Yukon University

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

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Executive Summary

River ice breakup sequences and hydrometeorological controls were investigated for the lower 50 km of the Klondike River near Dawson. Eight years of river ice observations were used to determine areas where the ice cover is weaker or stronger than average as breakup unfolds (Figure 4.1.1). Results reveal an important heterogeneity in the ice cover's resistance (or resilience to melt and degradation) with the weakest segments located in the mine tailings area and the strongest segments near Rock Creek and above Henderson Corner. The same spatial information was analyzed to evaluate the role of the tributaries during thermal and dynamic breakup scenarios (Table 4.2.1). It appears that most tributaries have a limited influence on breakup patterns and scenarios. The assessment of historical freeze-up congestions (Figure 4.3.1) and breakup ice jam locations (Figure 4.4.1) was largely inconclusive, in part because of the lack of observations (in the fall) and because of the broad range of possible breakup patterns. Nonetheless, a typical breakup sequence was proposed (Table 4.5.1) and locations where major ice jams form (including dominant ice jam locations where ice rubble accumulates on an annual or quasi annual basis and where flooding may happen) have been identified (Figure 4.4.2, Figure 4.6.1, Table 4.6.1; all kilometres measured from the Yukon River going upstream):

Location	**Impacted area**	**Frequency**	**Damage**	**Mobilisation**
Km 2-3	C-4 (Tr'ondëk) Sub., Klondike Highway bridge	Annual	Possible	< 250 m^3/s
Km 5-6	Eureka Drive	Annual	Unlikely	< 250 m^3/s
Km 12-13	Former beach area, Bear Creek Dev. Area	Annual	Unlikely	**>** 250 m^3/s
Km 17-18	Tr'ondëk Hwëtch'in Farm	Annual	Likely	**>** 250 m^3/s
Km 21-22	Rock Creek	Occasional	Likely	< 250 m^3/s
Km 23-24	Klondike Highway above Rock Creek	Annual	Unlikely	**>** 250 m^3/s
Km 25-26	Henderson Corner	Occasional	Likely	< 250 m^3/s
Km 30-32	Near Km post 686 of Klondike Highway	Annual	Unlikely	**>** 250 m^3/s
Km 45-46	Dempster Highway bridge	Annual	Possible	< 125 m^3/s

In terms of hydrometeorological controls, the analysis of 23 to 36 years of data (Table 5.1.1) suggests that the timing of breakup at Water Survey of Canada station 09EA003 (Klondike River above Bonanza Creek, at the Klondike Highway bridge) can be somewhat predicted using air temperature indicators (Figure 5.2.5 and Figure 5.2.6). The intensity of breakup at the same location seems to be a function of freeze-up intensity (Figure 5.2.8) and discharge during breakup (Figure 5.2.2): the presence of a freeze-up jam combined with a sudden rise in discharge represents the most critical scenario for flooding at that location. Large ice jams have been reported to occur when the April 1 snowpack is > 75% of normal at four Government of Yukon snow courses (snow rarely represents a limitation to ice jam flooding). It seems that the winter coldness (cumulated degree-days of freezing, Figure 5.2.7) and the ice cover degradation (effective cumulated degree-days of thaw, Figure 5.2.1) do not significantly influence breakup scenarios.

The authors recommend developing a river ice breakup model for the Klondike River at station 09EA003. The state of knowledge about river ice breakup at other sites is still limited; it is therefore advised to maintain spatial and temporal monitoring of breakup sequences for several years, emphasizing vulnerable sites and dominant ice jam locations.

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Two students, Joseph Boyd and Sasha Masson, participated in the preparation of data sets for this report. Their work is greatly appreciated.

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

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1. Introduction

The Klondike River (Tr’ondëk, in Hän) is in the heart of the Traditional Territory of the Tr’ondëk Hwëtch’in First Nation. This river served as a corridor for transportation, used by First Nations since time immemorial, and later by Westerners, explorers, and gold miners, eventually leading to the establishment of Dawson City. The Klondike River valley is where the Klondike Gold Rush mainly occurred more than 125 years ago. The lower Klondike River and many of its tributaries have been altered by over 100 years of placer mining, stripping the area of its important ecological functions and destroying habitat. From a fluvial morphologist’s point of view, the Klondike River is still responding to past drastic landscape modifications, and climate change is initiating a new cycle of modifications to the alignment of its channel through the alteration of its hydrological regime.

Hydrological events that affect the alignment, or lateral migration, of alluvial rivers are often tied to bankfull flow conditions or floods. Annual peak water levels in the Klondike River usually occur during the snowmelt period, not only because of high streamflow but often also because of the formation and release of breakup ice jams. Recent studies (Turcotte et al., 2021; Turcotte and Saal, 2022) confirm that ice jams generate by far the highest annual water level at several locations over the river’s lower reaches, mainly in single channel segments where there is a small or no floodplain (the 15 km between the Yukon River [Chu kon’ dëk] and the airport).

The risk associated with hydrological hazards has been tackled through several government initiatives (e.g., flood maps, subdivision development, channel restoration). Improving flood forecasting techniques in the Klondike River valley contributes to reducing the consequences of floods. Considering the dominance of floods caused by ice jams in the area, the Water Resources Branch (WRB) of the Government of Yukon’s Department of Environment expressed interest in improving river ice breakup forecast knowledge and developing tools that will support long-term (planning, preparation) adaptation strategies and short-term (emergency) responses to ice-induced floods.

To our knowledge, no numerical model of any type has been developed to forecast the timing and the intensity of river ice breakup in the Klondike River. As an intermediate step towards the development of such predictive tools, the objectives of this report are to compile existing observations and create new knowledge that relates to the winter and spring behaviour of the Klondike River near Dawson, with an emphasis on the spatial and temporal aspects, as well as on the hydrometeorological controls of river ice breakup.

2. Background

The literature about river ice breakup and river ice jams has mostly emphasized large, low-gradient rivers. Some concepts presented in the textbook edited by Beltaos (2008), mainly those referring to thermal processes, apply to small streams that are comparable to the size of the Klondike River. However, hydromechanical processes that assume the presence of a free-floating ice cover seem to depart significantly from what is observed in this river system. For instance, meanders do not seem to represent significant breakup-resisting points in the Klondike River compared to islands and shallow segments.

In 2017, Turcotte et al. presented a paper about ice-induced flooding in small rivers, which were defined as those draining an area of less than 2000 km^2, characterized by a bankfull discharge below 1000 m^3/s, or presenting a bankfull width of less than 100 m, or a bankfull depth of less than 5 m. In such cold region rivers, ice jams are often grounded (i.e., ice anchored or frozen against at least a portion of the channel bed). Moreover, the channel shape and varying gradient (often high) do not always allow for a theoretical ice jam profile (including an equilibrium section) to fully develop before overbank flooding occurs.

Despite draining a region of about 8000 km^2, the Klondike River falls in this category. Ice jams in this river are rarely longer than 2 km, but even ice accumulations as short as a couple hundred metres (roughly four channel width equivalents), combined with a flow of about 200 m^3/s, can generate flooding, as seen in 2015 at the upstream end of the community of Rock Creek. In 2023, a few ice jams (near Henderson Corner and the Airport) resisted a discharge above 450 m^3/s (flow generating bankfull conditions without the presence of ice at some locations). In both years, water was observed to flow on the ice cover surface near the toe of ice jams, a condition that would reduce the force acting on their anchor point (and grounding would also restrain mobilization). Defining the exact profile of such ice jams represents quite a challenge. However, it can be assumed that they included several contact points between the ice rubble (composed of ice floes of varying sizes and thicknesses) and the channel bed. Considering that the Klondike River presents several secondary channels (multiple anastomosed reaches, some of which could have been shaped by dynamic river ice breakup processes), a largely heterogeneous floodplain topography, a history of human disruption, significant beaver activity, sporadic infrastructure encroachment, and a generally dynamic sediment transport regime, predicting the location, timing, and intensity of ice jam floods in any given spring represents an ambitious mission.

