Yukon University

Developing new river ice breakup forecasting tools in the Yukon - Porcupine River at Old Crow

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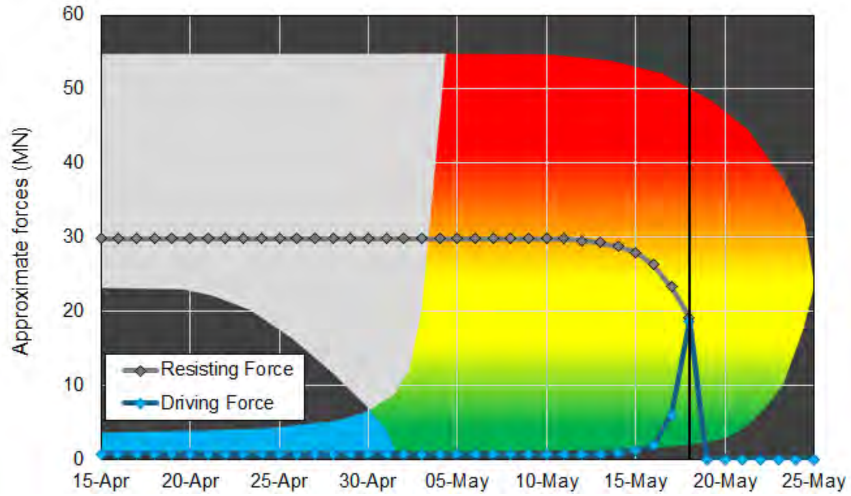
Executive Summary

The objective of this project is to develop knowledge about river ice breakup patterns and controls as well as to present a prototype model to forecast the timing and intensity of spring breakup in the Porcupine River at Old Crow. In addition to information found in key publications, observations from seven years (2018-2024) were examined to update existing knowledge about breakup patterns and up to 38 years (1987-2024) of data were analyzed to improve our understanding of breakup driving and resisting parameters along 240 km of the Porcupine River.

Results from Section 4 reveal the existence of dominant breakup ice jam locations along the Porcupine River, with positive (upstream ice storage) and negative (high local water levels) impacts for Old Crow (Figure 4.1.1). Some ice jam locations correspond to freeze-up consolidation sites (Figure 4.2.1). Ice cover segments of different strengths are identified (Figure 4.4.1) to better explain breakup patterns. The hydrological role that tributaries play during breakup is also investigated (Section 4.3). This research supports previous findings stating that the ice cover upstream of the Bell River (and more specifically 30 km upstream of that confluence) has not historically contributed to ice jam floods in Old Crow. However, this leaves up to about 150 km of river length that contribute to form ice jams potentially affecting the community. Typical breakup patterns of the Porcupine River are presented in Section 4.5.

Section 5 presents a review of parameters that could theoretically influence the timing and intensity of spring breakup in the Porcupine River. Undoubtedly, the lack of consistently available weather and hydrological data (spatially and over time) affected the correlations, on top of the complexity of interacting controls influencing both breakup drive and/or resistance. The most significant anomaly of the dataset is associated the breakup of 1991, which is unfortunately the most significant ice jam flood on record. Results of this analysis are summarized in Section 5.3.

The prototype version of the model developed in Excel is described in Section 6, including the simulated processes and the list of input parameters. An example of its use is presented for 2020, and results for 2024 are presented below. This 0D model uses physical and empirical equations to evaluate breakup driving and resisting forces at a daily time step. Breakup timing is indicated on the x axis whereas breakup intensity is presented on the y axis, and on a colour scale.



Section 7 presents recommendations to support future knowledge and model development.

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This project is taking place in the heart of the Traditional Territory of the Vuntut Gwichin First Nation. The authors would like to thank Paul Josie and William Josie who have provided information about river conditions in the last several years. It is the authors' intention to continue improving our level of collaboration with Vuntut Gwithin people and their government. Our worldviews about water connect through respect for, and admiration of, the Ch'oodeenjìk and its tributaries.

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1. Introduction

The Ch’oodeenjìk (Porcupine River) is the northernmost large river in the Yukon. It is also the most dynamic from a hydrological perspective. During the summer, it responds quickly to rain events. As winter transitions into spring, its flow can be multiplied by 100 within a couple of days, and its intact ice cover is quickly fragmented, pushed, and carried away by the rising discharge. Caribou are often seen caught on a drifting ice floe, surprised by the swiftness of breakup following the long winter. Ice runs last for hours while the sun does not set. They carry slabs of ice, generally a metre thick, over hundreds of kilometers without stopping.

These landscapes, mountains and streams are the home of the Vuntut Gwitchin First Nation. Their people have lived on these lands and have travelled in the drainage system of the Ch’oodeenjìk and beyond for millennia. The community of Old Crow is established at the confluence of the Ch’oodeenjìk and Chyàh Njìk (Old Crow River). The flowing water and the species it supports are central to the culture and traditions of its people.

Climate change is impacting this region and its ecosystems more than any others in the Yukon. The permafrost is warming and thawing. New water pathways are opening, and precipitation patterns are evolving. Like many other watercourses of the north, the future of the Ch’oodeenjìk remains largely uncertain, but it is anticipated that its morphology and hydrology will be forced to adjust. Dewatering episodes have already been reported in a large tributary of the Ch’oodeenjìk, the Ni'iinlii Njik (Fishing Branch River). Thaw slumps are becoming more frequent in the headwaters (e.g. Kokelj et al, 2021), and the water quality of streams in neighbouring watersheds is declining as metals are released from the ground (some creeks are turning orange; O’Donnell et al, 2024). Moreover, Janowicz (2017) reported that snowmelt events are becoming compressed, leading to a faster water level rise in the spring and higher peak flows.

The early spring behaviour of the Ch’oodeenjìk is important for several reasons, including flood risk management in Old Crow. The possibility of a flood can never be discarded as winter ends. Even when the snowpack is below average or after a mild winter, Old Crow can still be affected by high water levels. Mitigating the risk of flooding may involve reducing the frequency of the hazard or minimizing the impacts. Unfortunately, reducing peak water levels cannot be reasonably considered: Mother Nature would not tolerate an ice boom (to store ice upstream of Old Crow) and certainly not a large dam (to store snowmelt runoff upstream of Old Crow). Therefore, it is the level of consequence, or the exposure to floods, that needs to be addressed. One accessible action is to inform the population, either about the probability of a flood in any given year (through flood maps) or about the possible timing and intensity of a flood that is expected in the coming hours to days, to support emergency responses. The worst floods in Old Crow have been caused by breakup ice jams.

The Water Resources Branch of the Government of Yukon has expressed interest in developing a river ice breakup model for the Ch’oodeenjìk at Old Crow to reduce the impact of ice jam floods on the community. The objectives of this report are to develop knowledge about the river ice breakup regime over a ~300 km stretch of the Ch’oodeenjìk and to build a prototype river ice model that would forecast breakup timing and intensity at Old Crow.

2. Theory

2.1 Overview

River ice breakup is the most important hydrological event of the year on most northern rivers. It has historically meant that food accessibility improves and that moving across the land becomes more manageable (and safer), opening the possibility of reaching remote cultural sites by boat. Although breakup is generally celebrated, for several communities, the transition from ice-covered to open water conditions is also a time to be cautious: rivers can produce their highest annual water levels, not only because of snowmelt-driven peak flows but also because of sudden, dynamic changes in ice conditions that could result in the formation of ice jams. A stationary ice cover does not only occupy a portion of a river's cross-section (essentially blocking the flow, especially in shallow sections). The roughness of the ice rubble also slows the water velocity, resulting in higher water levels for a given (often rising) discharge.

The book *River Ice Breakup*, edited by Beltaos in 2009, includes chapters about the thermal and mechanical aspects of breakup and includes a chapter about forecasting breakup events. The spring behaviour of the Porcupine River corresponds to what is theoretically expected from a single-channel river (with very few islands or anastomosed sections) with a relatively simple morphology (long stretches of straight channel with occasional sharp bends and well-defined meanders). As the snow melts and the flow rises in the headwaters, the ice cover is lifted, longitudinal cracks form along the banks, and the formation of transverse cracks is soon followed by the mobilization of the ice cover over relatively long reaches.

What is unique about the Porcupine River is its geographic alignment: when including most of its main tributaries, it flows northward over a long distance, covering about 250 km as the crow flies. Over this distance, sub-watersheds are affected by different weather conditions. The headwaters in the south can see snowmelt initiating while the central portion of the watershed remains in winter mode. Simply stated, the water piles up in the tributaries and main stem of the river (stored behind ice jams), accumulating energy to be released later. Therefore, while it is true that breakup along the Porcupine River generally follows a typical sequence, ice conditions can evolve much faster than in rivers of similar size that are oriented differently.

2.2 Breakup regime of the Porcupine River

Jasek (1997) provided an overview of ice jam flood mechanisms on the Porcupine at Old Crow. To the authors' knowledge, this conference paper remains the most comprehensive description of the breakup sequence along the Porcupine River published to date. Janowicz partially revisited this topic in 2017 during a conference organized by the same research collaborators. He suggested that breakup severity was increasing at Old Crow, potentially because of a compressed snowmelt period and overlapping breakup and peak freshet flows. A subsequent investigation of peak water levels during both ice- affected and open-water conditions concluded that that open water peak levels are indeed trending upwards in the Porcupine River (Turcotte 2021). In contrast, the trend for ice-induced peak water levels was uncertain.

This data set was updated for the purpose of this report and is presented in Figure 2.2.1. The conclusion remains essentially the same: open water peak flows seem to be increasing over time, or at least fewer small peak flow events have been reported in recent years compared to the mid-1980s, the late 1990s, or the early 2000s. Also no trend could be identified for peak breakup events, in part due to the gaps in the Water Survey of Canada (WSC) record (station 09FD003 at Old Crow started operating in 2006, whereas the older 09FD001 station located downstream of Old Crow was decommissioned in 1995), but also because of uncertainties related to the transfer of ice-induced water elevations from the older downstream site to the newer station location. However, note that the four highest estimated ice jam peak water levels on record occurred before 2000. Janowicz may have consulted other data sources for his 2017 publication, including observations reported by citizens who have witnessed decades of breakup events at Old Crow.

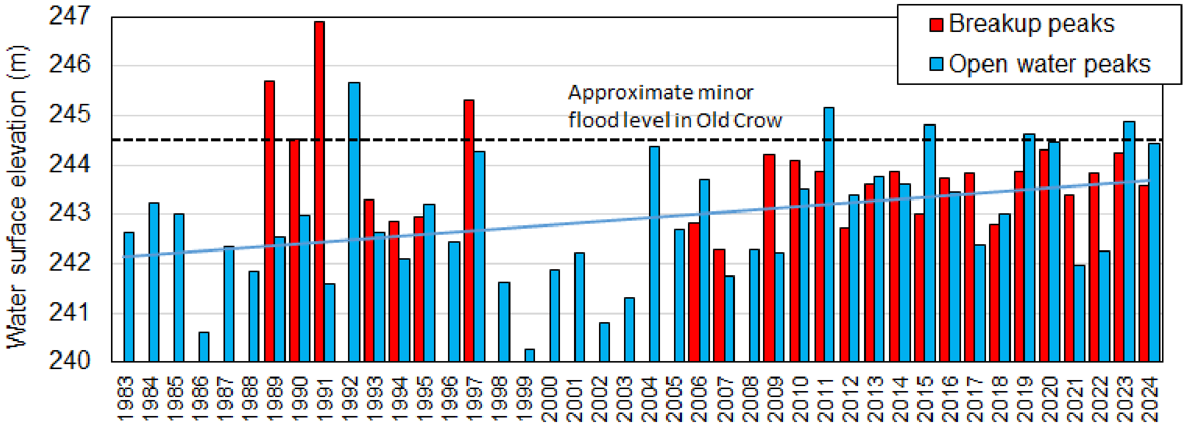


Figure 2.2.1. Peak water surface elevation (CGVD2013E2010) for open water and breakup conditions measured or estimated at station 09FD003 (Porcupine River below Old Crow River) over the last 40 years. The blue line is an interpolation through the open water data.

An analysis of 56 years of data from another hydrometric station (09FD002, Porcupine River near International Boundary) located 90 km downstream of Old Crow suggests that sharp and compressed freshet peak hydrographs (or compressed freshet hydrographs, as qualitatively defined by Janowicz, 2017) have occurred, on average, 60% of the years. This generally dynamic snowmelt regime is probably imposed by: 1. a relatively thin snowpack (150 mm of water equivalent, on average) that can mostly melt in less than a week and 2. the general northward orientation of the watershed, as described above, that translates into a superposition of snowmelt runoff waves from different tributaries. In addition, it appears that the frequency of compressed snowmelt hydrographs has increased in recent decades. Interestingly, the April 1 snowpack measured at four Government of Yukon snow courses has also increased since 1987 (beginning of simultaneous records), potentially a consequence of climate change. Based on a tendency identified by Janowicz (2017), warm air temperatures arrive more suddenly in the Porcupine River watershed at the end of winter, also a possible impact of climate change. Whereas this corroborates the rising trend in peak flows in the Porcupine River (Figure 2.2.1), it does not necessarily mean that ice jams are becoming more frequent or intense. Section 5 of this report analyzes breakup intensity controls in more detail.

It is also worth mentioning that, even if historical tendencies did not support the argument of climate change leading to a more dynamic breakup regime in the Porcupine River, extreme weather patterns may lead to hydrological anomalies in years to come. Specific weather sequences may translate into a combination of factors leading to a major ice jam flood. For instance, extreme ice jam water levels were reported in 2023 in the Yukon River at the Forty Mile River and along the Peel River above Fort McPherson. Therefore, even if winters are generally shorter and milder, the window for a record ice jam flood at Old Crow is probably still open.

Beyond water levels (and in the absence of a trend in breakup water levels; Figure 2.2.1), it is expected that reported changes to the hydrological regime of the Porcupine River over the last 20 or 30 years may have modified the timing and spatial aspects of the breakup regime. Jasek (1997) summarized several years of river ice observations from the 1990s and reported tendencies that may have evolved. For instance:

- Jasek reported that the Richardson Mountains (Bell-Eagle River watershed) seemed to have the most significant hydrological impact on breakup down to Old Crow. However, in recent years (e.g., 2020, 2024), breakup mainly occurred because of the high flow supplied by the Ogilvie Mountains (e.g., Whitestone River, Miner River) located at the southern end of the watershed. Breakup in the Bell River occurred later in both years.
- The hydrological role of small tributaries (e.g., Driftwood River) in triggering breakup fronts seems to be less evident in recent years than what Jasek (1997) reported, to a point where the authors recommend analyzing a high-resolution profile of the Porcupine River to confirm whether the reaches immediately downstream of such confluences are not simply steeper than upstream reaches.
- Jasek (1997) did not mention the quasi-annual formation of a significant ice jam upstream of Old Crow. The authors have observed its presence almost every year since 2018. This site also appears to be prone to freeze-up consolidations.

The spatial aspect of river ice breakup, or the breakup sequence, of the Porcupine River will be further explored in Section 4.

2.3 Breakup forecasting

To the knowledge of the authors, there has never been an official river ice breakup forecast model developed for the Porcupine River at Old Crow. The floods of 1989 and 1991 could have potentially been anticipated by citizens, but apparently no official notification was released by the authorities prior to these events. A river ice breakup forecast model can take many forms and does not need to involve complex computation algorithms (e.g., White, 2009). It could consist of:

- A summary of opportunistic, but organized observations reported by people that have been travelling on the land and frozen rivers during the winter season.
- A set of predefined thresholds associated with easy-to-measure parameters (e.g., if the ice cover is thicker than a given value, a major ice jam is possible).
- A statistics-based model that may include physics-based equations (including neural network approaches).

- An empirical model that includes some level of physics (such as the model developed by the University of Alberta to predict the timing of breakup on the Yukon River at Dawson, Gerard and Stanley, 1986).
- A hydrodynamic-based model that may include a Monte-Carlo selection of possible input variables that reflects weather and hydrological forecast uncertainties (e.g., Warren et al., 2017).

This list is by no means exhaustive, but rather emphasizes an increasing level of effort and computational power to provide an optimal breakup (or ice jam) forecast. The main challenge to forecasting breakup intensity (or maximum ice-induced water levels) at Old Crow is to develop a defendable approach or algorithm to evaluate the probability of the annual ice run stopping within a reach that would threaten Old Crow (i.e., a critical reach). Other communities in the North (and in cold regions in general) that are exposed to ice jam floods face the same issue. The key is to evaluate on one hand, if ice conditions offer more or less resistance than usual at the beginning of breakup in the critical river reach, and on the other, to foresee or anticipate if the ice run will come with enough momentum to plow through the ice cover (or freeze-up jam) of that reach without stopping.

In this project, the authors propose a hybrid approach, similar to what was done for the Yukon River (Turcotte et al., 2024a): A physics-based empirical 0-dimension (0D) model that evaluates breakup resisting and driving forces over time. The model considers key concepts as they relate to ice mechanics and channel hydraulics, but it excludes a hydrodynamic component that relies on documentation of the channel bathymetry over long distances. This model is described in Section 6 of the report.

3. Study area

The distance between the Whitestone River and Miner River confluence (the start of the Porcupine River on most maps) and the Yukon-Alaska Boundary is about 400 km. However, it appears that the reach located 140 km downstream of the confluence (and 170 km upstream of Old Crow) does not contribute to ice runs that cause ice jam floods in Old Crow. Moreover, the reach of the Porcupine River where ice jams can affect Old Crow is probably limited to less than 75 km downstream of the community. Therefore, Figure 3.1 emphasizes an area from Km 140 (distance increasing downstream from the Whitestone-Miner confluence) to Km 380 (at the head of a steeper section beyond which ice runs are generally carried directly to Alaska). The main tributaries of the Porcupine River are also included. Figure 3.1 will be referred to in the following sections of the report.

