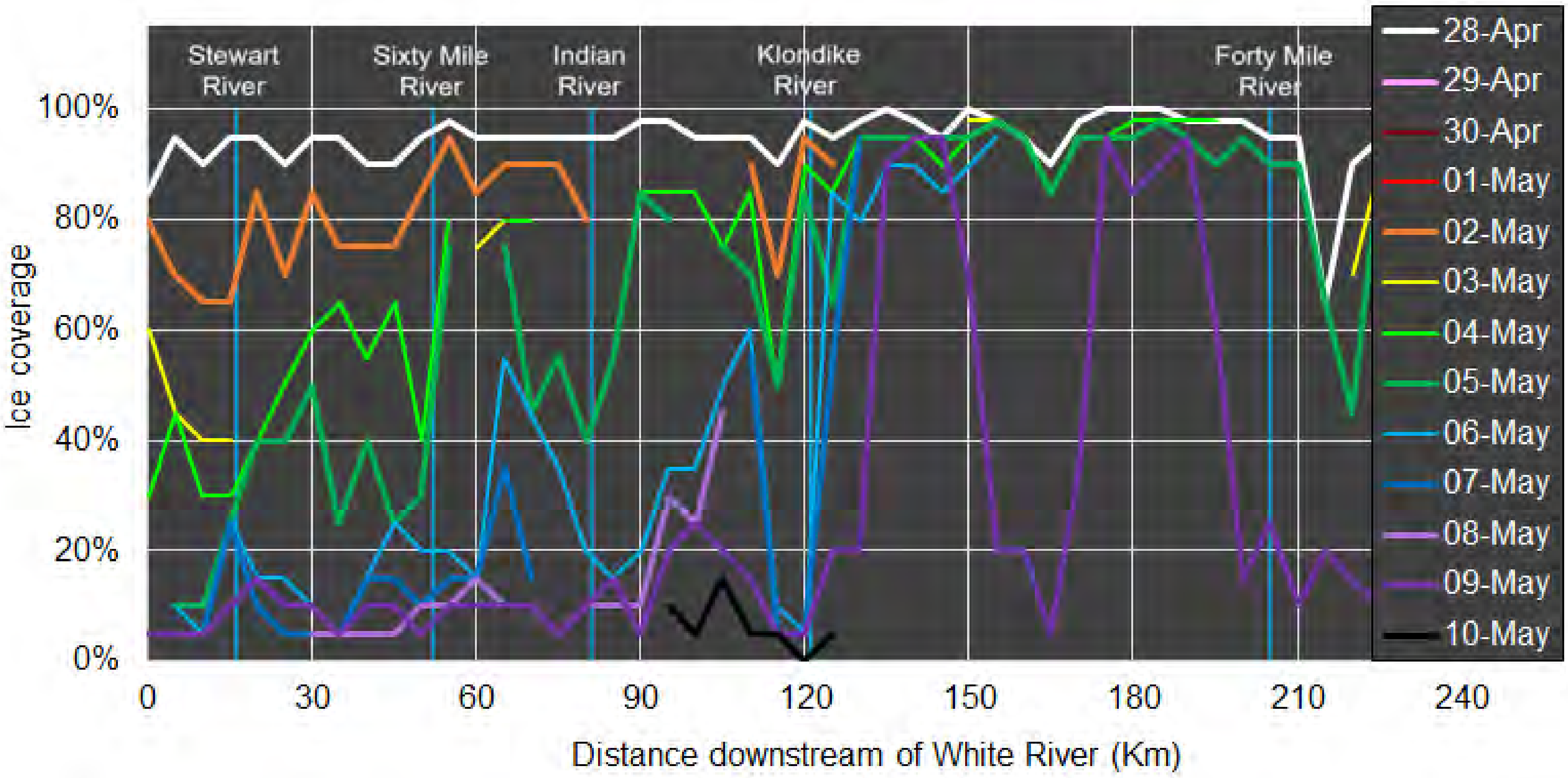
Cryograph from spring 2023.