From a theoretical standpoint, in small and steep rivers like the Klondike, ice jams can form in lower gradient channel segments, at shallow locations (often characterized by a channel widening with gravel bars), at tight channel bends, against islands, as well as at locations of small, side-channel heads. However, it is probably more reasonable to use historical observations (and testimonies) to confirm such locations than to rely on detailed bathymetry and/or a hydrodynamic model because observations will also take the actual river's breakup sequence into account. A comparable statement can be made when evaluating the range of hydrological conditions under which ice jams form and release in the Klondike River, and this can also inform the potential of ice-induced overbank flooding along its channel. Grounded ice jams not only cause a rise in water levels because of their thickness and roughness but also because they produce a physical blockage of a portion of the channel. This blockage can be simulated using a hydrodynamic model by disproportionally increasing the cross-section roughness (e.g., Manning's n) of the ice rubble or by imposing an obstacle (i.e., ineffective flow areas), but the resulting ice jam profile (and water surface across the channel) may not be representative. This manual adjustment can also impact the calculation of the ice volume contributing to the jam.

Ice-induced floods in the Klondike River can also take place during freeze-up, when the ice cover forms dynamically, either through the formation of anchor ice and ice dams (e.g., Turcotte et al., 2011) or, more likely, by the interception and compaction of incoming frazil slush and pans (a process comparable to the "frontal progression" described in Beltaos, 2013). This later process occurred at high flow during the fall of 2022 and is probably responsible for causing overbank flooding and icing at several locations along the lower Klondike River. Unstable weather conditions during the freeze-up period may also generate hydrological instabilities that mobilize fragile ice cover segments, resulting in a nearby or downstream consolidation, often referred to as a freeze-up jam (e.g., Beltaos, 2013). For example, a significant rise in air temperatures may cause an abrupt pause in the freeze-up depression (or bite) with a consequent rise in discharge that can be in the order of 50% (Turcotte, 2022) without the contribution of any rain or snowmelt runoff. A "cold breakup" is a process that has been reported during sudden, early winter, intense cold spells in streams that present characteristics similar to those of the Klondike River. In this case, the dynamic formation of an ice cover generates a progressive rise in hydrodynamic forces that eventually become greater than the resisting force of the downstream ice cover (Turcotte et al., 2017). Based on current knowledge, breakup ice jams seem to represent the dominant flooding processes along the lower Klondike River, followed by open water conditions. However, as is common in steep channels, freeze-up conditions may significantly influence breakup conditions. This phenomenon will be explored in Section 5.

Eventually, as Janowicz (2010) pointed out, mid-winter breakup events caused by rain-on-snow events may start affecting some small river systems of the Yukon. This consequence of climate change is threefold: It could cause mid-winter ice jam floods, partial breakup events could be followed by massive frazil ice production and overbank icing as cold conditions return, and this altered ice cover resistance would impact spring breakup patterns and intensities.

3. Study area

Locations of high flood vulnerabilities in the Klondike River valley extend from downtown Dawson, at the confluence of the Klondike and Yukon Rivers (this represents Km 0 of our study reach), to Henderson Corner (Km 24 to 27 of the Klondike River). Other locations where ice jams can impact people and transportation infrastructure are found further upstream, including at the Dempster Highway bridge, 46 km upstream of Dawson (following the Klondike River's main channel). Figure 3.1.1 presents a map of the studied river segment that extends to the confluence of the North Klondike River near Km 50.

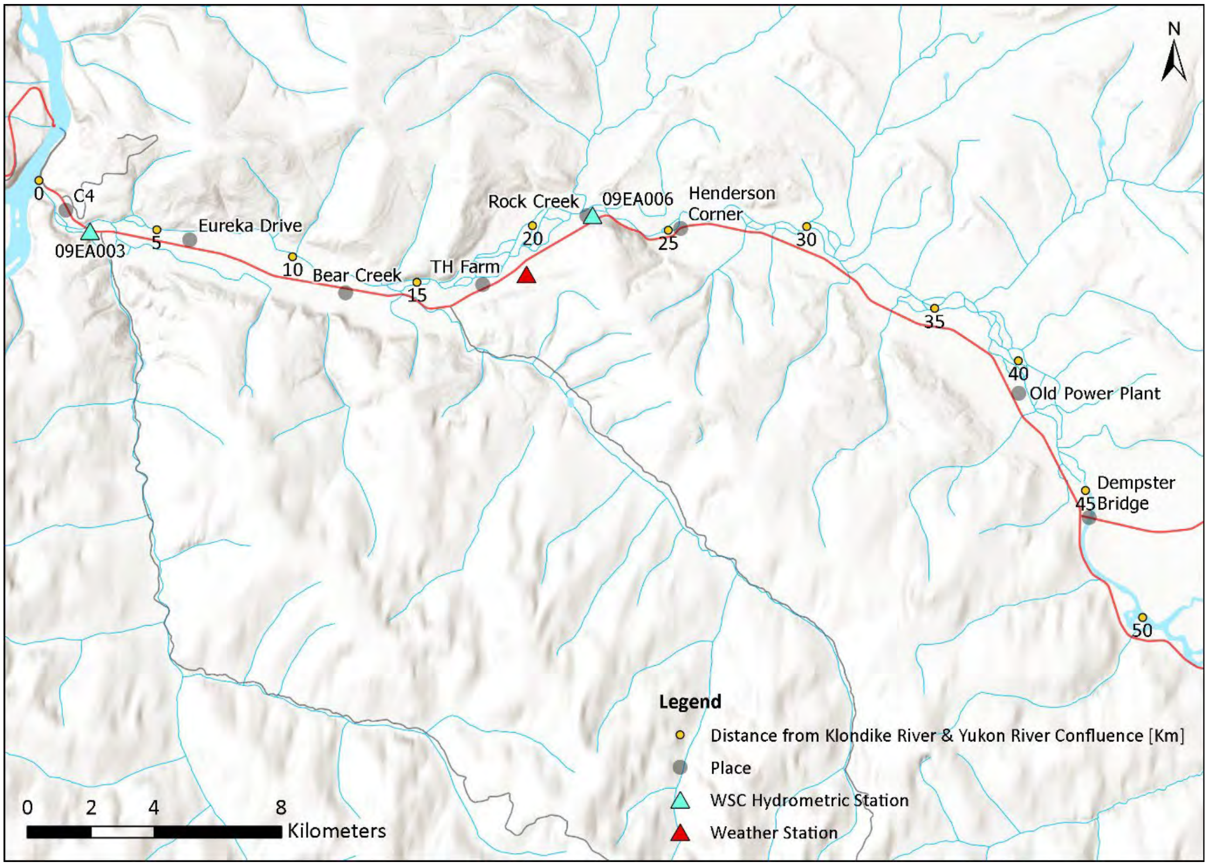

Figure 3.1.1. Study reach of the Klondike River between the Yukon River confluence (Km 0) and North Klondike River (near Km 50). The main channel is considered, and it takes into account the meander cut near Bear Creek Subdivision that occurred in 2023.

The kilometre points expressed in the following sections of the report correspond to those included in Figure 3.1.1.