Note that, during future research phases, it would be our respectful intention to consistently use (or at least mention) traditional names (in Gwich'in) for water courses that are referred to in this project, as was done in Section 1 (Introduction) above. Our team understands that Vuntut Gwitchin First Nation agreement and confirmation to use and share place names are essential.

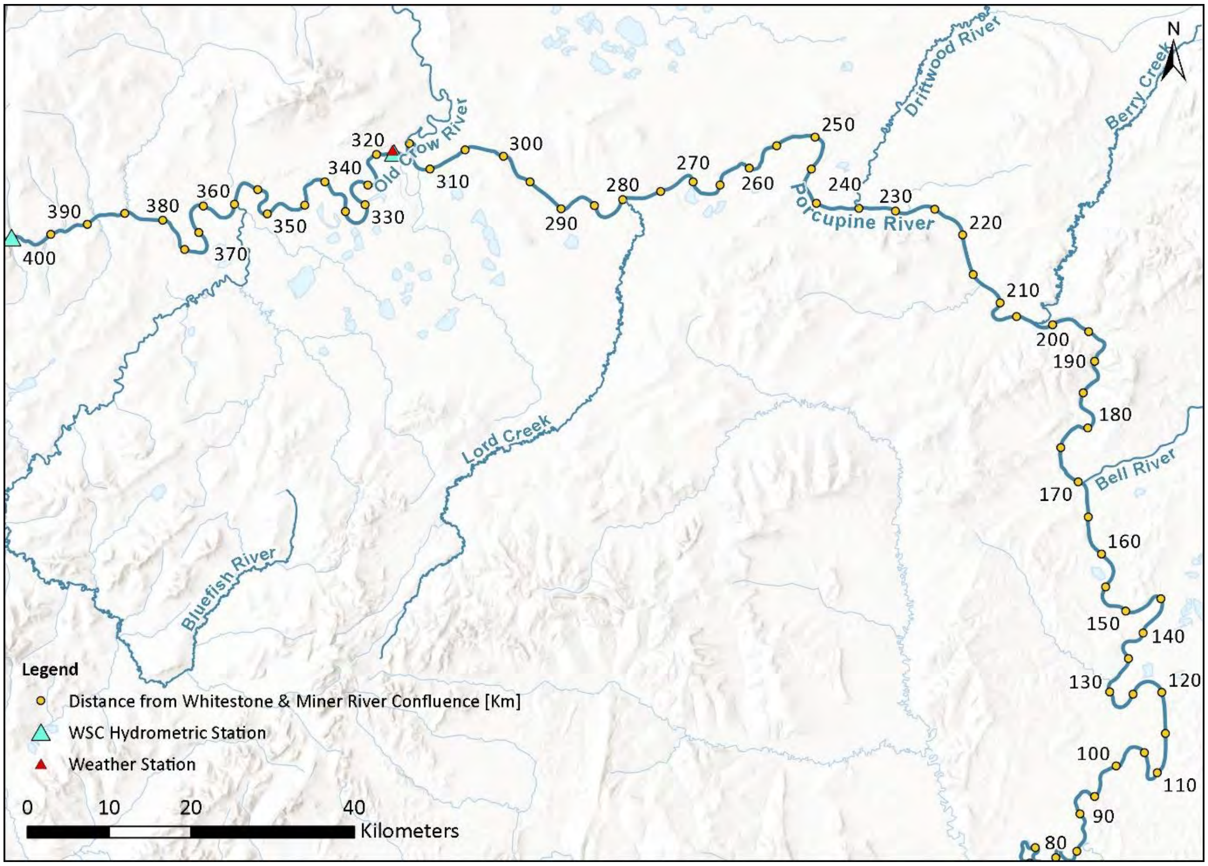


Figure 3.1 Study reach of the Porcupine River between Km 90 (downstream distance from the Whitestone River and Miner River confluence) and Km 400 (Canada-Alaska border).

4. Spatial aspects of breakup

Beyond hydrometeorological considerations, which is the focus of Section 5, the timing and intensity of river ice breakup ta any given river location depends on upstream and downstream ice conditions. Documenting the origin and behaviour of the annual ice run at Old Crow is key to understanding the possible range of water levels throughout the breakup period. The spatial aspect of breakup is explored in detail in this section.

4.1. Ice jam locations

The Porcupine River near Old Crow can respond very quickly to snowmelt runoff. In less than 24 hours, channel conditions can evolve from mostly ice-covered with minor ice accumulations to completely open over a distance of more than 200 km. This breakup scenario could be influenced by the widespread absence of an active layer (presence of permafrost and a generally frozen ground surface layer at the end of winter) that prevents snowmelt infiltration and forces meltwater to follow surface pathways to headwater creeks. The rapid evolution in ice conditions makes the documentation of dominant ice jam locations particularly challenging.

Since the location of historic ice jams help reveal different breakup sequence scenarios, an effort was made to identify ice jamming sites (toe of ice jams) between Km 140 and Km 380 (Figure 3.1). The upstream boundary, Km 140, was selected because, among the thirteen (13) studied breakup events, the residual ice run from the upper Porcupine River (upstream of Km 125) arrived at the Old Crow reach several hours to a few days after local breakup.

Figure 4.1.1 presents the location of historic ice jams toes (from 2007 to 2024, with gaps) at a resolution of 5-km segments. This assessment is based on satellite imagery, as well as photos taken from a fixed-wing aircraft during Government of Yukon breakup monitoring flights. Two ice jam types are distinguished (note that these represent approximate, Porcupine River-specific definitions that may differ from what is presented in Turcotte et al., 2024a for the Yukon River):

- Minor ice jams: They are associated with backwater, or stage rise, limited to approximately 2 m because they happen during an early breakup phase (or during extreme thermal breakup years), when driving forces are low. They are often relatively short (i.e., less than 2 km in length).
- Major ice jams: These jams can cause floods because they involve a greater quantity of ice rubble and occur at higher flow. They can be more than 30 km-long.

Figure 4.1.1 reveals that minor ice jams form annually near Km 140 (note that a long ice jam usually forms in a wide, straight segment of the Porcupine River between Km 110 and 120). Then, moving downstream, minor ice jams are relatively frequent above the Bell River confluence as well as in the canyon section between Km 175 and 195 (Jasek had reported an annual ice jam at the constriction between Km 188 to 190). Further downstream, minor ice jams frequently form downstream of the Driftwood River confluence (Km 235), and between Km 240 and 260. There are a few bends in the Porcupine River where an ice run can stall on its way towards Old Crow, but the dominant ice jam location in the whole system seems to be located just above Old Crow, at Km 313.

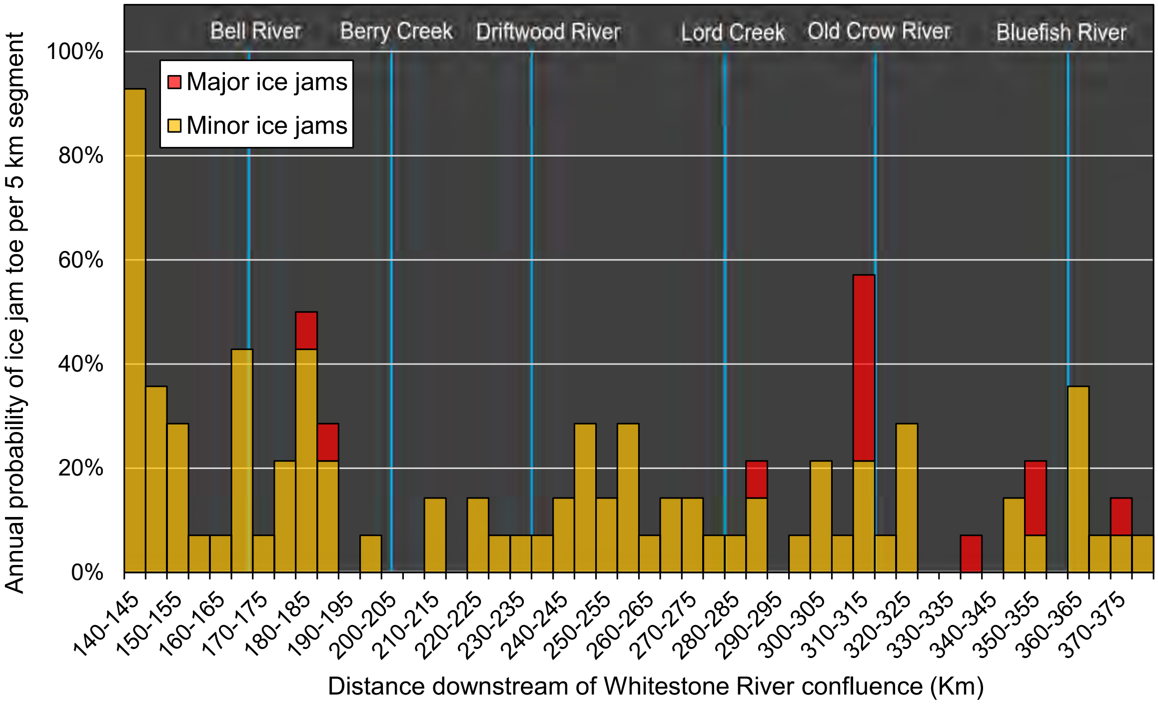


FIGURE 4.1.1. ANNUAL PROBABILITY OF MINOR AND MAJOR ICE JAMS OVER 240 KM OF THE PORCUPINE RIVER WITH KM 0 LOCATED AT THE WHITESTONE RIVER AND MINER RIVER CONFLUENCE. THIS ASSESSMENT IS BASED ON VISIBLE AND RADAR IMAGERY AS WELL AS ON PHOTOS AND INCLUDES DATA FROM 14 BREAKUP EVENTS BETWEEN 2007 AND 2024.

Once the (almost annual and often major) ice jam at Km 313 releases, it carries enough power to break the intact ice cover downstream of Old Crow over a significant distance, often beyond the Bluefish River (Sriinjìk in Gwich'in) confluence (Km 360). Further downstream, the river enters a relatively narrow canyon where the ice is usually less resistant and where any ice jam would have little to no influence on water levels at Old Crow. Between Old Crow (Km 315) and the Bluefish River, the main ice run (generally released from Km 313) occasionally stops, but the data presented in Figure 4.1.1 indicates that there is no defined, dominant location for this to occur. This is important as the occasional ice jam with a toe located between Km 335 and Km 355 represents the main flood concern for Old Crow. Its occurrence depends on a complex and relatively rare combination of ice cover resistance and ice run momentum. Note that no major ice jam formed immediately against the Bluefish River delta (and associated aufeis) in recent years, as shown in Figure 4.1.1 (Km 355 to 365).

Based on observations, it seems that ice jams in the Porcupine River are mainly caused by a narrowing of the channel (e.g., Km 185-190, Km 310-315), by tight river bends (Km 140-145, Km 180-185, Km 310-315, Km 350-355), or by the presence of freeze-up jams (see next subsection). The influence of slope breaks, if any, has not been investigated in detail as no high-resolution elevation data existed until very recently to support this assessment (the SWOT satellite mission provides an opportunity for such assessment as of 2024).

The spatial ice jam regime translates into a very narrow set of possible breakup scenarios for the Porcupine River, compared with other rivers (e.g., Yukon River at Dawson, Turcotte et al., 2024a):

- The main ice run at Old Crow initially comes from the Bell River (Km 169) area, a narrow channel segment at Km 188-190, or downstream of the Driftwood River (Km 235).
- This ice run contains 80 km to 150 km of river ice and often stalls at Km 313. There are virtually no ice rubble storage locations (no spatially consistent shear walls are observed after breakup) along the single channel upstream of Old Crow.
- Once this ice jam releases the resulting ice run usually carries enough power to break the downstream ice cover over at least 20 km. As the impeded ice run (Jasek and Beltaos, 2009) forces its way through a stationary ice cover, minor flooding can occur in Old Crow.
- Once every 4 years, approximately, this ice run will stall within a 20-km reach upstream of the Bluefish River confluence and the backwater will affect Old Crow. However, seeing a major (multi-kilometre) ice jam directly in front of Old Crow appears to be relatively rare (e.g., 1989). If this was the case, the minimum consequence would be minor flooding (unless breakup was extremely thermal, like in 2007) whereas a likely consequence would be a moderate to major flood.

4.2. Role of freeze-up fronts and jams

An investigation of the ice cover surface roughness during the months of October or November was performed using radar satellite imagery to evaluate the location of freeze-up congestion or consolidation areas. Figure 4.2.1 reveals that freeze-up jams generally form at Km 140 and 313, which may explain, at least in part, why these locations often intercept ice runs in the spring (Figure 4.1.1). In turn, the dominant freeze-up congestion site near Km 215 does not translate into a regular breakup ice jam site in the following spring for reasons that should be further investigated.

Figure 4.2.1 also presents several freeze-up congestion locations near Km 250 (mostly in channel bends), near Km 295 (a straight channel segment with some islands), and near Km 320-325 (a channel constriction and a meander bend just below Old Crow). Although breakup ice jams have also been reported near these locations in the spring, it seems that the momentum associated with major ice runs rarely result in the formation of significant ice jams at these locations. However, it is possible that the floods of 1989 and 1972 were associated with the formation of an ice jam against a freeze-up consolidation just below Old Crow. At least, such resistance would absorb a portion of the ice run energy.

During the fall of 2024, a rather reflective (high roughness) freeze-up consolidation formed at Km 320. It will be of interest to monitor the degradation and behaviour of the ice cover at that location in May 2025, especially in a context where it appears more resistant than the freeze-up jam above Old Crow (Km 313).

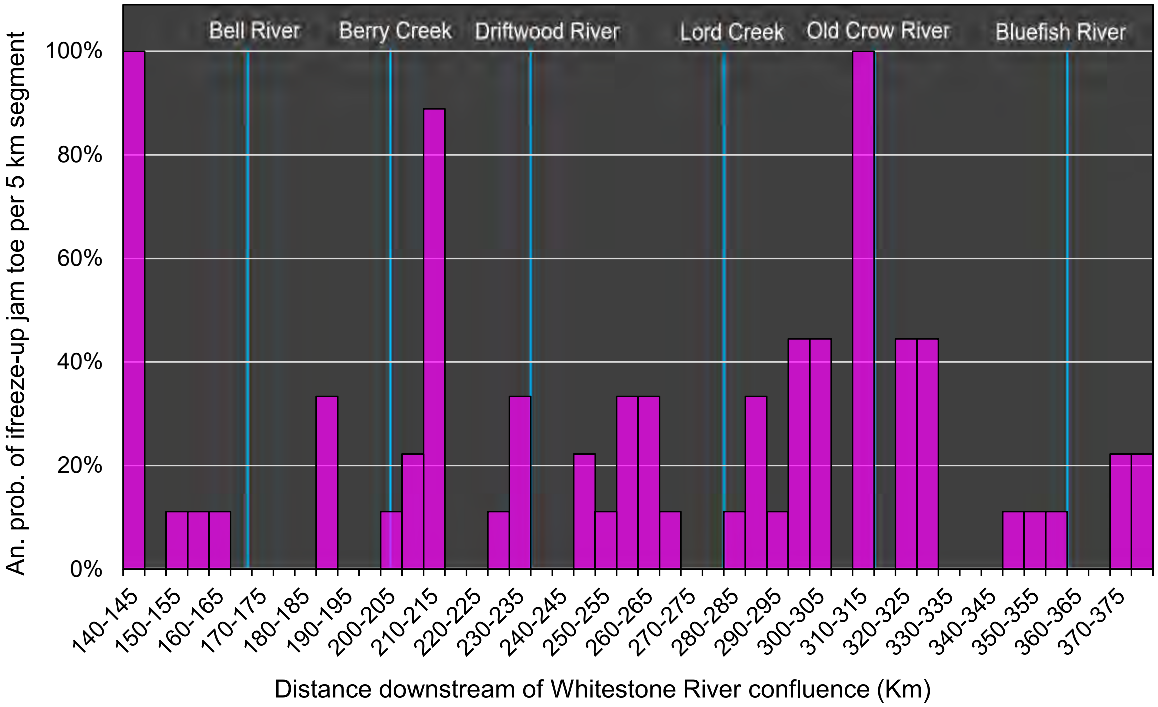


FIGURE 4.2.1. ANNUAL PROBABILITY OF FREEZE-UP CONSOLIDATIONS OVER 240 KM OF THE PORCUPINE RIVER WITH KM 0 LOCATED AT THE WHITESTONE RIVER AND MINER RIVER CONFLUENCE. THIS ASSESSMENT IS BASED ON RADAR IMAGERY FOR 9 YEARS BETWEEN 2017 AND 2024.

4.3. Role of tributaries

Subsection 4.1 revealed that breakup ice jams in the Porcupine River form at classic, textbook-type channel locations. However, it is important to investigate the influence of tributaries on breakup processes in the Porcupine River. Jasek (1997) reported breakup ice jam locations coinciding with confluences. Table 4.3.1 provides a summary of the apparent influence of several tributaries on the river ice breakup sequence of the Porcupine River as observed in more recent years.