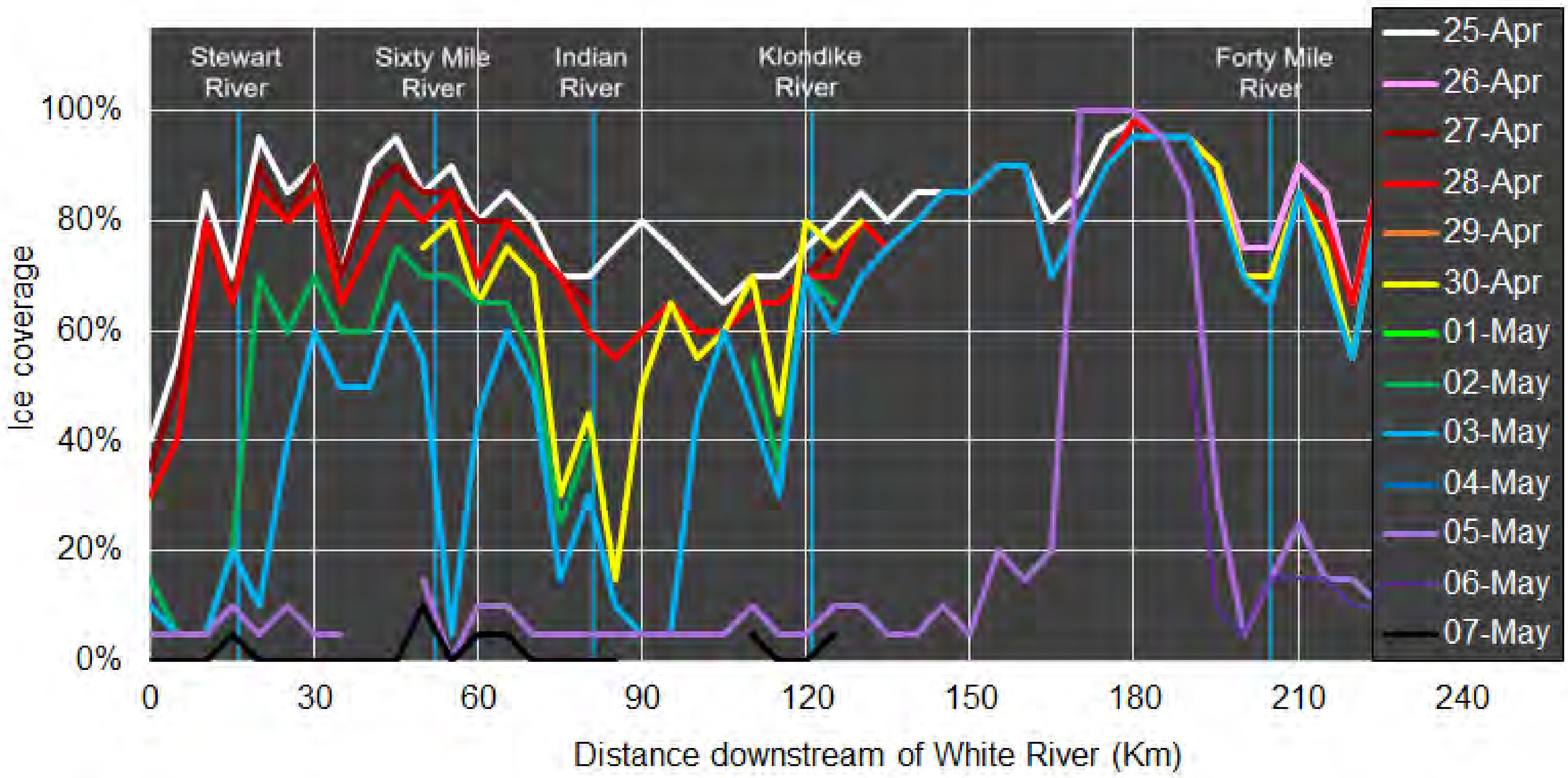
Cryograph from spring 2022.