4. Spatial aspects of breakup

The formation of ice jams depends on two important factors: the ice supply from a weak, upstream ice cover and a local, strong obstacle, such as a resistant ice cover, a hydraulic structure (e.g., bridge pier), or a specific channel form (described in Section 2). As the discharge increases in the spring due to snowmelt and as the ice cover becomes weaker because of warm weather and shortwave radiation (i.e., sun), most rivers presenting a heterogeneous planform or profile will go through the following breakup sequence:

- Intact ice cover at most locations.
- Minor ice movements where the ice cover is the weakest relative to local hydraulic conditions (i.e. flow velocity or Froude Number), with the consequent formation of short ice accumulations (i.e., juxtaposed types of ice jams).
- Formation of several small ice jams causing limited backwater (water usually contained within the banks), mostly downstream of fast flowing (or weak ice cover) river segments.
- Mobilization of small ice jams, occurrence of short ice runs, and formation of fewer, but longer and thicker ice jams at the most resilient river ice locations. These ice jams would produce a significant backwater that may not be contained within the channel banks.
- Occurrence of large ice runs, and mobilization of all remaining ice jams.

This sequence has been described by She et al. (2009) for the Athabasca River. Interestingly, very few studies have specifically emphasized the importance of typical or atypical river ice breakup sequences on the occurrence and intensity of ice jams, especially for small rivers. In most ice jam publications, upstream or antecedent ice conditions are poorly documented.

This section of the report uses various sources of information to investigate whether there are locations along the lower Klondike River where the ice cover consistently appears to be more resistant than at other locations. Sources of information include:

- Visible imagery captured by the Sentinel 2 satellites operated by the European Space Agency,
- Aerial photos taken by the Water Resources Branch, over recent years,
- Photos taken from the ground, generally from the channel bank or from a bridge, by the Government of Yukon or other contributors,
- Photos taken by automated cameras operated by the Water Survey of Canada, the Government of Yukon, or our own research team (with the support of the Tr’ondëk Hwëtch’in Government),
- Photos taken and observations made by our research team in recent years in the Klondike River valley (with the support of the Government of Yukon, Department of Community Services).

Beyond the resistance of the ice cover, additional spatial aspects of breakup in the Klondike River near Dawson are explored in the next subsections.

4.1. Ice coverage evolution during breakup

The thickness of the ice cover on the Klondike River appears to vary significantly over short distances, which is common for streams presenting a morphology composed of riffles, pools and rapids. In this context, it is not unusual to see, even during the heart of winter, narrow open water leads beside relatively thick freeze-up jams (at the same cross section). This may explain why snowmobile tracks are rarely observed in the snow covering the ice of such channels.

The first ice movements in the Klondike River are generally preceded by the formation of new – or the expansion of existing – open water leads, before any snowmelt runoff reaches the main channel. The breakup period, starting when the first ice movements occur and ending after the last ice run has been observed at Dawson, generally lasts 8 to 15 days, and the upper limit of this range does not necessarily represent a thermal breakup scenario, as observed in 2023.

Figure 4.1.1 presents the spatial evolution of the ice coverage in the Klondike River, at 1 km increments, between the Yukon River at Dawson (Km 0) and the North Klondike River confluence (Km 50). The graph presents the range (min and max) and average (centre-line) of the historical ice coverage during the 3 to 7 days before the annual ice jam near Km 2 (Tr’ondëk C-4 Subdivision and Klondike Highway bridge) releases. This graph was developed based on observations from 2018 to 2024 (7 winters, See Appendix A). Red bars in Figure 4.1.1 are associated with an average ice coverage of 75% or more, where little to no ice movements occur. Green bars indicate an average ice coverage of less than 60%, which means that the partial or complete mobilization of the ice cover along those segments is likely to happen before the ice jam at Km 2 releases. Yellow bars represent segments of moderate ice cover resistance (60% to 75% ice coverage).

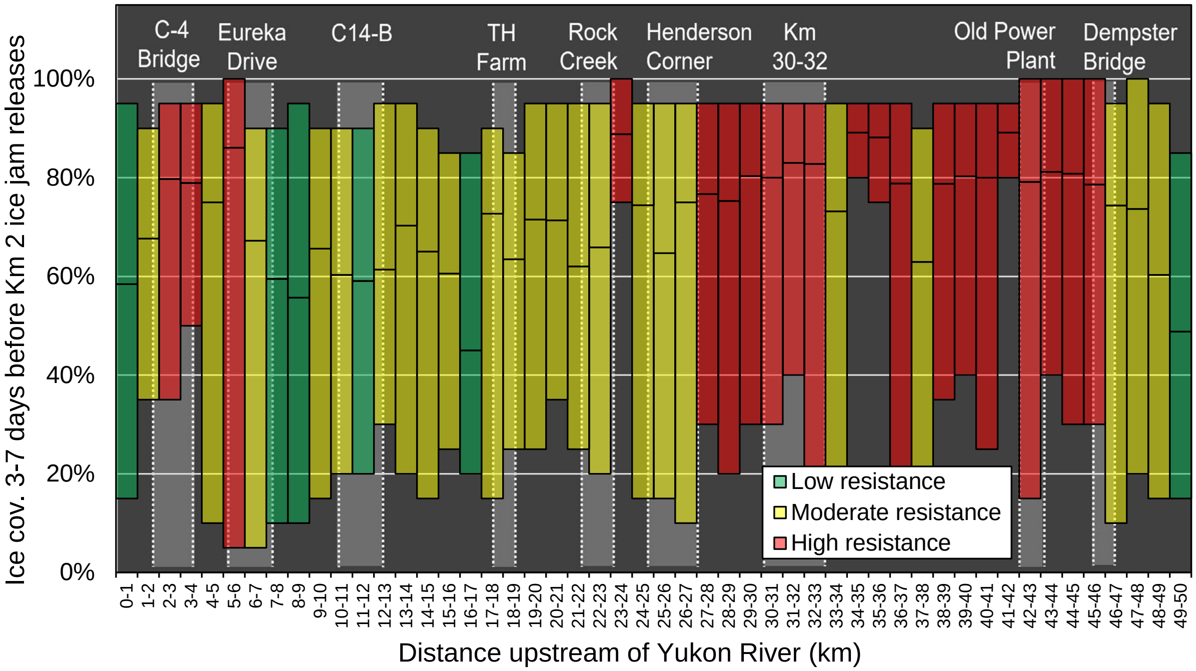

Figure 4.1.1. Minimum, maximum, and average (mid bar) ice-coverage on 1 km-long segments of the Klondike River over 50 km during the 3 to 7 days preceding breakup at the Klondike Highway bridge between 2018 and 2024.

Figure 4.1.1 also includes the name of key locations along the Klondike River, some of which can be referred to in Figure 3.1.1. Results show that weaker ice cover segments (green) are generally found within the tailings reach of the river (Km 0 to Km 15) and immediately downstream of the North Klondike River confluence. The rationale for the location of such weaker segments could be the presence of a single channel without an accessible floodplain and the existence of warm water sources, either from tributaries (e.g., North Klondike River) or from tailing ponds. The segments with the most resilient ice cover (which includes ice jam location) are found near the Klondike Highway bridge and Eureka Drive (lower gradient locations), at Tr'ondëk Hwëtch'in (TH) Farm (island), as well as between Rock Creek and Henderson Corner (lateral gravel bar and side channel). The presence of intact ice cover segments and small to large ice jams between Km 27 and Km 47 is common after breakup at Km 2.

From an ice supply perspective, these spatial patterns may seem to represent favourable (low ice supply) conditions for Rock Creek and Henderson Corner, and less favourable conditions for the downstream infrastructure near the Tr'ondëk C-4 Subdivision (significant ice supply). However, as written earlier, very short ice jams can cause flooding in the Klondike River, and a closer investigation of ice jam conditions is needed (refer to Section 4.4).