Based on the information presented in Table 4.3.1, it can be established that:

- The upper Porcupine River generally plays a purely hydrological role at breakup by supplying a significant ratio of the spring freshet flow that triggers breakup below Km 145, and more importantly below Km 169 (Bell River) and Km 188-190 (canyon constriction). Therefore, if a defined breakup front is observed upstream of Km 100, it should be expected to stall near Km 120 or 140, then reappear downstream some hours later.
- The Bell River may be the direct (ice run) or indirect (ice run to ice jam to ice run) cause of breakup at Old Crow. A major ice run from the Bell River could translate into the most intense breakup events near Old Crow, as reported by Jasek (1997).
- The aufeis that forms at the outlet of the Bluefish River blocks a significant portion of the Porcupine River channel in most years. However, the ice run that comes from Old Crow seems to rarely stop at that specific location.
- The impact of other tributaries seems to be mostly thermal.

Table 4.3.1. Role of several tributaries in the breakup sequence and intensity of the Porcupine River in the Old Crow reach and at Old Crow.

Tributary	Breakup timing/intensity	Potential impact on the Porcupine River	Potential impact at Old Crow
Upper Porcupine River (above Km 169)	Breakup at the Whitestone and Miner confluence occurs a few days before breakup at Old Crow, but it tends to stall near Km 100-120 / Breakup is usually dynamic up to this point.	Limited: Although the freshet wave makes it past Km 145, most of the ice remains upstream of Km 140 and melts in place.	Limited: Beyond snowmelt runoff from headwaters, the only contribution to breakup at Old Crow may be an additional supply of ice from Km 145 to 169.
Bell (Eagle) River (Km 169)	A couple of days before to one day after breakup at Old Crow / Breakup can either be entirely thermal, or somewhat dynamic, with a moderate ice run.	Major: It regularly causes, at least, a local breakup of the Porcupine River down to Km 188. In turn, the shift of one ice slab in the Porcupine River can block the Bell River ice run for several hours to days.	Moderate: Breakup in the Bell River may trigger breakup at Km 313 and contribute to the main annual ice run at Old Crow.
Berry Creek (Km 202)	A few days before breakup at Old Crow / Generally thermal (no major ice run)	Low: Mostly thermal, with limited damage to the ice cover beyond one km.	Limited: No ice movement near the confluence area has been seen to influence breakup at Old Crow.
Driftwood River (Km 235)	One to three days before breakup at Old Crow / Breakup is generally thermal with virtually no ice run.	Moderate: Generally thermal, with significant melt over a couple of kilometres. An occasional aufeis may temporarily impede upstream ice runs.	Low: Breakup has been seen to initiate downstream of the confluence, but aside from its thermal effect, the exact role of the Driftwood remains uncertain.
Lord Creek (Km 280)	One to four days before breakup at Old Crow/ Breakup is generally thermal with no ice run.	Low: Local, thermal impact. An occasional aufeis may temporarily impede upstream ice runs.	Limited: No ice movement near the confluence area has been seen to influence breakup at Old Crow.
Old Crow River (Km 315)	Two to several days after local breakup at Old Crow / Breakup is generally thermal, but it may involve the release of a moderate, unimpeded ice run.	Limited: It generally only contributes additional flow (beginning of the freshet) and potentially heat. However, there are virtually no dynamic impacts.	
Bluefish River (Km 360)	Two days before breakup at Old Crow / Breakup is initially thermal, but generally ends with a moderate ice run forming a jam in the Porcupine River.	Moderate: Can trigger breakup in the Porcupine River over a few kilometers, but this generally remains local. The annual aufeis may temporarily block upstream ice runs (generally indirectly, by preventing the upstream ice slab to move past the delta).	Moderate: It has been identified as a resistant point for a major ice jam that can flood Old Crow. However, this appears to be a rare occurrence, and the confluence is generally too far from the community (the ice volume represents a limitation).

4.4. Ice cover resistance

In addition to determining the location of breakup and freeze-up ice jams in the Porcupine River and confirming the role of tributaries, quantifying the average ice coverage at 5 km-long segments also supports knowledge development about breakup sequences. To perform this assessment, various sources of information were consulted, including Sentinel 1 and Sentinel 2 imagery, RadarSat-derived ice maps, and photos taken by the Government of Yukon's Water Resources Branch during spring river ice survey flights. Figure 4.4.1 presents the average ice coverage during the 3 to 6 days prior to breakup at Old Crow (i.e., not the breakup of the local ice cover, but the occurrence of the major ice run from upstream). The data from which this information is derived is presented in Appendix A.

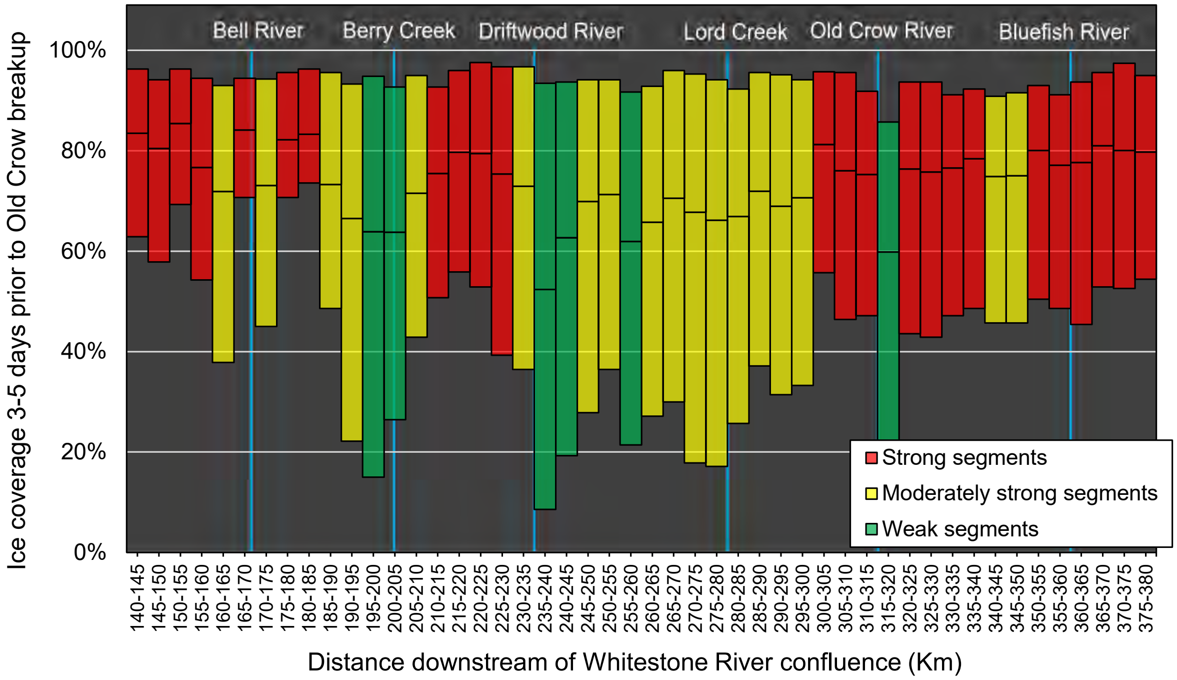


FIGURE 4.4.1. MINIMUM, MEDIAN, AND MAXIMUM ICE COVERAGE ON 5 KM-LONG SEGMENTS OF THE PORCUPINE RIVER OVER 240 KM DURING THE 3 TO 6 DAYS PRECEDING BREAKUP AT OLD CROW BETWEEN 2018 AND 2024 (7 YEARS).

Figure 4.4.1 shows the presence of relatively weak ice cover segments in green below Km 195, near Km 240 (downstream of the Driftwood River), near Km 255 (in a segment of heterogeneous ice cover conditions, including occasional freeze-up and breakup jams), and at Old Crow (downstream of a dominant freeze-up jam location). This indicates that open water areas may appear earlier at the end of winter at these locations, but it does not necessarily mean that the ice clearing process is entirely thermal or dynamic.

In turn, the most resistant and resilient ice cover conditions in red are found between Km 140 and 160 (tight and narrow meander bends upstream of the Bell River confluence), near Km 185 (narrower channel just upstream of the canyon-like morphology located at Km 188-190), upstream of the Driftwood River confluence, and immediately upstream of Old Crow. These stronger ice cover segments are often located upstream or downstream of dominant freeze-up (Figure 4.2.1) and breakup jam locations (Figure 4.1.1), which is consistent with breakup patterns.

Also relevant from Figure 4.4.1 is the consistent high strength of the ice cover downstream of Old Crow. Open water areas often appear along convex banks (e.g., wide point bars) of the Porcupine River between Km 320 and Km 360 as water levels rise. This provides lateral freedom for large ice slab movements during the ensuing ice run, which in turn attenuates the probability of ice jam formation in most years. When the ice jam upstream of Old Crow releases, the resistance of the downstream ice cover is, overall, comparable to that of the ice cover that was maintaining that ice jam in place. This means that the dynamic aspect of the ice runs (the driving force) plays a major role in the occurrence of an ice jam between Old Crow and the Bluefish River.

Finally, observations show that the ice coverage between Km 140 and 155 is higher (see median coverage in Figure 4.4.1 represented by the middle line of each vertical bar) than what is generally found below Old Crow. This supports observations reported above that the ice cover (or jam) near Km 145 is the last one to release, and it explains why the ice cover immediately downstream (down to Km 155 or 160) is not mobilized sooner (and mentioned by Jasek, 1997). The ice cover (and jam) in the canyon (Km 188-190) is statistically the most resilient of the whole system (ice coverage was generally above 75% during the last seven years prior to breakup at Old Crow). This high ice coverage often means that an ice jam remains in place at that location. This is important because the ice stored upstream of Km 190 could be required to form an ice jam that would be long enough to affect (or flood) Old Crow.

4.5. Typical and extreme breakup patterns

After investigating breakup patterns for 13 different spring breakup events (seven of which were documented in more detail) between Km 140 and Km 380 of the Porcupine River, it appears that the range of possible breakup scenarios, in terms of spatial sequences, is relatively narrow. Moreover, breakup patterns do not significantly differ between a thermal (2012) and a dynamic (2020) scenario, suggesting that different spring weather conditions result in a similar evolution of the balance between breakup driving and resisting forces.

Most breakup events in the Porcupine River at Old Crow are on the dynamic side of the breakup scenario spectrum, a probable consequence of the northward watershed orientation and widespread permafrost. Therefore, a breakup sequence involving ice jams and major ice runs with minor flooding at the western tip of the community and a water surface elevation of about 244.8 m at the Water Survey of Canada station 09FD003 were identified as a typical breakup sequence in Table 4.5.1.

A breakup scenario that would lead to a 20-year or 200-year (major) ice jam flood for Old Crow would involve a faster breakup sequence than is described in Table 4.5.1. In addition, ice and hydrological conditions would probably include:

- A very resistant ice cover downstream of Old Crow (either from a cold winter, from a dynamic freeze-up event, or from a cold and/or snowy spring),

TABLE 4.5.1. TYPICAL BREAKUP SEQUENCE IN THE PORCUPINE RIVER NEAR OLD CROW.

Days prior to local breakup at Old Crow	Ice conditions and dynamic events
- 5 days	Minor ice movements in the large tributaries of the Porcupine River (Whitestone, Miner, and Fishing Branch Rivers). Water on ice starting to appear along the banks of the Porcupine River at Old Crow. Beginning of overflow from smaller rivers and creeks. Ice coverage consistently above 95% downstream of Km 140.
- 3 days	Several ice jams forming in the large tributaries of the Porcupine River. Minor ice movements upstream of Km 100. Opening of Berry Creek and Lord Creek. Overflow or melt of the ice cover at each confluence, including the Bluefish River. Minor opening of the Porcupine River ice cover at some locations, including downstream of the Driftwood River as well as in front of Old Crow. Ice coverage above 90% in most river segments downstream of Km 140.
- 2 days	Clearing of the Porcupine River above Km 100. Ice movements in the Bell River. Small ice jams forming at several locations in the Porcupine River. Opening of all small tributaries. Ice run from the Bluefish River. Partial clearing of the ice cover in front of Old Crow. Ice coverage above 85% in most river segments, but km-long open leads forming at several weaker locations, including near the Driftwood River and Berry Creek confluences.
- 1 day	Ice run from the Bell River (Km 169). Ice jamming at Km 188-190 and/or Km 235. Major ice jam formation between Lord Creek and Old Crow, most likely at Km 313. Ice still covering 80% of the channel downstream of Old Crow, but widespread water on ice and degradation.
0 day	Mobilization of the Km 188-190 and Km 235 ice jams. Simultaneous or subsequent mobilisation of the ice jam upstream of Old Crow (Km 313) . Impeded ice run (ice run periodically slowing down) for several hours at Old Crow with unstable water levels.
+ 1 day	Main ice run reaching the Alaska Border. Low concentration ice run from Km 100 to 140 passing through Old Crow.
+ 4-7 days	Ice runs from Old Crow River.

- Possibly a weaker-than-usual ice cover or ice jam upstream of the community (Km 313 and above),
- A long (in terms of length or time) but potentially weaker (in terms of energy) ice run from upstream. The worse case scenario could be consecutive, smaller ice runs and javes (from the Driftwood River, then from Km 189, and then from the Bell River) because their energy could be absorbed by the head of the jam, enough to prevent the mobilization of its toe past the Bluefish River confluence.
- An ice jam toe located between Km 335 (like in 1997 and 1989) and 355 (possibly supported by a freeze-up jam or the Bluefish River aufeis, like in 1991).
- A rise in flow during the entire breakup sequence, to values comparable to what occurred in 2020 and 2024 (above 3000 m^3/s).

A resilient ice jam just upstream of Old Crow may therefore help reduce the likelihood of major ice jams downstream of Old Crow and the probability of a minor to moderate ice jam flood in Old Crow. This is because of the significant amount of energy of the ice run and associated jave. In contrast, a thermal breakup scenario, as documented in 2012 (as well as in 2021, to some extent), involves a longer breakup sequence than is described in Table 4.5.1. Thermal breakup scenarios involve the formation of several small ice jams that partially or entirely melt in place before a more powerful ice run occurs. In theory, thermal breakup scenarios would involve a thinner snowpack (reducing the potential for significant snowmelt rates) and relatively mild and stable sequence of spring air temperatures (extending the period of ice cover deterioration).

4.6. Ice indicators to forecast breakup at Old Crow

Section 5 the report will describe hydrometeorological factors that control or influence the timing and intensity of river ice breakup in the Porcupine River near, and at Old Crow. If, hydrometeorological conditions at the Whitestone River, at Eagle Plains, or at Old Crow are not known, (i.e., a major breakup event affecting hydrometric stations or a website malfunction), ice condition observations at key locations could support forecasting the timing and intensity of breakup at Old Crow. The following list is not meant to be comprehensive, but it can be used to forecast breakup at Old Crow some days in advance:

- Clearing of the Whitestone River usually occurs 2 to 5 days before breakup (the first large ice run) at Old Crow. There would be more lead time (e.g., 5 days) if the clearing was not following a consistent streamwise sequence (e.g., if several small ice jams form in the river) and less lead time (e.g., 2 days) if the river was entirely clear with significant ice rubble accumulation in abandoned meander bends.
- An ice jam usually forms near Km 100 or Km 110 between 1 to 3 days prior to breakup at Old Crow. It is unlikely that the ice upstream of this point will merge with the main ice run flowing past Old Crow, but the freshet flow will reach the Bell River confluence in the following hours and a dynamic breakup sequence could be reestablished below Km 169.
- Clearing of most small tributaries (e.g., Berry Creek, Driftwood River, Lord Creek, Bluefish River) takes place less than 2 days before breakup at Old Crow. Their lower channel will appear dark or black on visible and radar satellite imagery.
- Dynamic breakup of the Bell River would generally occur less than 24 hours before breakup at Old Crow. If a significant ice run exits the Bell River, and if it manages to clear the canyon near Km 188-190, ice clearance should happen all the way down to Km 313. The reasoning here is that if the Bell River releases a significant amount of water and ice, it means that a lot of water is already flowing from the southern portion of the watershed.
- A long (sometimes major) ice jam forms upstream of Old Crow (at Km 313, or at least downstream of Km 280) less than 24 hours before breakup at and downstream of Old Crow.
- If the ice cover is still white (snow covered) downstream of Old Crow, or if the freeze-up process was dynamic, the ice run is more likely to jam above Km 360 (Bluefish River).
- Once the main ice run has passed Km 380, the probability of an ice jam flood in Old Crow is virtually nil, but ice clearing could be followed by residual ice runs and high open water level conditions in the following hours or days, as pointed out by Janowicz (2017).

5. Hydrometeorological aspects of breakup

5.1. Hydrometeorological envelope

River ice breakup at Old Crow, like at any site on any other river, is controlled by hydrodynamic and mechanical forces. Breakup driving forces (those oriented downstream) tend to increase throughout the spring as snowmelt runoff rates increase. In contrast, breakup resisting forces (those oriented upstream) tend to decrease throughout the spring as the ice cover degrades and loses its structural integrity. Once driving forces become higher than resisting forces at a specific river location, ice movements occur, and open water areas form. Initial ice movements are often immediately followed by a downstream consolidation process, which can be considered a small breakup ice jam (juxtaposed type, with a low roughness). In this case, the ice accumulation causes resisting forces to temporarily rise above driving forces. Eventually, the river flow rises further, or additional fragments of ice cover come from upstream, and these hydrological variations cause an additional increase in breakup driving forces. At some point, the ice cover is broken and pushed downstream, and any other ice run from upstream does not meet significant resistance, marking the point where breakup driving forces have prevailed and the open water season has begun.