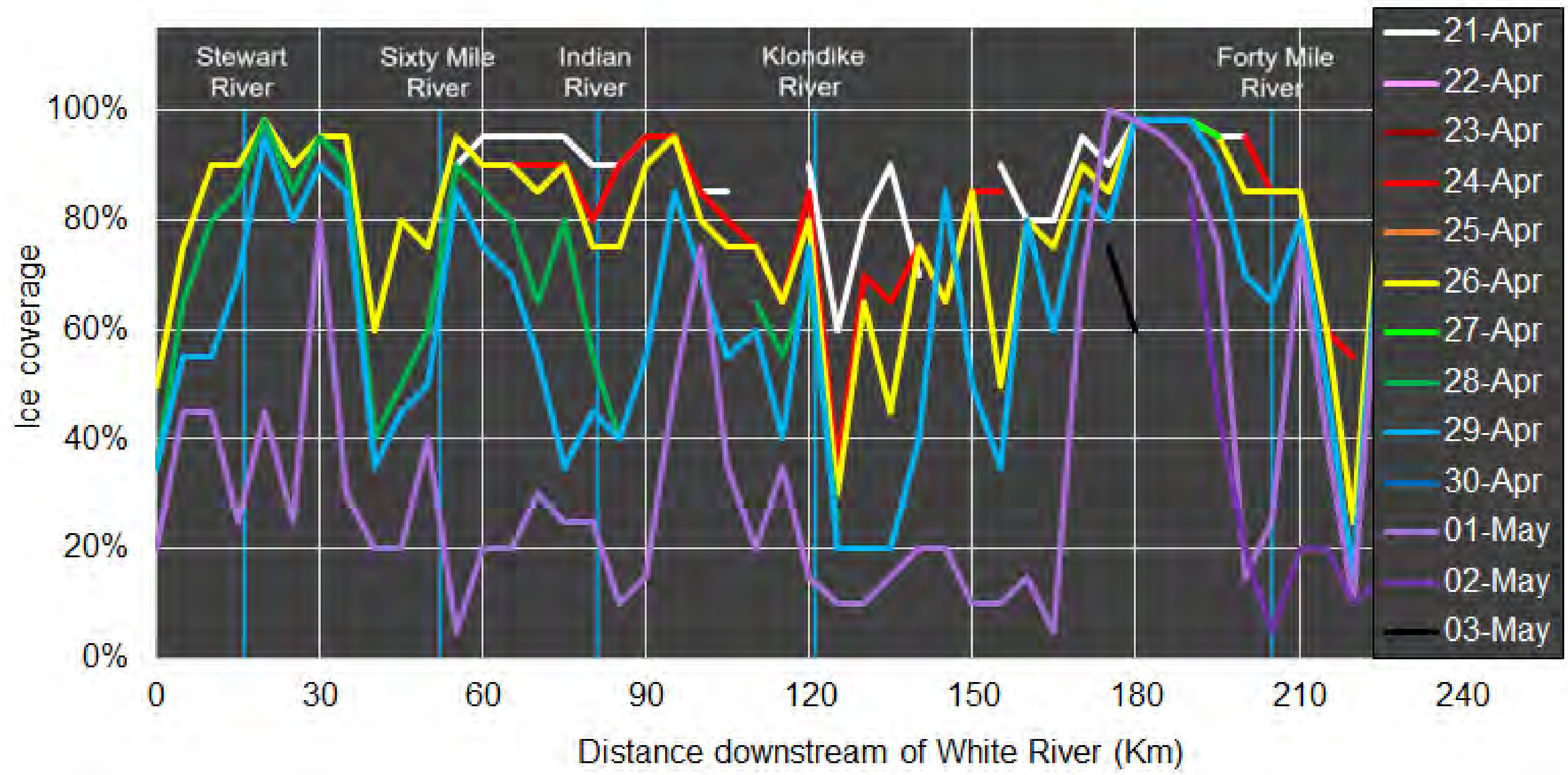
Cryograph from spring 2021.