A last observation that can be made about Figure 4.1.1 is the red bar at Km 5-6 (Eureka Drive) that extends from 5% to 100% (average of 86%). This range reveals that a long ice jam often forms at that location each year. Its release generally occurs after the clearing of the Km 2-3 ice jam, but it can also take place before (therefore explaining the lower range), which was the case in 2024, with consequent flooding upstream of the bridge (Infill #2 development area).

4.2. Role of tributaries

Tributaries are known to play a role at breakup, either through a passive hydrothermal influence or a dynamic cryo-hydrological contribution, as demonstrated in several studies (e.g., Jasek, 2019; Jasek et al., 2021; Blouin et al., 2021). However, this role remains unclear for very small or steep tributaries, which is the case for most creeks draining into the lower Klondike River. Table 4.2.1 provides an overview of the apparent influence of Klondike River tributaries on its breakup regime or sequence. Generally, it seems that no tributary has a significant local or downstream influence on the river ice breakup sequence, regardless of the breakup intensity.

Considering the information presented in Table 4.2.1, it is unlikely that Klondike River tributaries could generate large ice jams and flooding that could impact properties and communities. In turn, some tributaries may reduce the risk associated with ice jams and ice runs through a thermal influence. Rock Creek may play this role during some spring breakup scenarios, but its influence is probably more pronounced during thermal breakup years. It seems that historical river ice surveys have not emphasized this aspect of breakup, and therefore the exact role of some tributaries should be further investigated under different hydroclimatic scenarios (e.g., low or high snowpack, sudden or delayed spring conditions).

TABLE 4.2.1. PRESUMED ROLE OF SMALL TRIBUTARIES ON THE BREAKUP SEQUENCE AND INTENSITY OF THE LOWER KLONDIKE RIVER.

Tributary	Potential impact on the formation of ice jams	Potential impact on the mobilization of ice jams
Bonanza Creek (Km 2.1)	Limited: It seems that the creek is too small to be affected by a dynamic breakup event that could impact the Klondike River. It is mostly the local annual Klondike River ice jam that impacts the creek by blocking its outlet and causing upstream concerns.	Negligeable: Flow (and heat) from the creek could contribute to mobilizing the ice jam at Km 2.0 (based on a 2015 photo). However, it is likely that any meaningful flow or heat contribution from the creek reaches the river once local breakup has ended.
Hunker Creek (mainly Km 13.7)	Negligeable: The narrow (confined) creek goes through culverts and vegetated zones, and it merges with the Klondike River near a secondary channel. It cannot contribute a meaningful supply of ice or impactful hydrological instabilities.	Negligeable: The creek outlet does not seem to represent a dominant ice jam location. The heat carried by the creek is probably too little to have a significant downstream impact on the ice jam near Km 12.0 (former swimming area).
Rock Creek (Km 21.7)	Moderate: Photos (e.g., from 2015) suggest that ice jams (and therefore ice runs) can form in the lower creek. Although, this has not been observed by the authors, it is likely that small ice runs from the creek could damage the ice cover on the north side of the Klondike River at Rock Creek. It is uncertain, however, whether this can influence local ice jam formation.	Moderate: The creek has the potential to melt the toe of ice jams (just like it seems to be doing with the annual ice bridge at Rock Creek). In this case, the creek could contribute to attenuating the risk of ice jam floods at Rock Creek. This interaction needs to be further investigated, with the contribution of local knowledge.
Creek (Km 36.1)	Negligeable: Local thermal influence only.	Negligeable: Local thermal influence only.
Creek (Km 47.5)	Negligeable: Local thermal influence only.	Negligeable: Local thermal influence only.
North Klondike River (Km 50.3)	Limited: Ice runs from the North Klondike River have not been reported over 10+ years of observations, but such dynamic scenarios cannot be entirely discarded (if a rain-on-snow event occurs). Since the North Klondike River seems to be affected by a thermal breakup in most years (the lower reaches melt while the snowpack in the valley is still in place), even hydrological instabilities do not seem to influence downstream ice processes.	Limited: The most probable downstream influence of the North Klondike River is to supply a small heat quantity that would promote ice cover melting down to the Dempster Highway bridge. However, the bulk of the snowmelt freshet arrives later in the spring, so this influence is less than the upper Klondike River.
Upper Klondike River (Km 50.3)	Moderate: Breakup in the anastomosed reach above Km 50 is generally thermal with small ice jams, if any. Their release can generate ice jams above Km 47. However, the contribution of the upper Klondike River to the breakup regime of the lower Klondike River is apparently only thermal, thus preventing ice jam formation.	Moderate: It has been observed that small ice jams upstream of Km 46 could melt in place before being mobilized, a result of the assumed thermal influence of the upper Klondike River. It is also possible that hydrological instabilities could contribute to the mobilization of downstream ice jams, but this influence would probably fade (or attenuate) downstream of Km 42.

4.3. Role of freeze-up congestions

Sites of high resistance to ice cover or ice jam mobilization often correspond to specific morphological features. As stated in Section 2, in steep streams like the Klondike River, slow flowing channel segments (e.g., pools), shallow gravel bars, and islands or secondary channels are known to delay the mobilization of the ice cover and to intercept ice runs, often through a combination of energy dissipation and mechanical resistance. Mapping each of these features (as done in studies such as De Munck, 2017) along the lower Klondike River would be of limited value to breakup forecasting due to their extremely high frequency of occurrence along the river.

Fortunately, morphological features that favour the formation of breakup ice jams may also be affected by an early freeze-up (e.g., first ice bridge in the river), by a distinct freeze-up consolidation (thicker or rougher than average), or by a secondary consolidation (caused by the shifting of a newly formed upstream ice cover, with a result that compares with a breakup ice jam). Therefore, the intensity of spring breakup and the occurrence of breakup ice jams at the end of winter may be influenced by hydrological processes taking place many months earlier. An advantage of investigating the location of early-season freeze-up consolidations is that they normally stay in place for the entire winter period (at least in the Yukon), which supports drone or satellite-based assessments. On the other hand, the small width of the main channel, the unavailability of Sentinel 2 imagery after mid-November, the frequency of fog and high humidity episodes in the Klondike River valley during the fall, and generally cold air temperatures during the early-winter period all impede the success of a remote sensing investigation approach. The general lack of historical interest in early winter river monitoring means that limited information currently exists about river ice formation processes and sequences along the Klondike River.

Figure 4.3.1 presents the location of early ice cover formation (or ice congestion) locations along 50 km of the lower Klondike River during three consecutive late falls (2019 to 2021) when Sentinel 2 imagery was generally not affected by clouds and when freeze-up occurred early enough to be captured from space. Although associated with a high level of uncertainty, results suggest that the C-4 Subdivision and the Klondike Highway bridge area, Eureka Drive area, TH Farm, Km 30-32, and Km 39-40 are among the first to be covered with ice at the beginning of winter. This agrees with the locations of above-average ice cover resilience presented in Figure 4.1.1. Only the congestion location between Km 8 and 9 presented in Figure 4.3.1 does not correspond to a resilient ice cover location in the spring in Figure 4.1.1.

Once a freeze-up congestion begins to intercept the run of frazil slush and pans coming from upstream, the frazil ice contribution to the downstream ice cover may cease. The freeze-up process called frontal progression (e.g., Beltaos, 2013) was documented for the Yukon River (e.g., Turcotte, 2020; Turcotte et al., 2024a). Although its occurrence in a small, steep river environment may be limited in time and space (the frazil eventually finds its way under the ice cover), even a temporary ice interception may delay downstream ice cover development enough to result in a generally weaker ice cover. Alas, given the limited dataset available, such an assessment cannot be completed for the Klondike River, and the results presented in Figure 4.3.1 do not currently contribute to the understanding of breakup sequences in the spring.