From a force balance point of view, this narrative is simple. However, the forces involved in breakup processes are complex and cannot be quantified with enough certainty (e.g., those transferred to the banks) to determine when ice movements and jamming will occur. Therefore, there is a need to use simplified approaches that explore empirical relationships between accessible parameters that serve as proxies for the predominant driving and resisting forces.

Variables influencing breakup forces can be divided into hydrological (including ice-related) and meteorological parameters. It is of interest to know, during an early forecast model development stage, when and under what hydrological and weather conditions breakup occurs in the Porcupine River near Old Crow. Table 5.1.1 presents a summary of key variables.

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

Parameters	Historical range	Historical average	Years of record
Estimated peak breakup level at station 09FD003	242.3 to 247.0 m	243.9 m	29
Date of breakup peak level	May 2 to June 6	May 16	43
Estimated peak flow at peak level at station 09FD003	1200 to 4600 m^3/s	2800 m^3/s	24
Effective cumulated degree-days of thaw* at breakup at Old Crow	15 to 140 °C-days	90 °C-days	27
April 1 snowpack at 5 snow courses (water equivalent, SWE)	90 to 220 mm	140 mm	38
Max cumulated degree-days of freezing at Old Crow (CDDF)	3400 to 5000 °C-days	4300 °C-days	36
Estimated discharge before freeze-up at station 09FD002	80 to 800 m^3/s	300 m^3/s	36

* ECDDT, based on corrected air temperatures to take sun radiation into account

5.2. Correlations between breakup indicators

Several factors influence the timing of river ice breakup in the Porcupine River at Old Crow. However, one must keep in mind that, in most years, the river ice coverage drops from nearly 90% to 5% (residual ice deposits and shear walls) over 200 km in less than 4 days (refer to Section 4). This leaves a very short amount of time to document how breakup driving and resisting parameters evolve. Ice movements are probably responsible for triggering sudden changes to those parameters. For instance, sudden flow variations are caused by ice movements at different locations in the river, and such movements were initially triggered by a gradual rise in discharge. Therefore, it is not surprising to find no clear trend or correlation between river ice breakup dates (when the maximum ice-induced water level occurs) and other parameters that must play a role in breakup, such as effective cumulated degree-days of thaw (ECDDT) at Old Crow (this is a breakup resistance proxy), April 1st snow water equivalent (SWE) in the Porcupine River watershed (mainly a breakup drive proxy), or cumulated degree-days of freezing (CDDF) at Old Crow (mainly a breakup resistance proxy).

In addition, the hydrometeorological record at Old Crow is relatively thin, and may contain errors. The federal monitoring network also prevents evaluating the effect of snowmelt runoff rates that are driven by weather conditions south and east of Old Crow. This may explain why four historical breakup scenarios are consistently altering most of the correlations and trends that have been investigated (they are often highlighted in red and green in the graphs of this section):

- 1997: Possibly the 3rd highest ice-induced water level since records began in Old Crow: It seems that the peak water level in Old Crow was caused by an early-season ice jam on May 7 (only 45 ECDDT at Old Crow). The jam moved in the following days and its toe settled near Km 353. It melted in place before releasing on May 14. No hydrometric record is available for the event; the data from station 09FD002 appears unreliable and can be disregarded. This event followed a cold winter (4900°C-days) with an extensive Bluefish River aufeis. Flow during the preceding river ice formation period was probably above average.
- 1991: The highest ice jam water level in the Water Survey of Canada record. It occurred late in the spring, in terms of ECCDT at Old Crow (140°C-days), after a year of average SWE. It is puzzling that the ice cover could maintain significant resistance downstream of Old Crow for so long, considering that peak water levels usually occur at 90 ECDDT (Table 5.1.1). In this case, it is possible that the January 25-26 thaw event (with wet snow or light rain) led to a higher resistance of the ice cover by reducing the snow insulation. Significant air temperature variations and consistently cold temperatures (4600 CDDF) could have also played a role in the thickening of the ice cover and in the development of the Bluefish aufeis (Jasek, 1997). Freeze-up flow in 1990 was relatively low.
- 1989: The second-highest ice-jam water level on record. In contrast, this event occurred after only 42 ECDDT at Old Crow, which aligns with a typical dynamic breakup scenario. The winter of 1988-89 was also characterized by very cold temperatures (4400 CDDF with lows below -50°C) and a mid-winter thaw event (February 9-10). On April 1, 1989, the SWE was close to average, but it had been significantly depleted at low altitude by April 30 (this is the only time between 1986 and 2024 that the five snow courses in or near the Porcupine

watershed reported no SWE on May 1), so one may wonder where the breakup driving flow came from 5 days later.

- 2007: The lowest breakup water level on record. This thermal breakup was well-documented by the Government of Yukon through breakup survey flights. It occurred after a normally cold winter, but most importantly, after only 16 ECDDT at Old Crow. The SWE at the end of winter 2007 was well below average, and therefore, it is assumed that the ice cover melted in place and was dislodged by a relatively small hydrodynamic (runoff-induced) force (just like on the Yukon River in 2019, Turcotte et al., 2024a).

These four events are contrasting, not only between each other but also compared to other breakup events. Collectively, they confirm that air temperature measurements (and derived river ice breakup proxies) at Old Crow are not indicative of river ice breakup timing and intensity in the Porcupine River upstream, at or downstream of Old Crow.

5.2.1. Influence of air temperatures on breakup dates

Figure 5.2.1 explores if ECDDT at Old Crow may explain the date of breakup. The blue (linear correlation) trend is defendable: the later the breakup happens, the more ECDDT should be expected, on average. However, it is of interest to appreciate the trend in black without two anomalous breakup years listed above: clearly, they represent outliers.

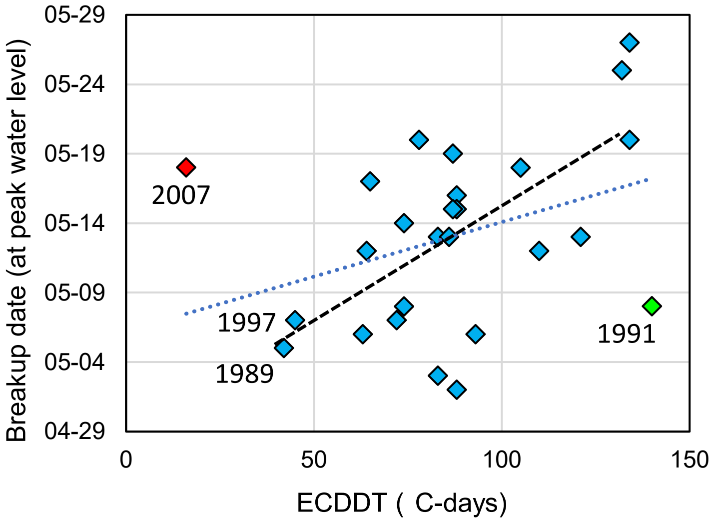


Figure 5.2.1. Breakup date (at peak water elevation) expressed as a function of effective cumulated degree-days of thaw at Old Crow (data from 1989 to 1997 and from 2006 to 2024). The blue doted line is the linear correlation through all the data points. The black trend is the linear correlation without the two outliers.

No meaningful correlation was found between breakup dates and other easily measurable parameters (i.e., accessible weather or hydrological data) that can be associated with river ice conditions in the spring. This makes sense, considering that spring conditions can be delayed in some years and occur earlier in others. The next step was to investigate the impact of such parameters on breakup intensity.

5.2.2. Influence of discharge on breakup intensity

The most obvious parameter that controls breakup intensity, expressed in terms of peak water level during the breakup period, is the discharge. Any river ice textbook (e.g., Beltaos, 1995) would describe that for a given river ice condition, the higher the discharge, the higher the resulting water level. Moreover, a higher discharge also compacts the ice rubble and thus generates a thicker and rougher ice jam. The discharge data at Old Crow was reconstructed using data from the Water Survey of Canada station 09FB001 (Porcupine River below Bell River) from 1989 to 1995 (the ice cover is often gone from that location before breakup at Old Crow, see Section 4) and from a rating curve developed by the authors for station 09FD003 (Porcupine River below Old Crow River) for 2006 to 2023. In the latter case, the ice-induced backwater was estimated from the stage data series using a technique described in Turcotte (2022).

Peak water surface elevation during the period where station 09FD001 was in place (2.3 km downstream of the current Old Crow station) could only be tentatively transferred to station 09FD003 when it appeared that those peaks were caused by an ice run. Peak water levels at Old Crow during ice jam events (1989 and 1991) were obtained from Jasek (1997).

Figure 5.2.2 presents measured peak water levels expressed against estimated peak flows on the same day. The approximate open water rating curve at Old Crow is also presented in addition to a linear interpolation. The 2007 thermal breakup event (1600 m^3/s, 242.3 m) does not represent an outlier on this graph. However, other breakup years are contributing to a low correlation or an unexpected trend:

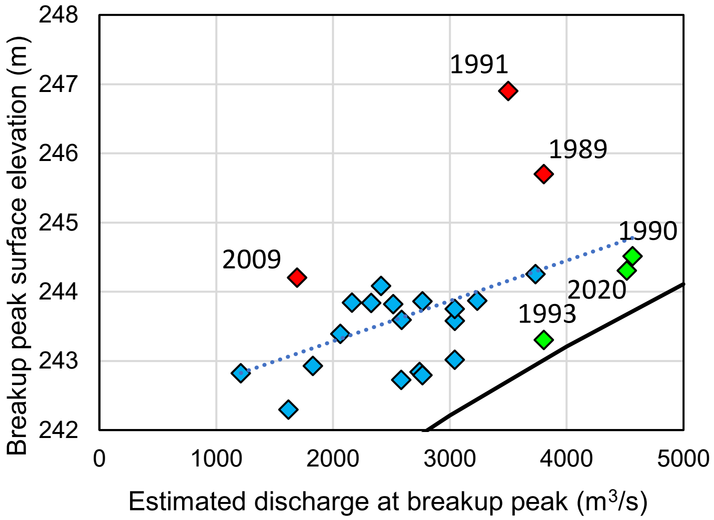


FIGURE 5.2.2. MEASURED BREAKUP PEAK LEVELS (WATER SURFACE ELEVATIONS) EXPRESSED AS A FUNCTION OF ESTIMATED DISCHARGE DURING CORRESPONDING PEAKS AT STATION 09FD003 (DATA FROM 1989 TO 1995 AND FROM 2006 TO 2024). THE APPROXIMATE OPEN WATER RATING CURVE (BLACK LINE) AND A LINEAR INTERPOLATION THROUGH ALL DATA POINTS (DOTTED BLUE LINE) ARE PRESENTED.

- Water levels were low in 1990, 1993, and 2020 considering their respective estimated discharge (Figure 5.2.2). In 2020, the ice run did not stop at Old Crow, and the backwater was probably low if one considers the departure from the rating curve. It is possible that a similar scenario occurred in 1990 and 1993. However, the more significant discharge uncertainty during those years prohibits further assessment.

- Water levels were well above the interpolated trend and rating curve in 1989, 1991, and 2009. In the two former years, it is known that a significant ice jam flood occurred in Old Crow. What is known about 2009 is that breakup occurred relatively early (63 ECDDT) after a cold winter (4770 CDDF). The Government of Yukon reported an ice jam downstream of Old Crow, and the 2.4 m difference between the ice-affected peak stage and the daily average stage on May 6 perfectly agrees with that. The water level probably remained low (minor flooding) simply because the discharge was limited (the daily-averaged air temperature in Old Crow on May 6 was -6°C, which tends to attenuate regional runoff).

One could propose that a line connecting the breakup data points of 2009 and 1991 in Figure 5.2.2 would represent an upper ice jam water level envelope for the Porcupine River at Old Crow. However, Jasek (1997) judiciously pointed out that the ice jam in 1991 would have generated an even higher water level if it had extended upstream to Old Crow. What can be summarized is that Figure 5.2.2 probably shows multiple (undistinguished) data sets associated with different ice conditions: unimpeded ice runs, impeded ice runs, ice jams downstream of Old Crow, and ice jams at and through Old Crow. The challenge from a breakup intensity forecasting perspective will be to foresee these conditions and to reasonably estimate the discharge during breakup at Old Crow. The rate at which the discharge rises at the onset of breakup also requires further investigation.

5.2.3. Influence of snowmelt runoff potential on breakup intensity

Breakup data expressing peak ice-induced water levels as a function of the average April 1st snow water equivalent (SWE) at five Yukon Government snow courses is presented in Figure 5.2.3. This is of interest as this information may be more accessible than flow estimates and represents a direct indicator of potential spring flow volumes. The low correlation between breakup peak levels and April 1 SWE in Figure 5.2.3 was expected. However, linear correlations (hand drawn; there is not enough information about ice processes during all breakup events) seem to exist among known major ice jam floods and known thermal breakup events. Three different families of data points are therefore tentatively explored:

- Thermal breakup events with unimpeded ice runs,
- Major ice runs or moderate ice jams near Old Crow,
- Major ice jams near Old Crow.

Figure 5.2.3 may not represent a useful tool to predict breakup intensity, at least not more than a few days in advance, because it is difficult to foresee whether the ice run will stop downstream of Old Crow. However, this graph reveals that the snowpack may not represent a limitation to breakup intensity in most springs (unless the snowpack was below 100 mm, but the data cannot confirm it). Furthermore, a very significant snowpack has the potential to produce minor flooding even through a relatively thermal breakup scenario. For instance, in 2022, a relatively weak ice jam (it kept consolidating as the discharge was rising) downstream of Old Crow represented a concern. The same applies to an impeded ice run (e.g., 2020, 2023), a common breakup scenario (it is associated with a minor flood).

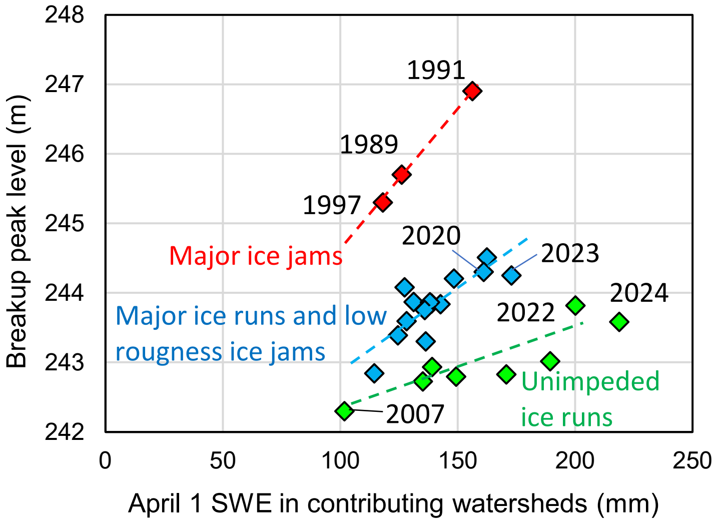


FIGURE 5.2.3. MEASURED BREAKUP PEAK LEVELS (WATER SURFACE ELEVATIONS) EXPRESSED AS A FUNCTION OF APRIL 1 SNOW WATER EQUIVALENTS (SWE) AT FIVE YUKON GOVERNMENT SNOW COURSES (RIFF'S RIDGE, 09FA-SC01; EAGLE PLAINS, 09FB-SC01; EAGLE RIVER, 09FBEA-SC02; OLD CROW, 09FD-SC01, OGILVIE RIVER, 10MA-SC02). DATA FROM 1987 TO 2024 IS USED.

A similar investigation was performed using the May 1 snowpack data, but this showed no correlation (which is expected because the data set contains years with early-May breakup events).

5.2.4. Effect of ice cover degradation on breakup intensity

Another important factor that controls breakup intensity is the state of degradation of the ice or its residual resistance to breakup. As mentioned in Section 5.1, it is very difficult to document the resistance of the ice cover directly, therefore an ice degradation (or ice melt) indicator is needed. This analysis was performed using local ECDDT, and results are presented in Figure 5.2.4.

Even when testing different air temperature corrections to take solar radiation into account (defining the "E" for effective in ECDDT), the scatter remains excessive and the correlation is close to nil (i.e., random). Not only does Figure 5.2.4 present a trend opposite of what should be expected (an intact ice cover should produce the most dynamic breakup scenarios, and ice jam events from 1989 and 1997 agree with that), but data points from 1991 and 2007 continue to represent outliers as pointed out earlier in this section.

One could argue that 2007 was a low snowpack year and that breakup unfolded very gradually over several days. However, the 1991 data point is dramatically out of bounds. Inaccuracies in the Old Crow weather record (station 2100800) were potentially identified during the month of May 1991, with possible air temperature overestimations between May 1 and May 10. The lack of alternative weather data prevents our research group from confirming this. It is also possible that errors exist in data sets from other years. What can be said about Figure 5.2.4 is that the degradation state of the ice cover, approximated through ECDDT, could play a role that compares to other breakup-resisting factors in explaining the Porcupine River breakup intensity at Old Crow.