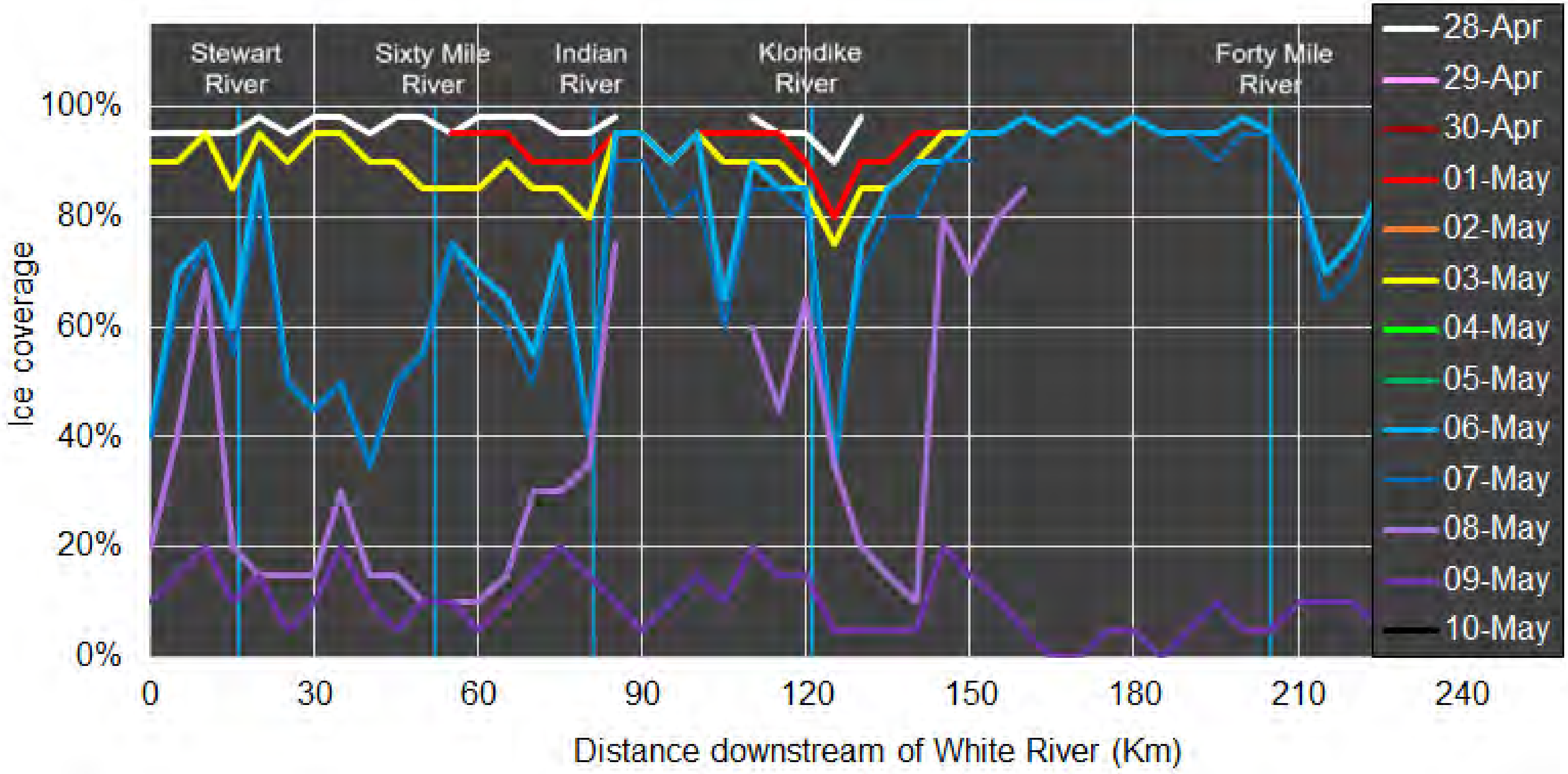
Cryograph from spring 2020.



Cryograph from spring 2019.



Cryograph from spring 2018.



Appendix B

The following Copernicus Sentinel-2 images (using the Highlight Optimized Natural Color filter) can be considered as a guide to determine the albedo of the ice cover surface on the Yukon River during breakup.

Albedo of about 0.9

Albedo of about 0.8

Albedo of about 0.5 (ice cover only)