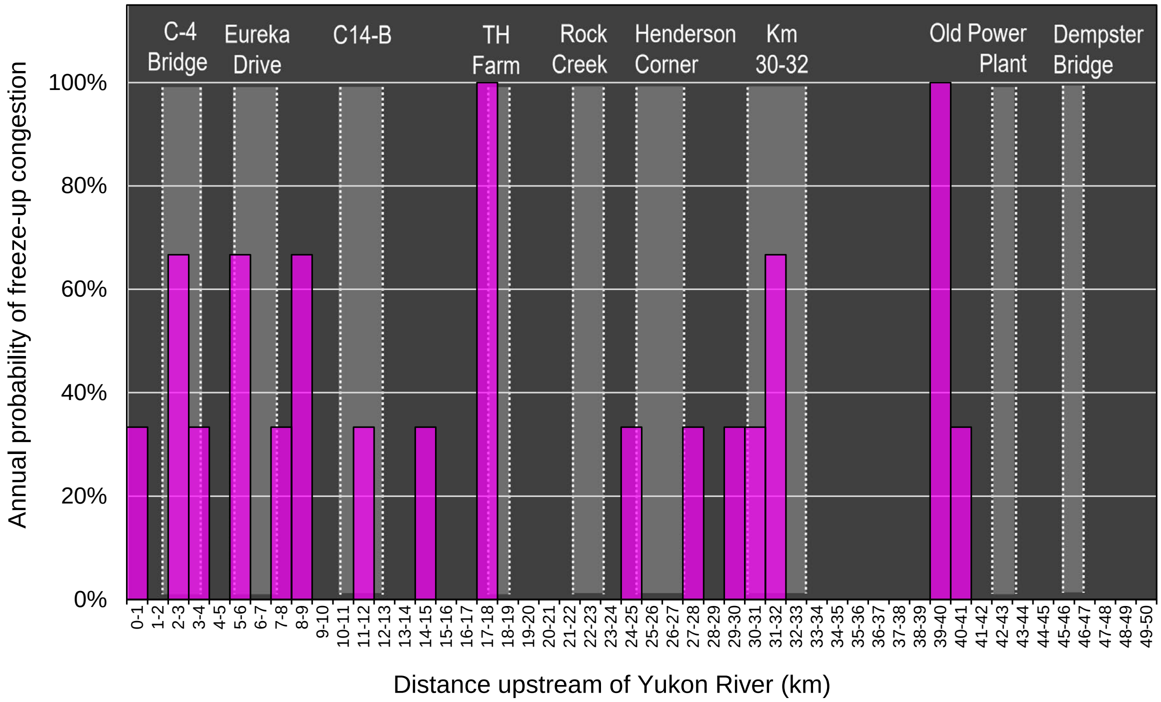

FIGURE 4.3.1. APPROXIMATE PROBABILITY OF FREEZE-UP CONSOLIDATIONS OVER 50 KM OF THE KLONDIKE RIVER WITH KM 0 LOCATED AT THE OUTLET INTO THE YUKON RIVER AT DAWSON. THIS ASSESSMENT IS BASED ON SATELLITE IMAGERY FROM THREE YEARS: 2019 TO 2021.

4.4. Locations of breakup ice jams

It has been mentioned in previous sections that the location of breakup ice jams should correspond, to some extent, to the presence of a highly resistant/resilient ice cover, including freeze-up consolidations, and that most tributaries did not seem to play a large role during breakup. It was also stated that the lower Klondike River presents numerous, morphological features where ice jams should theoretically form, and this is reflected in the results presented in Figure 4.4.1. Through the analysis of 9 well-documented spring breakup sequences (2015 and 2017 to 2024), the location of ice jams was compiled. Two types of ice jams were distinguished (the definition of these categories differs from those presented in Turcotte et al. (2024a,b) for similar figures on distinct, larger rivers):

- Minor ice jams: Ice accumulations that do not cause flooding, are relatively short (generally less than 500 m), are formed by less than 1 km of upstream ice cover (i.e. the open water area upstream of the ice jam is less than 1 km-long) or are mobilized early during the spring breakup period.
- Major ice jams: Ice accumulations that may cause flooding, are long (generally more than 500 m), result from breakup over multi-kilometer upstream river segments, or persist later into the breakup period despite the increasing snowmelt runoff.

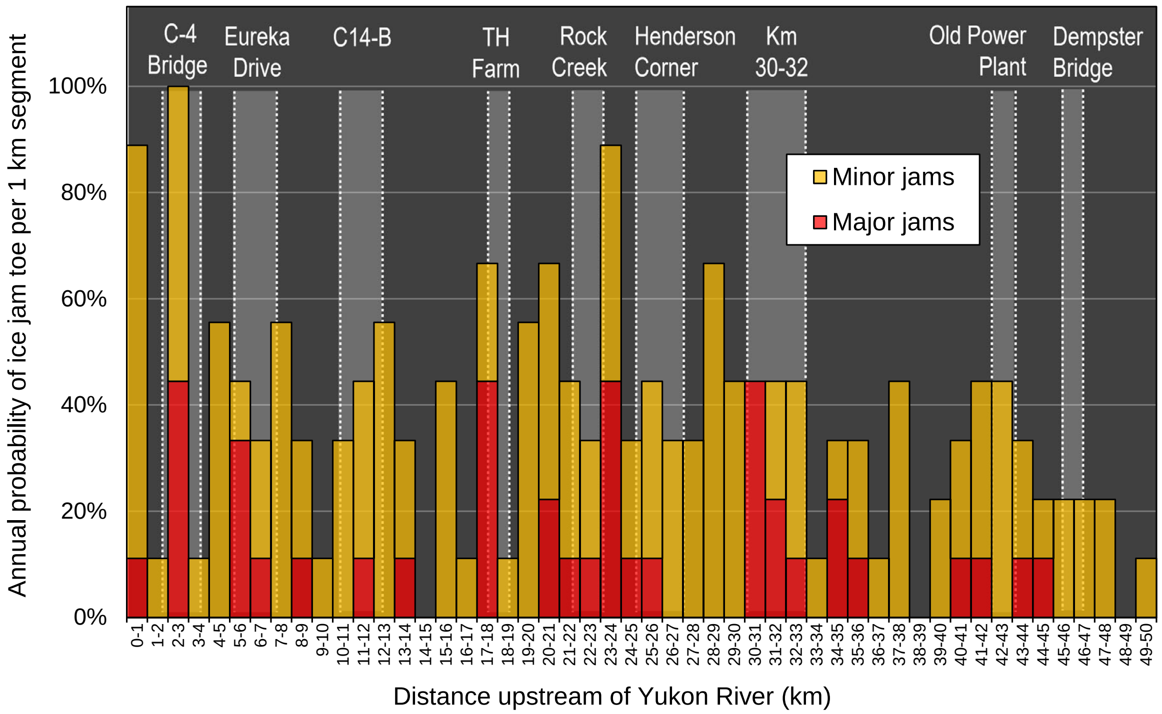

Figure 4.4.1. Annual probability of minor and major ice jams over 50 km of the lower Klondike River with Km 0 located at the outlet of the river into the Yukon River. This assessment includes data from 9 years (2015, and 2017-2024).