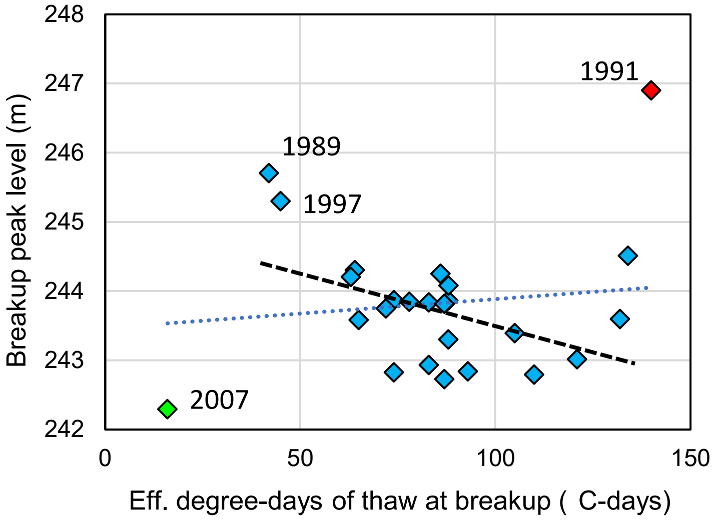


Figure 5.2.4. Measured breakup peak levels (water surface elevations) expressed as a function of effective (cumulated) degree-days of thaw at Old Crow on the date of breakup. Data from 1989 to 1997 and 2006 to 2024 is used. The more reasonable black interpolation ignores the 1991 and 2007 outliers.

5.2.5. Effect of ice cover thickness on breakup intensity

The late-winter (i.e., initial breakup) resistance of the ice cover is often associated with its thickness, which is logical and certainly practical, especially for a year-to-year resistance comparison. One downside of this parameter is that it does not take the spatial variability of ice cover characteristics into account. For instance, it could overlook the presence of a freeze-up ice jam, unless an exhaustive ice thickness monitoring program were implemented. Moreover, the characterization of different ice types (columnar and snow-ice) and their state of degradation (or exposure to short-wave radiation) may be as or more informative than a simple measure of thickness.

Another downside of relying on ice cover thickness measurements along the Porcupine River near Old Crow to understand and predict the intensity of breakup is that monitoring campaigns have not been consistently completed in recent years and decades. The Water Survey has initiated a record that dates back to 2001 on the Porcupine River near the Alaska Border. Figure 5.2.5 presents a simple analysis linking the maximum breakup water level at Old Crow with the ice cover thickness measured at WSC station 09FD002 (generally during the last winter site visit between mid-March and mid-April). Results suggest there is no clear trend, likely in part because ice conditions vary between the two hydrometric stations. Details about the measurement technique could help identify opportunities to develop a representative ice resistance monitoring program.

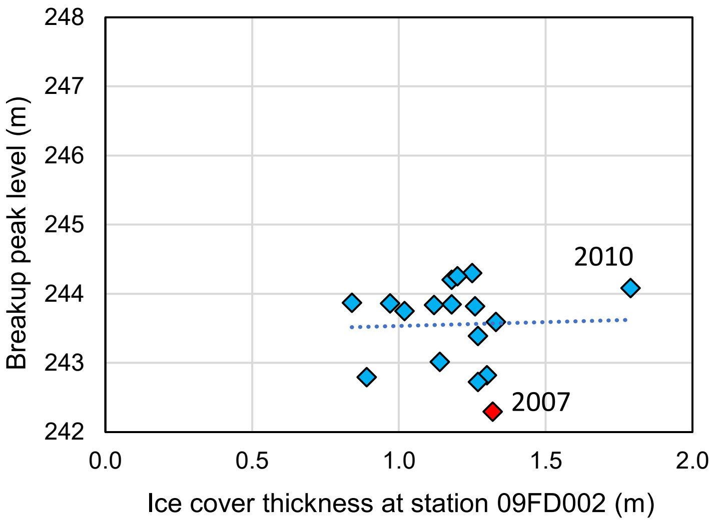


FIGURE 5.2.5. MEASURED BREAKUP PEAK LEVELS (WATER SURFACE ELEVATIONS) EXPRESSED AS A FUNCTION OF ICE THICKNESS AT THE END OF WINTER AT THE WATER SURVEY OF CANADA HYDROMETRIC STATION 09FD002. DATA FROM 2006 TO 2023 IS USED.

Despite the poor relationship presented in Figure 5.2.5, an attempt was made to test if a proxy of the maximum ice cover thickness, end-of-winter cumulated degree-days of freezing (CDDF) at Old Crow, could relate more reasonably to the local breakup intensity. In fact, one of the oldest and simplest river ice equations in the literature is the Stefan equation (e.g., Michel, 1971), which approximates a heat budget through air temperatures to evaluate the thickness (or thickening rate) of an ice cover. This equation continues to be widely used even if it is known to be of limited accuracy, partly because it neglects several heat transfer processes (e.g., Ashton, 2013). Figure 5.2.6 presents peak breakup water levels expressed as a function of their corresponding maximum winter CDDF. The linear trend is logical (a greater ice cover resistance produces higher spring breakup water levels), and the correlation is, as expected, relatively low (because of all the other parameters that come into play during breakup).

The outliers that depart the most from the linear correlation in Figure 5.2.6 are the usual ones, but it is interesting to investigate another breakup event that departs from the correlation. In 2012, after an average winter in terms of coldness and snow, breakup occurred a few days later than usual at an average ECDDT. Photos shared by the Government of Yukon suggest that breakup was progressive upstream of the Bell River and Porcupine River confluence, with several small ice jams forming upstream of Old Crow. When the main ice run finally transited through the community, it did not carry much energy, and the downstream ice cover offered little resistance. Overall, it seems that the headwaters remained cold and did not significantly contribute to the breakup process near Old Crow.

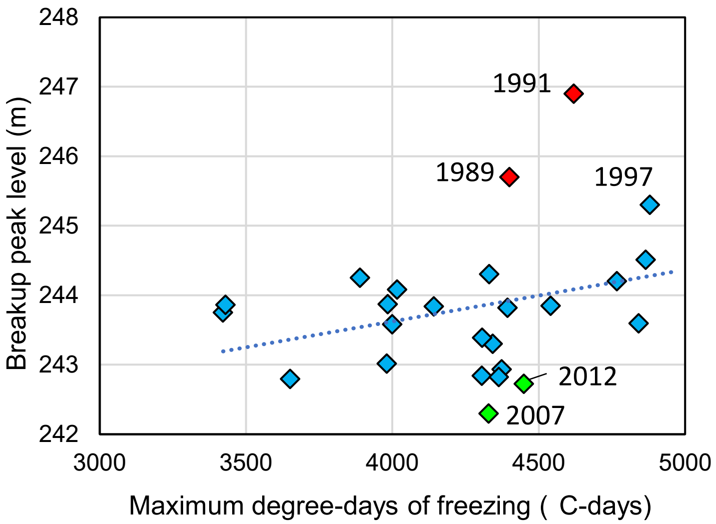


Figure 5.2.6. Measured breakup peak levels (water surface elevations) expressed as a function of the maximum (cumulated) degree-days of freezing at Old Crow during the preceding winter. Data from 1989 to 1997 and from 2006 to 2024 is used.

Note that no correlation nor any clear relationship was identified between maximum (end-of-winter) CDDF at Old Crow (as presented in Figure 5.2.6) and late-winter ice cover thicknesses measured near the Alaska Border (Figure 5.2.5) for corresponding years. Several reasons can explain this lack of agreement, but an important one is that the ice thickness is probably sensibly spatially variable. One take-home message from Figure 5.2.6 is that climate change, with its associated warmer and shorter winter, could be reducing the probability of severe ice jam floods in Old Crow through a thinner and less resistant ice cover downstream of the community. This, however, would need to be investigated in more detail because most of the ice cover thickening probably occurs during the first winter cold spells.

5.2.6. Effect of freeze-up intensity on breakup intensity

Breakup intensity is often influenced to some degree by hydrological processes taking place more than six months earlier. Freeze-up jams in subarctic rivers usually remain in place for the entire cold period and can offer significant resistance to breakup. Examples of such dynamics are the freeze-up jam of 2002 in the Klondike River that led to an ice jam flood in the spring of 2003 near the Klondike Highway bridge (e.g., Janowicz, 2010; Turcotte et al., 2024b) and the freeze-up jam of November 2022 near Km 220 of the Yukon River (100 km downstream of Dawson) that contributed to a major ice jam flood at the Village of Forty Mile in May 2023 (Turcotte, 2023).

Regrettably, the WSC station 09FD003 is not operated during the freeze-up period, so the “stage up” response to the ice cover formation at Old Crow has not been consistently documented. Even if a record existed, it seems that Old Crow is located downstream of a dominant freeze-up jam location (Figure 4.2.1), and therefore, the freeze-up discharge depression could represent the most direct indicator of freeze-up intensity near the community. To the knowledge of the authors, an analysis linking the shape and amplitude of a freeze-up depression (or “bite”) with the intensity of freeze-up is not something that is typically performed. This feature of the annual hydrograph is often inaccurate or simply missing from historical discharge records (e.g., Turcotte and Rainville, 2022). Since an intense freeze-up event is generally promoted by high pre-freeze-up flows, estimated flows at station 09FD002 (far downstream of Old Crow) prior to the local formation of an ice cover (after which flow estimates may be unreliable) were compiled. The selected date for the freeze-up discharge record corresponds to a cumulative heat loss of 20 degree-days of freezing at Old Crow (enough to cool the water near 0°C, but not enough to generate a significant quantity of ice). This criterion could be revisited and tested for accuracy in a future project phase.

The relationship between peak breakup water levels and estimated freeze-up flows is presented in Figure 5.2.7. Results show a low correlation and a trend that is the opposite of what would be expected: more flow would generate thicker freeze-up jams that would represent higher resistance points in the river system at the onset of spring breakup.

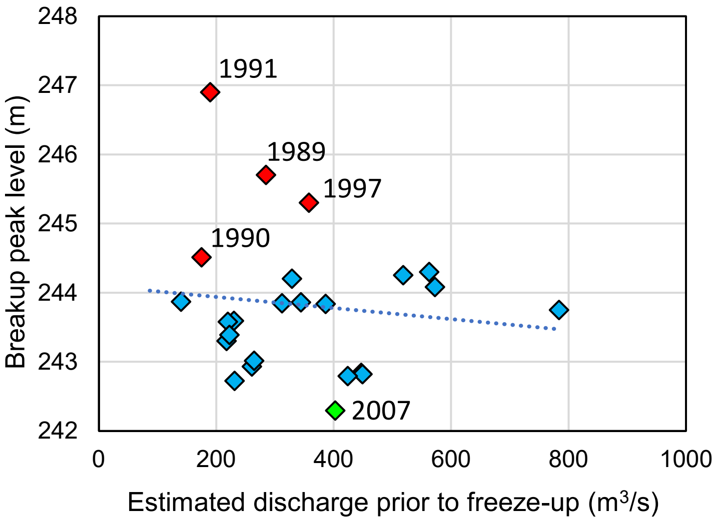


FIGURE 5.2.7. MEASURED BREAKUP PEAK LEVELS (WATER SURFACE ELEVATION) ON THE PORCUPINE RIVER AT OLD CROW (STATION 09FD003) EXPRESSED AS A FUNCTION OF THE ESTIMATED DISCHARGE (STATION 09FD002) WHEN 20 DEGREE-DAYS OF FREEZING ARE CUMULATED AT OLD CROW (DURING THE PRECEDING FALL). DATA FROM 1989 TO 1997 AND FROM 2006 TO 2024 IS USED.

Interestingly, the four most intense breakup events on record, those producing water levels above the 244.5 m elevation (red data in Figure 5.2.7), were all associated with an estimated low to average freeze-up flow (and assumed low intensity or ice consolidation). This could be interpreted from different angles:

- A low freeze-up elevation could translate into an early breakup event (after a limited stage rise at the end of winter) upstream of Old Crow. The premature formation of an ice jam below Old Crow (with an ice thickness that could still be significant) could create a resistant point against which subsequent ice runs pile up. Even if the ice jam toe was temporarily mobilized each time a jave occurs, the set of meanders in the Porcupine River downstream of Old Crow would not easily let an impeded ice run move past the Bluefish River confluence.

- It is possible that some breakup resistance in the Porcupine River near Old Crow is acquired through the process of grounding (the ice cover is frozen against a portion of the bed and does not float freely as the discharge increases in the spring).
- The discharge in the Porcupine River at Old Crow may be correlated to some extent with the discharge of the Bluefish River. If the ice cover in the Bluefish River freezes against its banks and bed, this condition may generate overflow and aufeis development at the delta (Km 360) may result.

Nonetheless, this logic seems to challenge the volumetric aspect of ice runs and ice jams that can cause flooding in Old Crow: a low freeze-up elevation (and intensity) could mean that there is less ice in the river (not in terms of thickness, but in terms of channel width). The role that freeze-up plays during the breakup period is confirmed in other rivers (e.g., Turcotte et al., 2024a,b), and it should be further investigated for the Porcupine River. If the lack of historical data or observations prevents such assessment, a form of direct freeze-up hydrological record should be initiated.

5.3. Breakup indicators at Old Crow

The preceding section revealed that simple and accessible parameters expected to correlate with the timing and intensity of breakup are apparently unreliable for forecasting purposes at Old Crow. In other words, parameters such as estimated flow prior to freeze-up and during breakup, estimated snow water equivalent (SWE) in April and May, cumulated degree-days of freezing (CDDF), and effective cumulated degree-days of thaw (ECDDT) may point towards a wide range of breakup timings and intensities, which is not useful. However, breakup along the Porcupine River must respond to driving and resisting forces, and there must be a way to identify reasonable indicators for those forces.

Unfortunately, several key hydrometeorological parameters have not been consistently monitored or documented over the years near Old Crow or in the Porcupine River watershed (or they have not been monitored over a long enough period). For example, the SWE in watersheds of major tributaries of the Porcupine River is currently poorly documented, historical air temperatures in the headwaters (potentially significantly different than air temperatures at Old Crow under most breakup scenarios) can only be derived from climate reanalysis products (e.g., ERA5-land), freeze-up conditions at different locations in the Porcupine River watershed are essentially unknown, and ice conditions in the river at the end of winter have not been documented (historical ice maps provide very little information before obvious open water areas and rough ice jams form).

Based on the assessment that has been completed using accessible data, intense breakup events that generate major ice runs and ice jam floods at Old Crow could be caused by one or more of the following criteria:

- More than 4000 CDDF at Old Crow at the end of winter,
- The occurrence of mid-winter thaws near Old Crow followed by extreme cold temperatures,
- A normal to above-normal late-winter SWE (e.g., above 85% of normal at five snow courses),
- Suddenly warm air temperatures in the headwaters (need to be measured or estimated),
- A discharge during breakup above 2500 m^3/s.

In turn, a thermal breakup scenario with no flooding could be anticipated for the following conditions:

- Less than 3800 CDDF at Old Crow,
- A very low snowpack (e.g., below 85% of normal at five snow courses),
- Cold temperatures during breakup upstream of Old Crow (needs to be measured or estimated),
- A discharge that remains below 2000 m^3/s during breakup.

In 2020, the discharge of the Whitestone River (WSC station 09FA001) after local breakup was estimated at about 800 m^3/s. Based on a simple watershed ratio calculation, this information alone suggested that the peak flow at Old Crow would have been on the order of 4000 m^3/s in the following couple of days, and this is exactly what materialized. Therefore, it is critical to obtain consistent water level data from that station as soon as snowmelt begins and to apply the rating curve as soon as the ice cover has been cleared from the local reach in order to foresee how breakup driving forces could evolve at Old Crow in the following hours and days. The use of reliable hydrological forecasts emphasizing headwater runoff rates could represent a significant benefit to breakup forecasting.

In terms of tracking ice movements in the Porcupine River upstream of Old Crow, it seems that the discontinued station 09FB001 (Porcupine River below Bell River) was important to detect major ice runs travelling towards Old Crow (Jasek, pers.com.). If a major ice run was observed at that location while the ice jam upstream of Old Crow is still in place or when the ice cover downstream of the community is still largely intact, this could inform the flood response. This additional volume of ice may not be needed for a flood to occur at Old Crow when the ice jam toe is located near Km 335. However, if the ice jam toe was located further downstream (e.g., Km 355), a flood in Old Crow could probably only happen if this additional ice volume was added to the jam.

Weather stations at Old Crow have not consistently documented sky conditions during May. This parameter plays a significant role in the heat budget (e.g., Ashton, 2013), including during the breakup period, because overcast conditions can be associated with a direct reduction of shortwave radiation that normally weakens the ice cover but also through the occurrence of (even light) snowfalls that protect the ice cover against solar radiation. Our research team has developed an empirical equation to estimate sky conditions near Old Crow based on air temperature variations to include it in the breakup forecast model (presented in Section 6), but this numerical tool can be improved.

Rain on snow events have not been investigated yet as a potential factor to account for during the breakup period in northern Yukon. This could be explored during the next phase of the project. A consolidated list of recommendations is presented in Section 7.

6. Prototype breakup model

6.1. Driving force indicators

Results presented in Section 5 are only partially useful to identify the best proxies for the forces acting on the ice cover of the Porcupine River near and below Old Crow to mobilize it. Also, as mentioned in Section 4, breakup may occur relatively quickly in the Porcupine River, which obscures the identification of those proxies. Therefore, river ice theory is used to support the development of useful breakup drive indicators (watershed scale, at least upstream of Old Crow):

- ➢ Late-winter and pre-breakup water supply-related indicators:
  - Snowpack in the watershed (snow courses located at Eagle Plain, Eagle River, Riffs Ridge, Old Crow, and Ogilvie River [this one is in another watershed], Figure 5.2.3). Ideally, the snowpack would also be monitored near hydrometric station 09FA001 (Whitestone River near the mouth),
  - Ripeness of the snow cover (ECDDT before noticeable runoff begins),
- ➢ Short-term, dynamic weather and ice condition-related indicators:
  - The swiftness of the transition from winter to (consistent) spring conditions (with above freezing night temperatures) in the headwaters (mainly down near the Whitestone-Miner confluence, but also in the Eagle River watershed),
  - The occurrence of widespread rain events in the headwaters,
  - Estimated or calculated flows during breakup (starting with the headwaters, but also based on local stage trends in the Porcupine River near Old Crow),
  - The occurrence of breakup downstream of the Driftwood River (Km 235),
  - The occurrence of an ice run through the canyon between Km 188 and 190,
  - The formation of a major ice jam between Km 313 and 295 (immediately upstream of Old Crow,
  - The occurrence of a major ice run through Old Crow associated with a significant rise in water levels (in the order of 2 m or more).

A temporary return to colder-than-average air temperatures in the headwaters (i.e., snow melting conditions only lasting a few days) can significantly attenuate the freshet surge, which would then favor the melting-in-place of ice jams that had originally formed dynamically.

6.2. Resisting force indicators

The river ice theory was also required to identify resisting force proxies, but results from Sections 4 and 5 offered a constructive complement. The breakup resistance is mainly associated with ice conditions from Old Crow at Km 315 to the Bluefish River confluence at Km 360:

- ➢ Fall to pre-breakup hydrological, weather and ice-related indicators:
  - Flow prior to freeze-up (a lower flow seems to favor ice jam occurrence) or weather instabilities during freeze-up,
  - The confirmed existence of freeze-up jams (mainly between Km 320 and 330 or between Km 345 and 360),
  - The occurrence of mid-winter rain events or mid-winter thaws,

  - The confirmed presence or lack of a thick and/or extensive aufeis at the outlet of the Bluefish River (Km 360),
  - Winter coldness (a threshold of 4000 CDDF could tentatively indicate more resistance) or the number of significant, individual cold spells,
  - Ice cover reflectance, or albedo (a highly reflective ice cover or ice covered with a fresh layer of snow would represent a higher resistance)
- Short-term ice and snow condition-related indicators:
  - Local air temperatures during breakup (e.g., freeze-thaw cycles, consistent warm conditions, or consistently cold local conditions),
  - Sky conditions during breakup (i.e., cloud coverage),
  - Ice cover albedo throughout the breakup period (e.g., presence of new snow, highly reflective ice crystals, degraded ice, water on ice),
  - Formation of an ice jam downstream of Old Crow (with special attention to Km 340 and 355).

Unlike driving forces, which generally rise but can also stabilize and even decrease during the breakup period, resisting forces tend to only decline as breakup progresses (unless an ice jam, with the toe anchored against the riverbanks or aufeis, forms downstream of Old Crow).

6.3. Model development

The intention of the authors is to develop a model that forecasts both the timing and the intensity of river ice breakup in a reach of the Porcupine River extending from Km 315 (Old Crow) to Km 360 (the Bluefish River confluence). Along that reach, an ice jam can generate a significant rise in water levels that affects the community. 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 that can be found in the textbook edited by Beltaos (2009). The model translates input parameters into daily breakup drive and resistance forces. When the driving force becomes higher than the resisting force, breakup occurs. The timing of breakup is indicated on the X axis and the intensity of breakup corresponds to the intersection of the forces on the Y axis. The breakup intensity is also visually supported by a colour index ranging from green (thermal breakup, no flooding should occur) to red (dynamic breakup, flooding is likely to occur). The forecast perspective of the model is limited by the accuracy of regional weather forecasts. It is recommended to consider the difference in climate model forecasts (e.g., GEM, GFS, ICON, ECMWF) for Old Crow (and in the headwater regions, to guide an approximate flow forecast if no hydrological model is used) before entering the data into the breakup model spreadsheet. Note that the prototype version of the model begins on April 15 (no expected runoff or ice degradation before that).

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, either in single cells or in time-dependant columns).

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

Parameter	Source	Physical role/impact
Freeze-up intensity (e.g., ice cover reflectance) **(optional)**	Sentinel 1 and reported observations	Affecting ice thickness t_{ice} calculation if ice thickness is not measured
Late winter ice thickness t_{ice} **(optional)**	WSC, reported measurements (ideally from different sites)	Used to calculate resisting forces
Maximum cumulative degree-days of freezing $CDDF_{max}$ **(optional)**	ECCC station 2100807	Used to roughly assess t_{ice} if it is not measured
Maximum daily air temperature $T_{air\ max}$	ECCC station 2100807	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 300 to 380	Reduces shortwave radiation (SW_{net}) affecting ice cover integrity, or strength.
Observed open water ratio *OW*	Sentinel-2, Km 315 to 360	Affects shortwave (*SW*) absorption
Observed, spatially averaged, ice cover surface albedo $Albedo_{ice}$	Sentinel-2, Km 315 to 360	Controls shortwave radiation (SW_{net}) absorption by the ice cover, affecting its integrity, or strength.
Late winter aufeis at Bluefish River (optional)	Observations from WSC, Sentinel 1 or 2, or community members	Affects the calculation of the resisting force F_r downstream of Old Crow
State of aufeis degradation $\mathrm{Auf}_{\mathrm{deg}}$	Observation from Sentinel 2 or flight surveys	
Water level in the Porcupine River at the boundary $\mathrm{Y}_{\mathrm{boun}}$	WSC station 09FD002	Used to estimate the discharge at Old Crow (Q_{estOC}) one day before and the backwater (*BW*). This ultimately impacts the calculation of the flow velocity (*U*), and shear stress.
Ice-induced water level variations at the boundary Y_{rises} **(when occurring)**		
Last winter discharge (*Q*) measurement in the Porcupine River near the Alaska Border	WSC station 09FD002 or NHS Hydrological North (contact at ECCC for historical WSC data)	Used to estimate the April 15 ice-induced backwater (*BW*)
Water level (*Y*) during the last winter disch. measurement		
Discharge in the headwaters ($\mathrm{Q}_{\mathrm{whitestone}}$, $\mathrm{Q}_{\mathrm{Eagle}}$) (**optional**)	WSC stations 09FA001 and 09FB002	Used to estimate the discharge at Old Crow (Q_{estOC}) two days later
Local stage in Old Crow (**optional**)	WSC station 09FD003	For visual purposes, to support the estimation of the local flow
Confirmed or anticipated presence and intensity of ice jams upstream of, or at, Old Crow *Loc. Jam* **(when occurring)**	WSC station 09DF003, Sentinel-2, local observations, informed anticipation based on ice coverage and presence of small or large upstream ice jams	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 takes into account several processes (Table 6.3.1) that influence river ice breakup timing and intensity:

- Presence of freeze-up jams (any value between 0 and 1) and ice cover thickness (cm) and aufeis at the Bluefish River confluence,
- Degradation of the ice cover over time (using shortwave radiation and considering cloud coverage and ice surface albedo, in Watt-days per cubic meter, W d/m^3),
- Melting of the ice cover (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 ice jam-release waves, or 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 shear stress into a driving force (MN) is completed using the Boundary Constraint Criterion (Beltaos, 2009, equation 6.10, which emphasizes 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 Old Crow). In its current, prototype state of development, the model does not consider a rise in resistance caused by a consolidated ice jam with forces absorbed by the channel banks (or bed), but rather always considers the resistance of the ice cover downstream of the ice jam toe.

The river ice breakup model is structured around physics-based empirical equations and calibration parameters or constants. These 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 0.017,
- An estimated cloud coverage ($Cloud_{emp}$) based on daily air temperature variations with empirical variables calibrated using Sentinel-2 imagery (cloud coverage observations, to be used when $Cloud_{obs}$ are not available). Clouds had been outlined by Jasek (1997) as an important factor controlling breakup.
- Absorption of shortwave radiation by the snow at the ice cover surface for highly reflective cover values (high $Albedo_{ice}$) and until the snowpack on the ice is mostly depleted,
- 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 the Porcupine River at the border 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 site-specific empirical parameters,
- The backwater (*BW*) induced by the presence of an ice cover or an ice jam with an initial value estimated using a discharge measurement and stage (generally at the end of winter),
- Watershed ratios to transfer discharge estimated at different upstream sites to Old Crow,
- 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 (thermal erosion) at the ice-water interface,
- A channel gradient (*Slope*, initially estimated to 0.023%) that accounts for the occurrence of javes of varying intensities (proportionally increasing the driving force).

The possible range of the end-of-winter breakup resisting forces is relatively wide, varying from 22 MN to 55 MN. Therefore, the model is relatively sensitive to ice cover related variables (e.g., ice thickness, presence of freeze-up consolidations, presence of an extensive aufeis). The time-dependent ice surface albedo also has a significant impact on the calculation of the residual breakup resisting force. Sentinel 2 images are presented in Appendix B to guide the selection of reasonable albedo values to improve the representativeness of the ice cover degradation over time. In turn, the most sensitive breakup driving parameters are the presence (or expected formation) of a local ice jam and the occurrence (and expected occurrence) of javes (unsteady aspect of the model). This sensitivity reflects the actual impact of these thermal and dynamic processes on an ice cover that has not yet been set in motion: if the flow does not increase, the shear stress remains low and ice movements upstream of Old Crow would be limited; therefore, there would be little incentive for the downstream ice cover to become fragmented. In this case, it is likely that open water areas would gradually expand over time until the residual resistance of the ice cover becomes low enough that the ice cover (degraded, or candled) collapses and creates its own, local instabilities. Table 6.3.2 is meant to guide the judgment of model users in defining appropriate *Loc. Jam* and *Jave* values for current and 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 types in front of Old Crow. Minor stage rise	0.1 – 0.2
	Minor ice jam at or downstream of Old Crow. Stage rise in the order of 1 to 2 m.	0.3 - 0.4
	Moderate ice jam with a toe between Km 335 and 355. Flow in the order of 2500 m^3/s. Possible flooding at Old Crow	0.5. – 0.7
	Major ice jam downstream of Old Crow. Flow above 3000 m^3/s, likely flooding at Old Crow (if ice jam head extends upstream of Km 330)	0.8 – 1.0
Jave	No ice movements upstream of Old Crow. Local stage signal is smooth.	0, default
	Some ice movements downstream of the Bell River. Stage fluctuations at Old Crow in the order of 0.1 m	0.1 – 0.2
	Presence of small to moderate ice jams between the Driftwood River (Km 235) and Old Crow. Stage fluctuations in the order of 0.5 m.	0.3 - 0.4
	Presence of a moderate to major ice jam between Km 313 and 325 (just upstream of Old Crow). More ice travelling towards this jam. Discharge rising above 2500 m^3/s. Stage rise of 2-4 m during jave	0.5 – 0.7
	Major to extreme ice jam above Old Crow (more than 30 km-long, flooding observed) or major ice run travelling towards Old Crow (more than 50 km-long with full concentration, including ice from above Km 190). Flow rising above 3000 m^3/s. Stage rise > 4 m during jave.	0.8 – 1.0

6.4. Example of model use – Spring 2020

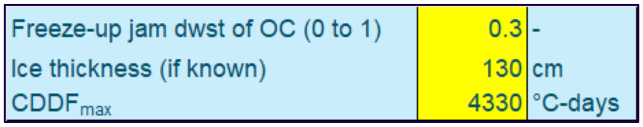
The prototype of the model was developed using data from spring 2021. Several parameters were then adjusted and calibrated using breakup data from spring 2019 and 2023. The model was then tested during the breakup of 2024. Some adjustments were completed to respond to comments from the Government of Yukon. This section presents a new test of the model to reconstruct the breakup event of 2020.

The monitoring of this breakup event was affected by COVID-19. The Water Survey of Canada (WSC) station 09FD003 (Porcupine River at Old Crow) was turned on only a few hours before the peak water level of the year (evening of May 12). This section presents an example of model use in this specific context (if the model had been available then).

6.4.1. Starting the model on April 15

Sentinel 1 (SAR urban filter) revealed that the post-freeze-up ice cover appeared relatively smooth downstream of Old Crow, with no obvious consolidations. It was therefore established that the freeze-up intensity (that affects the ice cover resistance downstream of Old Crow) was below average. On the other hand, the usual freeze-up jam had formed just upstream of Old Crow, at Km 313, and the flood forecaster would have to keep in mind that the potential for an intense jave in the next few weeks would be relatively high.

WSC had reported an ice cover thickness of 125 cm at station 09FD002 on March 14, when about 3600°C-days had been accumulated. Using judgment, given the maximum CDDF of 4200°C-days on April 15, it was decided to impose a slightly thicker cover. Initial breakup resistance conditions were set as:



Freeze-up jam dwst of OC (0 to 1)	0.3	-
Ice thickness (if known)	130	cm
$CDDF_{max}$	4330	°C-days

Aufeis conditions at the confluence of the Bluefish River (Km 360) had not been documented (or this data could not be accessed) and the delta remained hidden under the snowpack during April. The aufeis intensity input parameter was left blank until more information could be obtained.

The winter period ended with an ice cover albedo ($Albedo_{ice}$) of 0.9 (white cover with fresh snow, theoretical value) as well as an open water ratio (OW_{ratio}) of 0% (as revealed by Sentinel 2). These values are typical of the Porcupine River in mid-April. The April 15 resisting force (F_r) of the ice cover downstream of Old Crow was estimated to be 41 MN.

The flow in the Porcupine River at station 09DF002 (near the Alaska Border) was not known because of COVID-19-related access challenges. The late-winter discharge of the river does not really impact the accuracy of the model in the following weeks, but a value is needed to initiate the calculation. Typical values of 7.1 m for the stage and 87% for the backwater were adopted. The initial flow was therefore estimated to be 21 m^3/s using the model's rating curve. This translated into a breakup driving force (F_d) of 0.8 MN.

6.4.2. Conditions on May 5

Cold temperatures persisted until the end of April, and hydrological and ice conditions on the Porcupine River did not change substantially during that time.

The contour of the Bluefish River aufeis only became visible on the Sentinel 2 image on May 3: It extended to the opposite bank of the Porcupine River, and it was about 1.5 km-long (in the Porcupine River, Sentinel 2 False colour filter, Figure 6.4.1). While ignoring its thickness, its blockage effect was potentially substantial, and an aufeis intensity value of 0.6 was estimated (on a scale of 0 to 1).

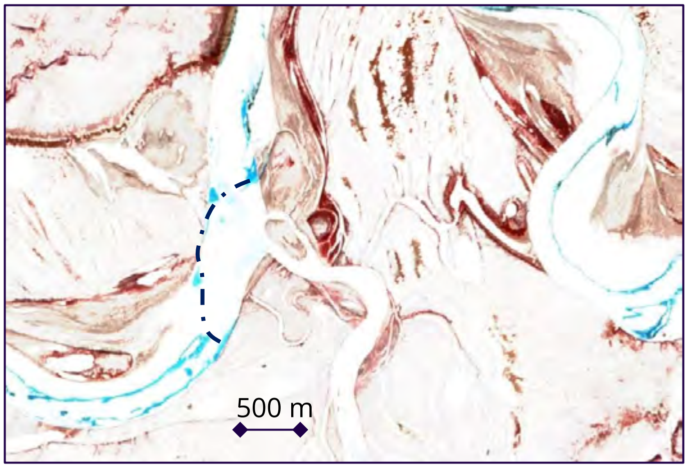


FIGURE 6.4.1. COPERNICUS SENTINEL-2 IMAGE (FALSE COLOUR) FOR MAY 3, 2020, SHOWING THE DELTA OF THE BLUEFISH RIVER IN THE PORCUPINE RIVER. THE BLACK DOTTED LINE DELINEATES THE AUFEIS.

ECDDT started accumulating on May 5. At that moment, the value of $Albedo_{ice}$ had barely changed and remained high: 0.85. The reduction was associated with the presence of water on about 15% of the ice cover at and downstream of Old Crow. Note that thin layers of new snow (or the freezing of that surficial water) seemed to accumulate on the ice (or to occur) at least twice during breakup. This contributed to maintaining a relatively high ice cover albedo despite the sunny conditions. Small open water segments were visible, and the value of OW_{ratio} was set to 2% (exactitude not critical for the model accuracy at that point).

No information had yet been obtained regarding flow conditions, but the confluence of the Whitestone River and Miner River was still snow covered. It was assumed that spring runoff had not started yet. Values of F_r and F_d remained unchanged.

6.4.3. Conditions on May 9

On May 9, 2020, air temperatures were supposed to be relatively high in Old Crow as well as in the headwaters. ECDDT was 35°C-days and this variable would rise steadily in the next few days. The value of $Albedo_{ice}$ had dropped to 0.7 (extensive areas of exposed thermal ice) and the value of OW_{ratio} was now about 5% (Figure 6.4.2). The aufeis at the Bluefish River confluence still appeared intact (the value of Auf_{deg} remained at 1.0). The resistance of the ice cover downstream of Old Crow (F_d) remained high at 35 MN, and it could drop to 25 MN by May 12 (based on the weather forecast).

FIGURE 6.4.2. COPERNICUS SENTINEL-2 IMAGE (TRUE COLOUR) FOR MAY 8, 2020, SHOWING KM 343 TO 362 OF THE PORCUPINE RIVER. THE BLUEFISH RIVER AUFEIS APPEARS INTACT WHEREAS THE UPSTREAM ICE COVER (ON THE RIGHT) IS BECOMING EXPOSED TO SHORTWAVE RADIATION.

No hydrological information (water levels) was yet available on May 9, but it could be assumed that the flow in the Porcupine River had slightly increased to about 50 to 100 m^3/s. Given the intact state of the ice cover upstream of Old Crow, values of *Loc. Jam* and *Jave* were still 0 (blank). A hydrological model could have suggested that the flow would rise sharply in the headwaters in the following few days, but such a tool was not yet available. However, the snowpack on May 1 was about 150% of normal in the watershed, hence snowmelt runoff would not represent a limitation to breakup intensity.