Despite the simplicity of the proposed categories, ice jam classification usually relies on a certain level of subjectivity, and the smallest and less resilient ice accumulations (e.g., juxtaposed, or single ice floe layer-type of ice jam) are often excluded from the retained ice jam list. While consulting Figure 4.4.1, readers may emphasize the following key elements:

- Single km locations where ice jams are observed almost every year (Km 0-1, 2-3, and 23-24),
- Cluster locations (2 or 3 consecutive km) where ice jams form regularly (Km 4-6, 11-13, 19-22, 27-30, 30-32, 40-43),
- Locations of frequent major ice jams (Km 2-3, 5-6, 17-18, 20-21, 23-24, 30-32, 34-35),
- River segments where ice jams seem to rarely form (Km 14-15, 33-34, 36-37, 38-40, 48-50).

The following list can be considered a summary of the most common dominant ice jam locations along the Klondike River, from downstream to upstream (which is not the general breakup sequence; this will be described in the following section):

- Km 0-1: Apart from extremely thermal spring breakup scenarios (e.g., 2019), a minor ice jam forms annually on the alluvial fan of the Klondike River with a toe that is often lodged against the ice cover of the Yukon River. This ice jam does not pose a high flood risk since the delta could store a significantly larger volume of ice without threatening the Dawson dike.
- Km 2-3 (Figure 4.4.2 A): An ice jam forms behind the Tr'ondëk (C-4) Subdivision every spring, and it has the potential to affect the subdivision and the nearby compounds, as well as the Klondike Highway (as was the case in 1986 and 2003; see analysis presented by Turcotte

and Saal, 2022). Although the Klondike Highway bridge is usually not impacted by ice jams and ice runs, there is a 10% annual probability that the highest ice floe reaches to within 1 m of the bridge soffit. This ice jam can be 1.5 km-long, which poses a risk to other isolated properties (e.g., in Infill #2, as in 2023 and 2024). Note that Km 2.2 is also a typical freeze-up consolidation location (Figure 4.3.1) and a site for thick freeze-up jams (e.g., 2003 [Janowicz, 2010] and 2023). It has been suggested that ice and flow conditions in the Yukon River (near Km 0) can influence this ice jam, including its formation and mobilization, but observations and studies (e.g., Turcotte et al., 2021) indicate that this is generally not the case. Only a major ice jam in the Yukon River could affect the Klondike River up to Km 2, and this breakup sequence is unlikely.

- Km 5-6 (Figure 4.4.2 B): This is a (artificially) straight segment of the Klondike River presenting a lower gradient compared to upstream and downstream reaches (Turcotte et al., 2021). In some years (roughly 25% of the time) the release of the ice jam at that location triggers the mobilization of the Km 2-3 jam. However, it may also stay in place slightly longer than the Km 2-3 jam (50% of the time). The latter scenario is the most favourable as it reduces the probability of ice jam floods in C-4 and immediately upstream of the Klondike Highway bridge. In the remaining 25% of the cases, like in 2024, the Km 5-6 ice jam releases first and the ice run is intercepted by the Km 2-3 ice jam.
- Km 11-12 (Figure 4.4.2 C): A minor ice jam often lingers in this wide-shallow channel segment during breakup. It does not represent a major flood threat (though water may start flowing through the tailing ponds, e.g., 2022), but its early release could cause downstream concerns.
- Km 17-18 (Figure 4.4.2 D): An ice jam forms on a quasi-annual basis at the tip of the island located immediately downstream of the Tr’ondëk Hw’etchin Farm. This ice jam may be among the most resilient in the lower Klondike River and often (50% of the years) causes overbank flooding (e.g., 2017, 2018, 2021, 2023).
- Km 23-24 (Figure 4.4.2 F): An ice jam is visible on the side of the Klondike Highway every spring at that location. It is generally formed by less than 2 km of broken ice cover (downstream of Henderson Corner) but may extend and consolidate when the Henderson Corner ice jam releases. This ice jam does not pose a flood risk in most years, although the Klondike Highway freeboard can be less than 1 m (e.g., 2013, 2022). It is often among the most resilient jams in the Klondike River, which is positive for Rock Creek as it reduces the supply of ice from upstream until the local ice cover or ice jam has been mobilized.
- Km 30-32 (Figure 4.4.2 H): This is the segment of the Klondike River presenting the most resilient ice cover (Figure 4.1.1). The presence of numerous islands, secondary channels, log jams, shallow gravel bars, and channel bends impedes ice cover mobilization, causing the formation of minor or major ice jams in the area. This ice jam could be the most resilient of the spring breakup season. Interestingly, in 2023, its release caused the consolidation of the Km 17-18 ice jam, exacerbating the local flooding situation.

Figure 4.4.2. A. Ice jam at Km 2 (2021), B. Ice jam at Km 5.8 (2021), C. Ice jam at Km 11 (2021), D. Ice jam at Km 17 (2021), E. Ice jam at Km 21.8 (2013). F. Ice Jam at Km 23.2 (2021), G. Ice jam at Km 25 (2021), H. Ice jam near Km 31 (2015). Photos credit: Government of Yukon.

The fact that Rock Creek is (statistically) often flooded during breakup does not mean that a long ice jam forms near or at the community every year (Figure 4.4.2 E). The vulnerability of Rock Creek (Km 21.0 to 22.5) is mostly associated with its relatively low elevation compared to the Klondike River channel. In most years, the water is less than 0.5 vertical meters from flooding some properties. Instances of houses surrounded by water (e.g., 2015) or flooded (e.g., 2006, 2013, 2023) are common, even in the absence of a long ice jam. Flooding can result from breakup along a small (less than 1000 m-long) channel segment, which would limit the efficiency of a breakup detection system.

Henderson Corner (Km 24.5 to 26.5, Figure 4.4.2 G) also sees the formation of an ice jam on a regular basis, initially at Km 27.0, and eventually at the head of a short multi-channel segment near Km 25.5. This ice jam may reduce the volume of the downstream (Km 23) ice jam. In most years, this ice jam does not generate extremely high water levels and extensive floods on both sides of the Klondike Highway as it did in 2023, but properties located on the North (river) side of the Highway are frequently exposed to flooding when the jam toe is located near Km 25.5, as was the case in 2006, 2012, and 2013.

4.5. Breakup sequences

One of the most useful pieces of information to forecast the timing and intensity of breakup along a river consists of identifying typical, atypical, and unfavorable breakup patterns, or sequences. This spatiotemporal perspective is also important to inform local authorities about the risk of flooding over the next few hours or days. Characterizing a range of possible breakup patterns in the lower Klondike River is challenging for various reasons: 1. There are several ice jam locations with obvious (downstream) hydrological interaction and possible (upstream) hydraulic influence, 2. Every year in which breakup sequences were documented, they were slightly to largely different. 3. Recent years have included extreme breakup scenarios (e.g., thermal in 2019, dynamic in 2023). 4. The river is evolving relatively quickly through morphological adjustments, in part because past man-made interventions have imposed a channel alignment and gradient that is incompatible with the energy regime.

An advanced understanding of breakup sequences in the lower Klondike River is important for reasons beyond breakup and ice-jam-flood forecasting, including for infrastructure design, development planning, and flood mapping. In this context, the YRC team initiated an intense survey program during the spring of 2022, with equipment provided by the Government of Yukon's Department of Community Services. For three years in a row, water level loggers and remote cameras were deployed along the river with the contribution of the Tr'ondëk Hwëtch'in Government. These datasets, in addition to the data provided by the two Water Survey of Canada stations (09EA003 and 09EA006), have help tracking the mobilization of ice covers as well as the timing and origin of ice jam release waves and associated ice runs. This continuous data set is a valuable complement to time-specific flight surveys or Sentinel 2 satellite images.