River ice conditions on May 9 suggested that active river ice monitoring surveys should be initiated on the Porcupine River in the following day.

6.4.4. Breakup on May 12-13

On May 11, a report of very high flow, ice-free conditions, and signs of a dynamic breakup at the Whitestone River and Miner River confluence was transmitted from WSC staff to the flood forecaster. Considering the estimated flow of about 800 m^3/s at the Whitestone River station 09FA001, a simple watershed ratio calculation (performed by the model) suggested that the flow at Old Crow could rise to about 4000 m^3/s in the next 24 to 48 hours. Remembering the freeze-up jam at Km 313, the value of the *jave* intensity was set to 0.7 for May 12 and May 13. The combination of input parameters indicated that a relatively intense breakup with potential flooding (yellow to orange area of the model, Section 6.4.5) could occur in the next 24 to 48 hours at and downstream of Old Crow.

Flight observations on May 12 confirmed flooding near Km 105 (high flow and ice jam), an ice cover still in place upstream of the Bell River confluence (Figure 6.4.3), and an ice jam at Km 185 (Figure 6.4.4). This represented fair news as it indicated that the amount of ice travelling towards Old Crow would not be at its maximum possible value (heat would also make the ice melt).

FIGURE 6.4.3. CONFLUENCE OF THE PORCUPINE RIVER AND BELL RIVER (LOOKING EAST) SHOWING INTACT ICE COVER ON MAY 12 AT 4:45 PM (ONLY LAST 3 KM OF THE BELL RIVER ARE OPEN.

FIGURE 6.4.4. INTACT ICE COVER AT KM 188 AND JUXTAPOSED ICE JAM UPSTREAM OF THAT POINT ON MAY 12 AT 4:45 PM.

Further downstream, however, the ice cover between Km 190 and 305 had entirely been mobilized, and the ice run was accumulating against an ice jam whose toe was located at Km 313 (Figure 6.4.5). This jam could release at any time.

FIGURE 6.4.5. TOE AREA OF THE ICE JAM UPSTREAM OF OLD CROW ON MAY 12 AT ABOUT 5:15 PM. THE OLD CROW AIRSTRIP IS VISIBLE IN THE BACKGROUND (LOOKING NORTHWEST).

A small ice jam composed of local ice had formed at Km 320 (value of *Loc.Jam* set to 0.3). Further downstream, the ice cover between Old Crow (Km 320) and the Bluefish River (Km 360) was somewhat degraded, but it had not shifted. The aufeis at the mouth of the Bluefish River was covered by an ice jam (from that river) and by overflow, but it was assumed that its integrity was still about 0.8 (Auf_{deg}). Overall, the downstream resistance to breakup F_r was 25 MN.

FIGURE 6.4.6. DELTA OF THE BLUEFISH RIVER UNDER ICE RUBBLE AND WATER ON MAY 12 AT 5:45 PM.

The Km 313 ice jam released at around 7:00 pm on May 12 (at an ECDDT of 65 °C-days). The ice ran at full concentration on the Porcupine River at Old Crow for several hours. Minor flooding was observed at about 9:00 pm and the stage peaked at about 10:00 pm. Water level measurements reported by WSC from station 09FD003 suggest that the ice run managed to plow through the intact (but degraded) ice cover down to the Bluefish River without stopping (the driving force was higher than the resisting force, and the occurrence of a short-lived ice jam upstream of the Bluefish River could not be confirmed). Subsequent ice runs from above Km 190 followed over the next few days. However, the peak stage of the year was caused by the impeded ice run on the evening of May 12.

6.4.5. 2020 Model results

With the information that was available at that time, breakup timing and intensity could have only been forecasted 3-4 days in advance, at the most. Questions arise about the extension of that horizon in a context where all WSC stations would have been fully operational at the beginning of May. Given the swiftness of the snowmelt runoff event in 2020, a common scenario (Janowicz, 2017, Table 4.5.1), it seems that the proposed model prototype is most useful to evaluate the potential intensity of breakup by considering different runoff scenarios. Overall, if values of $Albedo_{ice}$ are reasonably representative, and if ice cover-related parameters are available on April 15, time dependent values of F_r should be fairly accurate. Then, a combination of information sources (i.e., water level rise and variations at Old Crow, ice conditions between Km 140 and 315) could support the estimation of reasonable *Loc. Jam* and *Jave* input values that largely dictate the breakup driving force F_d (their intensity is generally proportional to the water level and flow).

Figure 6.4.7 presents the results of the breakup model, based on information compiled several years later (the model was only created in 2024). Given the drastic change in hydrological conditions (driving forces) between May 11 and May 13, even if the model had been used with limited data back in 2020, there would have been limited room for performance failure. What is comforting about the results from Figure 6.4.7 is that breakup occurred at a force of about 20 to 25 MN and this level of intensity (yellow) is in agreement with the peak stage of 244.30 m at station 09FD003 in Old Crow and with the occurrence of minor flooding. Model results from additional years are compared with maximum stage at station 09FD003 in Figure 6.4.8. The trend and correlation appear reasonably consistent, but a wider range of breakup scenarios would be needed to confirm model performance.

Although the authors and users agree that learning how the model works will take some time, it is encouraging to know that a physics-based simulation tool can now be used to understand the river ice breakup of the Porcupine River at Old Crow. The next challenge for model developers and flood forecasters will be to test it in a scenario involving an ice jam between Km 335 and 355 (where F_d and F_r would be comparable for the duration of the jam). The next phase of the project will test the model for the breakup event of 2022 (as well as other years after 2024).

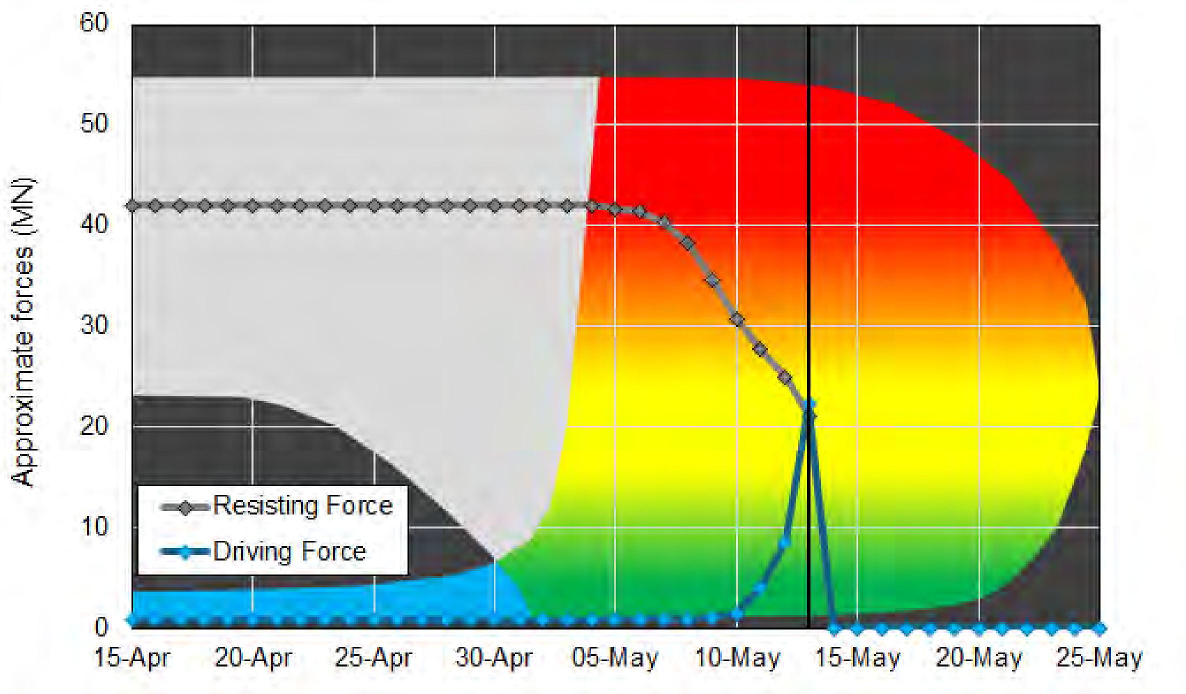


FIGURE 6.4.7. MODEL RESULTS FOR THE 2020 BREAKUP EVENT. THE COLOURED AREA REPRESENTS THE POSSIBLE BREAKUP TIMING AND INTENSITY, BASED ON DOCUMENTED HISTORICAL EVENTS AND THEORETICAL CONSIDERATIONS. BREAKUP OCCURS BETWEEN MAY 12 AND MAY 13 DOWNSTREAM OF OLD CROW.

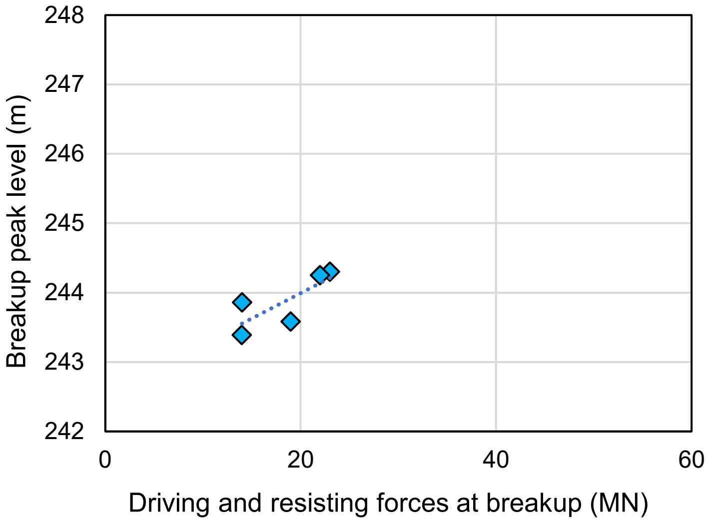


FIGURE 6.4.8. BREAKUP PEAK WATER LEVELS EXPRESSED AS A FUNCTION OF ESTIMATED BREAKUP DRIVING AND RESISTING FORCES AT THE TIME OF BREAKUP. YEARS 2019, 2020, 2021, 2023, AND 2024 ARE USED. A LARGE SCALE IS USED TO ILLUSTRATE THE POSSIBLE RANGE OF MISSING BREAKUP SCENARIOS.

7. Summary and recommendations

Historical data and recent observations were analyzed to improve our knowledge about the spatial and temporal aspects of river ice breakup on the Porcupine River (Ch'oodeenjìk) in the traditional territory of the Vuntut Gwitchin First Nation. Sections 4 and 5 of this report presented important updates about the spring breakup regime of this unique northern river since Jasek (1997) presented a paper on the same topic a few decades ago. The current report greatly benefited from free online access to satellite imagery (Copernicus Sentinel Hub) that provides a snapshot of ice conditions almost every day. The prototype of a new physics-based, 0D, breakup forecast model was introduced in Section 6. This model can be used to forecast the timing and the intensity of spring breakup on the Porcupine River at Old with a horizon that is mostly limited by real-time hydrometeorological data and weather forecasts.

The authors propose a list of recommendations to support further knowledge development about the spring breakup regime of the Porcupine River:

- Develop a respectful collaboration with the Vuntut Gwitchin Government and Old Crow citizens to create a space for sharing knowledge about the winter behaviour of the Ch'oodeenjìk, its tributaries, and its different forms of ice,
- Promote the collection of continuous data (e.g., hydrometric and weather data), spatially distributed data (e.g., ice thickness measurements) and observations as they relate to freeze-up, mid-winter and breakup. The reaches of interest extend from Km 140 (30 km upstream of the Bell River confluence) to Km 380 (20 km downstream of the Bluefish River). Special attention should be given to ice conditions between Km 310 (meander upstream of Old Crow) to Km 360, including the annual aufeis that forms at the confluence of the Bluefish River,
- Install a weather station (two independent air temperature sensors at a minimum, to reduce the possibility of record gaps) near the confluence of the Whitestone River and Minor River to better foresee the onset of snowmelt in the headwaters of the Porcupine River. This represents the most important monitoring gap for breakup forecasting in the watershed,
- Use reanalyses weather products to reconstruct historical air temperature data at the above-mentioned confluence, starting with years where breakup on the Porcupine River resulted in ice-jam flooding at Old Crow,
- Improve the reliability of stations 09FD002 and 09FA001 during the winter period, operate station 09FD003 (Porcupine River at Old Crow) from April to December (instead of May to October), and consider reestablishing station 09FB001 (Porcupine River below Bell River) or another seasonal (April to June) station near Km 190 or the Driftwood confluence (for water levels only). New technologies could contribute to a more resilient monitoring system in the Porcupine River watershed,
- Complete a complementary investigation of the impact of freeze-up elevations on breakup patterns and breakup intensity. Some information suggests that a low freeze-up level could generate higher water levels in the spring. There must be a link between flows during freeze-up, elevation of the ice cover after freeze-up, and the presence of freeze-up jams,

- Consider measuring the flow in the Porcupine River at Old Crow prior to or immediately after the main annual ice run, if ice conditions appear adequate. This information would be useful to better understand the factors leading to the formation of ice jams downstream of Old Crow,
- Support the development of a community monitoring program to measure the thickness of the ice cover prior to the onset of breakup at a few locations between Old Crow and the Bluefish River. This should include documenting the spatial extent and surface elevation of the Bluefish River aufeis. This data will contribute to calibrate future versions of the river ice breakup model,
- Generate a high-accuracy profile of the Porcupine River from its headwaters (Water Survey of Canada station 09FA001 on the Whitestone River) to the Alaska Boundary (WSC station 09FD002) using the recently accessible SWOT data. This spatial information will help improve our understanding about freeze-up and breakup patterns of the Porcupine River, therefore explaining, at least in part, the location of dominant (and unusual) ice jam locations,
- Investigate how mid-winter thaws and rain-on-snow events impact river ice conditions on the Porcupine River, with special attention to the Bluefish River aufeis (in 1991, the breakup flood was preceded by a winter with significant air temperature variations),
- Reconstruct breakup hydrographs for any available year and hydrometric station in the watershed, using all the data accessible, in order to improve the results presented in Figure 5.2.2. The discharge is a key parameter directly and indirectly influencing the calculation of the driving force in the model, and it would be important to gain a better understanding of its impact on ice processes,
- Improve RCM- and Sentinel-1-derived ice maps by adjusting the backscatter classification to clearly differentiate ice conditions. Ice maps are of limited use in the spring until the backscatter of the ice cover becomes spatially diverse (when breakup begins), and in a river where breakup occurs rapidly, forecasters cannot afford to lose a single day of data,
- Continue to support observational data collection from the air as more detail can be acquired at low elevation over several minutes than from space in a second,
- In the context of climate change, perform a morphological study emphasizing the stability of upstream and downstream reaches to assess how the main river channel and its tributaries are evolving over time. For example, if the river is becoming wider and shallower over time, this will certainly impact the breakup regime.

Possible modifications to the prototype model would include (there is no certainty that this will make the model more accurate or more reliable):

- In a context where this model should remain simple (and 0D), improve the representativeness of the river cross-section used for calculating the driving force. The prototype version of the model includes an approximate cross-section near Km 355,
- Identify and apply a methodology that better captures the effect of changing ice roughness conditions on Manning’s n. The current version of the model considers an increase in average ice undercover roughness as a result of thermal erosion (e.g., ripples forming at the

underside of the ice cover, which is commonly observed on stranded ice floes that have been flipped over during breakup), but it also considers an increase in average roughness when ice jams form, independently of their length and location. There may be value in better capturing this specific aspect of breakup,

- Similarly to the point mentioned above, the increased thickness of the ice cover resulting from the formation of an ice jam could also be better represented in the calculation of the downstream ice cover weight component that is included in the calculation of the driving force,
- A Manning (instead of a backwater) approach could be adopted to support the evaluation of the discharge in the Porcupine River. The model could also enable the discharge to be estimated (or imposed) at Old Crow (station 09DF003) in addition to other locations (09FD002, 09FA001, 09FB002),
- Once the impact of varying freeze-up scenarios on breakup resisting forces is better understood, improve the representation and role of key freeze-up parameters (e.g., flow, level, backscatter) in the model. The key question is: what aspects of freeze-up mostly influence breakup: 1. freeze-up jams (possibly high fall flow; included in the current model), 2. ice grounding (low fall flow), 3. early mobilization of the ice cover in the spring (low fall flow)?
- Explore alternative options to calculate the driving force applied to the downstream ice cover. The current prototype uses the Boundary Constrain Criterion (Beltaos, 2008) that considers meander bends as a limitation to breakup. In the Porcupine River, the downstream movement of thick ice slabs have been observed to be limited by thigh meander bends, but also by channel narrowing and by the presence of mid-channel gravel bars or aufeis,
- Include a module that simulates an increase in ice cover resistance forces when an ice jam is anchored against the banks or bed. This will become useful to simulate the possible duration of ice jam floods beyond 24 hours (one time step). This new module could be calibrated using data from the breakup event of 2022,
- Allow users to input different hydrometeorological forecasts (or current conditions) in the model in order to represent an uncertainty range in the breakup forecast. This range of uncertainty will probably be reduced as users gain experience with the model,
- Taking advantage of the hydrodynamic HEC RAS model developed for flood mapping purposes at Old Crow, update the figure presented at the end of Jasek's (1997) paper that evaluates possible water surface elevations at Old Crow for a range of flows and ice jam head locations. This tool would nicely complement the breakup intensity aspect of the current model.