Figures 4.5.1 to 4.5.3 present the simplified results of the three spring surveys. Datasets from different sites are presented from upstream (top of graph) to downstream (bottom of graph) over time. Each data sets starts with an intact ice cover on the left at mid relative elevation. Higher relative levels mean ice jams (varying consolidation intensities) or ice runs (spikes) whereas lower water levels indicate open water conditions (end state of each data set on right). Vertical lines were added to identify the origin of instabilities and their progression down the river. It normally takes about 4 to 5 hours for an ice run from Rock Creek (Km 22) to reach the Yukon River (Km 0), which means that small ice-jam-release waves (probably partially impeded) in the system travel at about 4 to 6 km/h. However, larger (unimpeded) ice runs can travel as fast as 20 km/h.

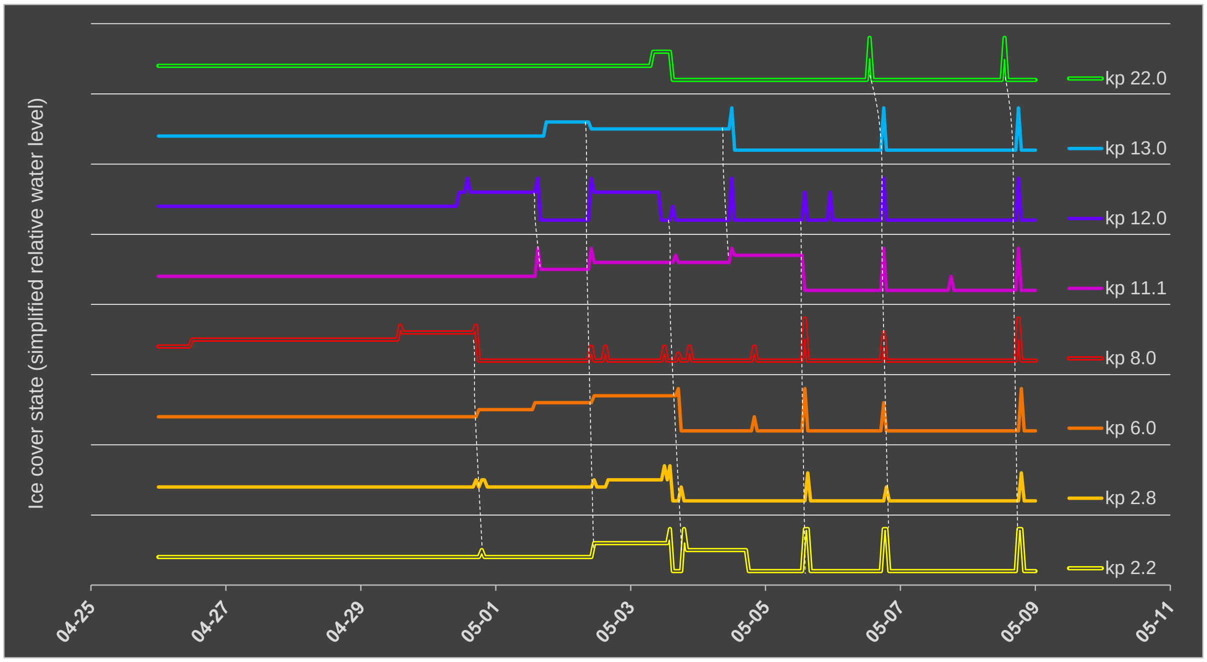

FIGURE 4.5.1. SIMPLIFIED WATER LEVELS FROM 8 MONITORING SITES SPREAD OVER 20 KM DURING THE 2022 BREAKUP SEQUENCE OF LOWER KLONDIKE RIVER.

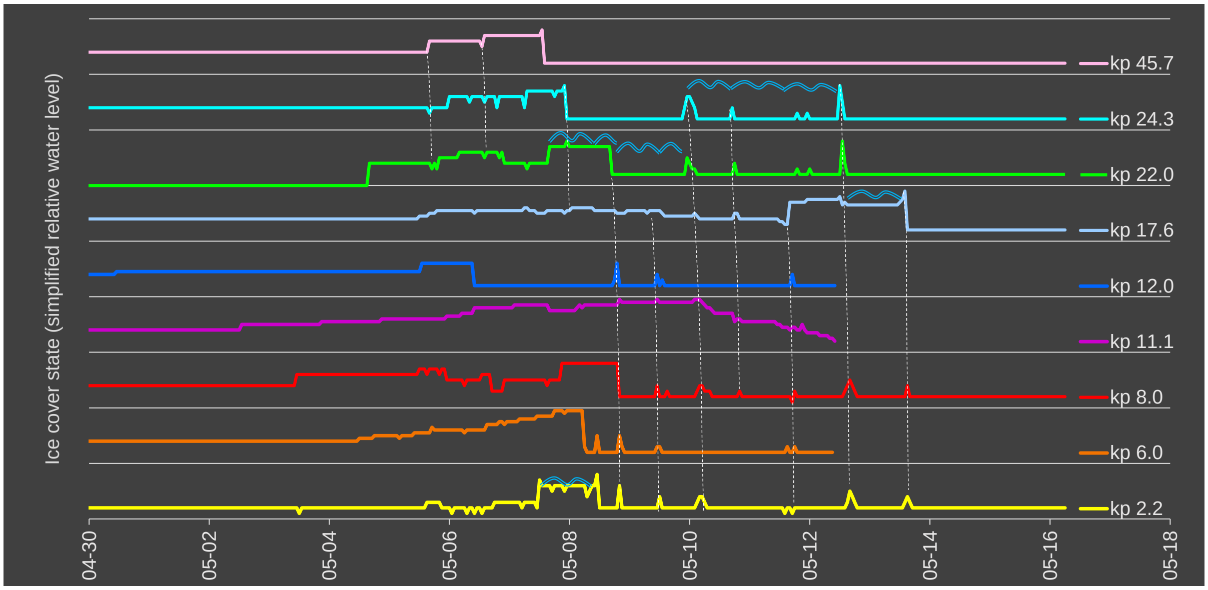

FIGURE 4.5.2. SIMPLIFIED WATER LEVELS FROM 9 MONITORING SITES SPREAD OVER 45 KM DURING THE 2023 BREAKUP SEQUENCE OF LOWER KLONDIKE RIVER. THE BLUE WAVES INDICATE FLOODING.