The proposed model improvements should not significantly alter its complexity. The model will still require the judgement and experience of users (i.e., flood forecasts and researchers), who will in turn learn from its successes and inaccuracies.

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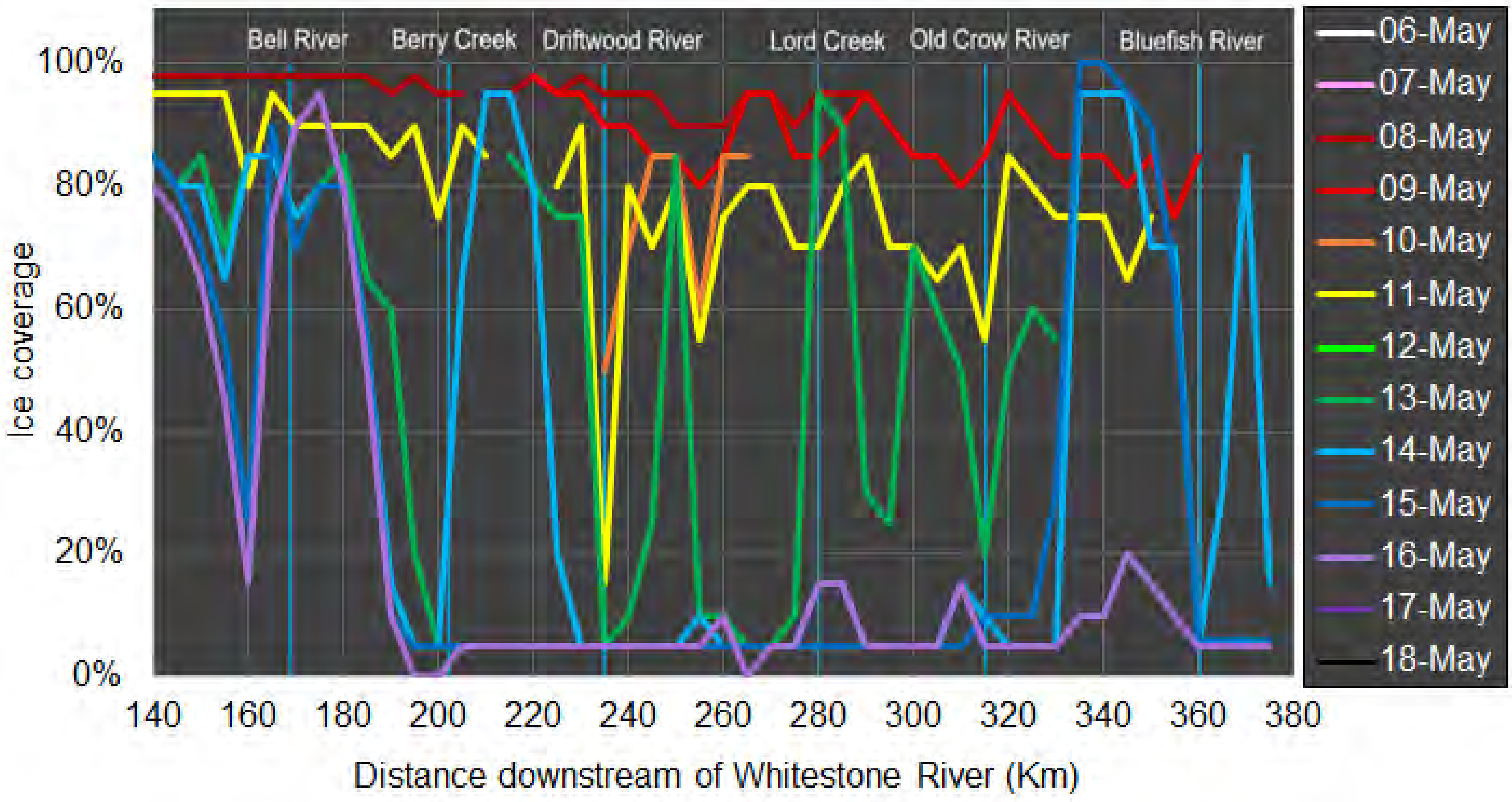
Appendix A:

Cryograph from spring 2024.

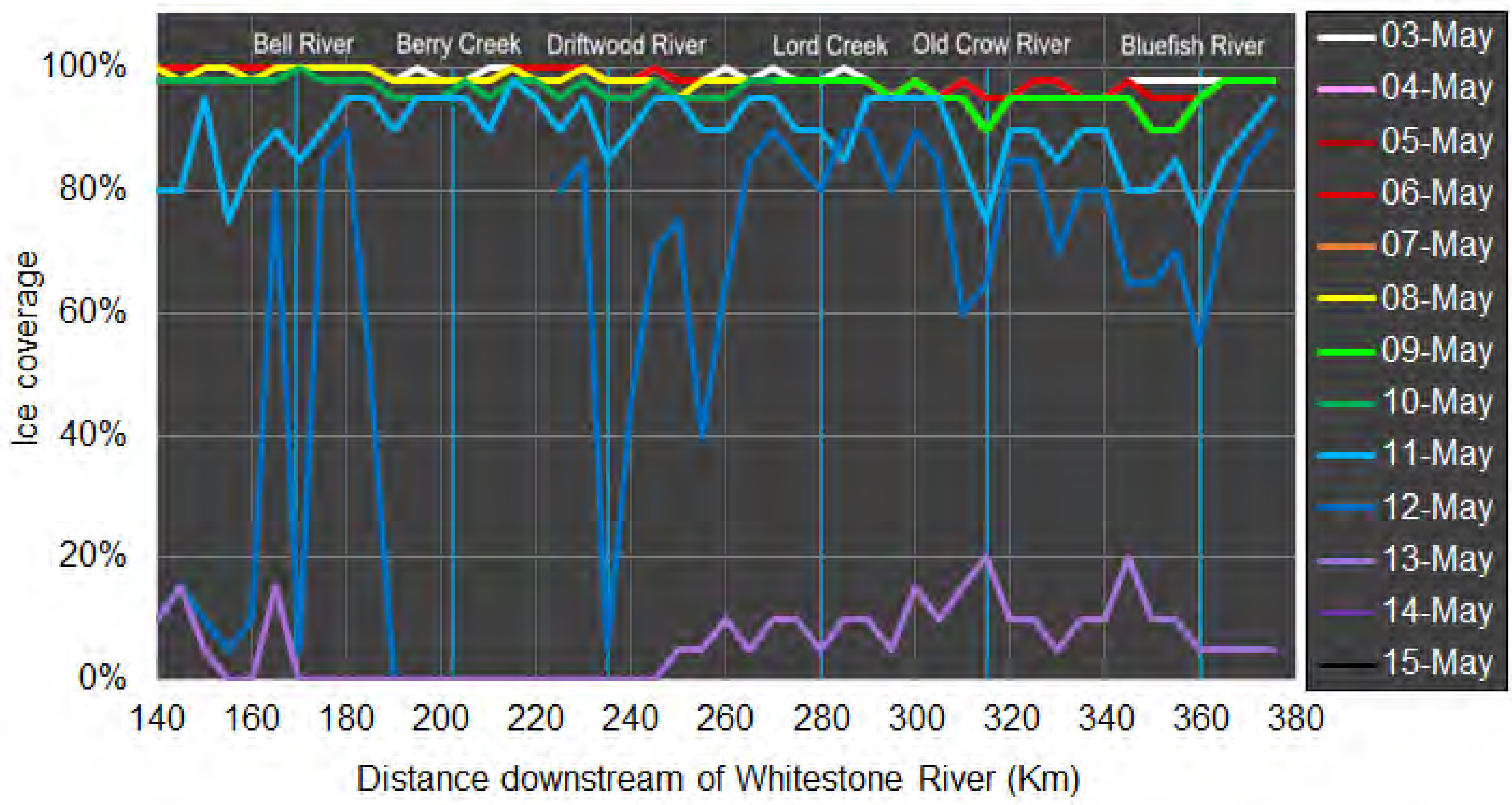
Cryograph from spring 2023.

Cryograph from spring 2022.

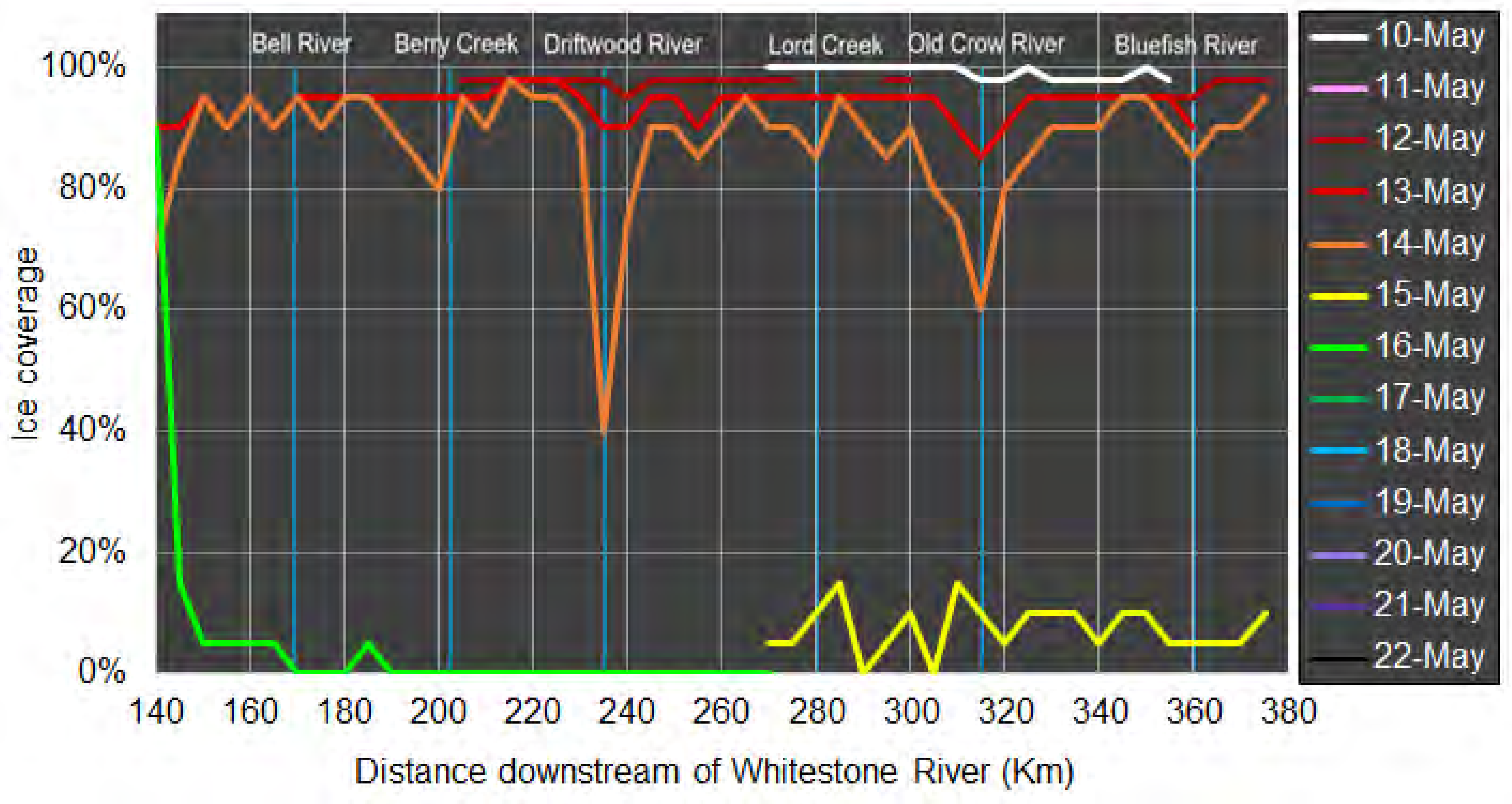


Cryograph from spring 2021.

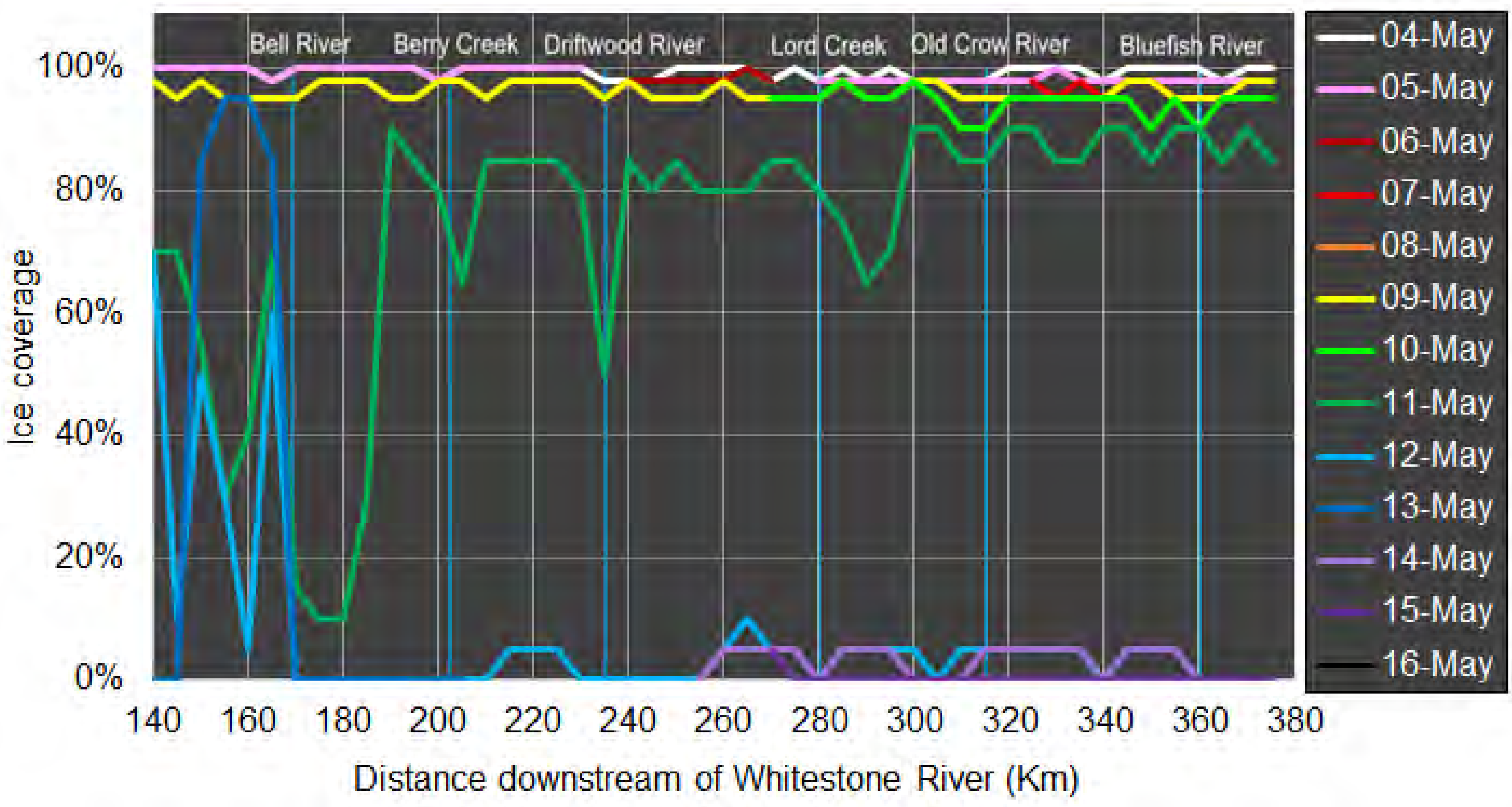
Cryograph from spring 2020.



Cryograph from spring 2019.



Cryograph from spring 2018.

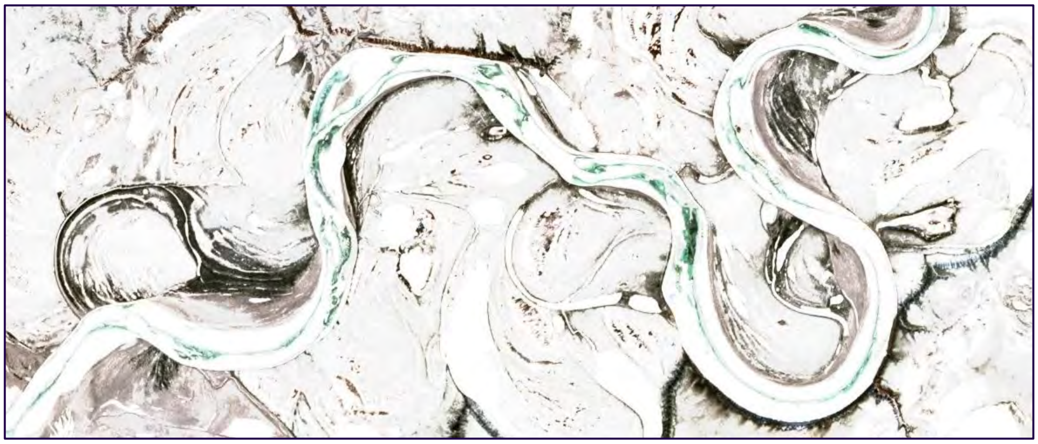


Appendix B

The following Copernicus Sentinel-2 images (using the True Colour) can be considered as a guide to determine the albedo of the ice cover surface on the Porcupine River during breakup.

Albedo of about 0.9 (open water ratio of 0%)

Albedo of about 0.85 (open water ratio estimated to 1%)



Albedo of about 0.7 (open water ratio estimated to 10%)