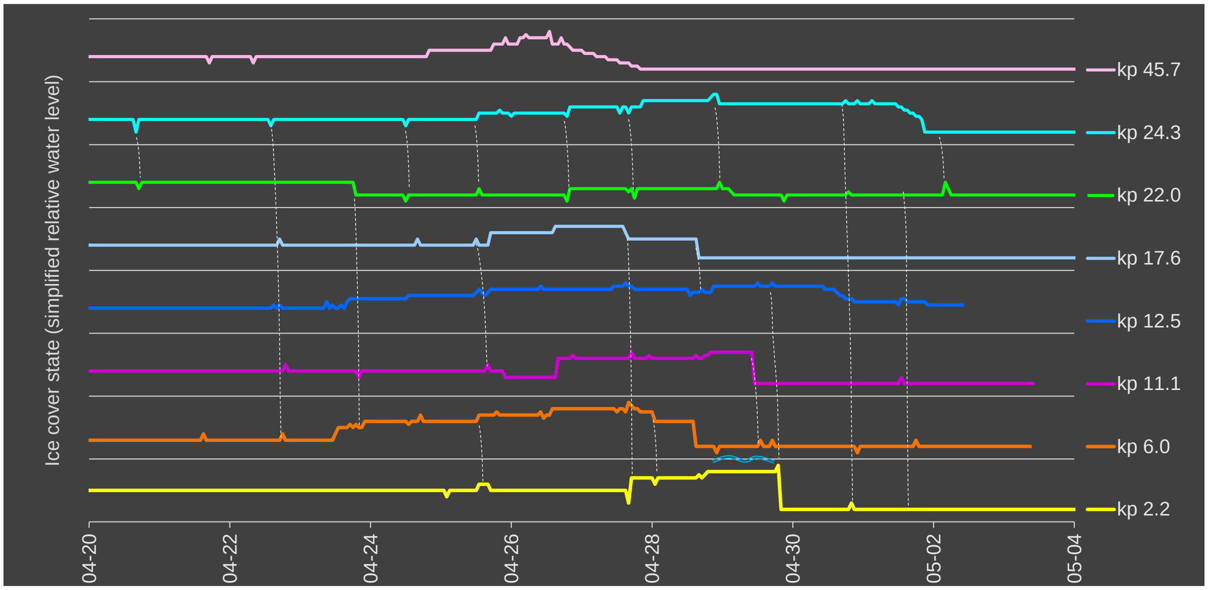

FIGURE 4.5.3. SIMPLIFIED WATER LEVELS FROM 89 MONITORING SITES SPREAD OVER 45 KM DURING THE 2024 BREAKUP SEQUENCE OF LOWER KLONDIKE RIVER. THE BLUE WAVES INDICATE MINOR FLOODING.

While three years of data are not sufficient to draw definitive conclusions, the following patterns are noted:

- The ice jam at Km 2.2 releases relatively early at breakup, unless it is supported by a freeze-up jam (2024; Figure 4.5.3).
- Prior to the meander cut at Km 12.5, the reach of Km 11 was intercepting ice runs from upstream to create a weak ice jam. It now seems that the new Km 12.5 morphology will play that role, at least for some time, which is positive for downstream subdivisions.
- The ice jam above Rock Creek (Km 24.3) released early in 2023, which exacerbated flooding at Rock Creek. This was not the case in 2022, and 2024.
- There is an obvious hydrological disconnection between Km 45.7 (Dempster Highway bridge) and the reaches at - and downstream of - Henderson Corner (Km 27) during breakup. This means that monitoring ice movements upstream of Km 27 may not be useful to forecast breakup and ice jam floods at vulnerable locations in the Klondike Valley.

Information collected in recent years by Government of Yukon, local observers and the YRC was compiled to develop the preliminary version of what is anticipated to represent a typical breakup sequence (of average intensity) for the lower Klondike River. This is presented in Table 4.5.1, with the release of the ice jam at Km 2 (Klondike Highway bridge, the most documented site) taking place at Day 0. During that breakup sequence, the discharge in the Klondike River at station 09EA003 would rise from 20 m^3/s to above 250 m^3/s. Readers will understand that the described sequence may be inaccurate by 1 to 4 days if the discharge rises faster (like in 2023), more gradually (like in 2024), or not at all (like in 2019); therefore, it can be considered as a starting point for the development of breakup forecasting tools and models. An important point raised in Table 4.5.1 is that, based on observations, it seems that a TH Farm flood is part of a typical breakup scenario along the lower Klondike River.

TABLE 4.5.1. PRESUMED TYPICAL BREAKUP SEQUENCE IN THE LOWER KLONDIKE RIVER WITH THE RELEASE OF THE KM 2 ICE JAM SET AS DAY 0.

Days	Ice conditions and dynamic events
- 10 days	First open water leads forming in the river and several areas with (turbid) water on ice.
- 5 days	Formation of multiple ice accumulations at 10s of locations between Km 0 and 28 as well as between Km 40 and 48.
- 2 days	Breakup of Km 0 to Km 1.5. Formation of minor ice jams near Km 0, 2, 7, 12, 19, 20, 22, 24, 27, 28, 32, 37, 42 and 46 (Dempster Highway bridge).
- 1 day	Consolidation of ice jams at Km 2-3, 5-6, 11 (now 12.5), 23-24, 25-26, 30-31 and 40-42.
0 day	Release of Km 2 ice jam and Km 5-6 ice jam (clearing of Km 1 to 10). Formation of ice jam at Km 17, flood of TH Farm. Consolidation of ice jams and formation of major ice jams at Km 23, 25.5, and 30.
+ 1 day	Release of Km 11 ice jam and Km 22 ice jam (open water at Rock Creek).
+ 2 days	Release of Km 17 ice jam and Km 25.5 ice jam
+ 3 days	Release of Km 23 ice jam, Km 30 ice jam and Km 12.5 ice jam, open water conditions with only residual ice runs from the clearing of secondary channels.

4.6. Summary of ice jam flood risk

For exploratory purposes, Table 4.6.1 presents ice conditions leading to ice jam floods at vulnerable locations along the lower Klondike River. Note that, for all sites, a reasonably high late-winter snowpack (not necessarily above average), late-winter snowfalls, and a sudden spring warming or a rain event exacerbate flood risks, whereas a low snowpack and consistent freezing at night attenuate flood risks. The hydrometeorological aspect of breakup will be further explored in Section 5.

The knowledge presented in Table 4.6.1 should be refined through further research phases and additional years of observations and monitoring, especially in a context where key observations could eventually be used to identify signs of imminent ice jam floods as well as to develop an ice jam flood forecast system composed of models, instruments, and local observers.

Finally, Figure 4.6.1 presents the results of an analysis of historical ice jam extent and intensity (a complement to what is presented in Section 4.4 and Table 4.5.1). Yellow segments indicate locations where ice jams are usually minor but could still generate the peak water level of the year. Orange segments indicate locations of major historical ice jams and where it is therefore expected that ice jams represent the dominant flooding process. Red segments indicate reaches of major ice jams that have caused severe floods in recent years, as revealed through the analysis of aerial photos. Finally, blue segments denote river reaches where high flows in open water conditions could represent the dominant flood mechanism. This figure should be improved over time as research about the breakup regime of the Klondike River enters a second phase.

Table 4.6.1. Conditions leading to ice jam flood damage along the lower Klondike River.

Location	Conditions leading to ice jam floods and/or structural damage to infrastructure
C-4, bridge area (Km 2-3)	A thick freeze-up jam and an ice run from Km 5 may cause severe overflow at this location. The contribution of additional ice as far as Km 12 can only aggravate the situation and can even threaten the bridge. This ice jam usually releases at a flow below 250 m^3/s.
TH Farm (Km 17)	Dynamic freeze-up or a cold winter can generate a highly resistant ice cover at the head of the island at Km 17. A small ice contribution (from Km 18 and 19) may be enough to cause flooding, but ice runs from up to Km 27 can worsen the situation.
Rock Creek (Km 21-22)	The shortest ice jams that caused flooding in the lower Klondike River have been observed here. Intense freeze-up, a thick ice bridge, or a generally thick or grounded ice cover can probably generate enough resistance to cause an ice jam at Km 21.5. Although only 500 m of broken ice can cause a flood, the contribution (an early release) of the Km 23 ice jam can cause further flooding (but it could also cause the release of the local ice jam). This ice jam resisted a flow of 400 m^3/s in 2023.
Henderson Corner (Km 25-27)	The ice cover near the island at Km 25.5 seems to offer significant breakup resistance every second spring. However, in addition to high flow, an ice jam at that location would require the ice contribution from Km 26 to 28 to be considered “major”. Additional ice from Km 29, or even from Km 30-32, would probably cause the mobilization of this jam. If this was not the case, major flooding would result, with water levels potentially higher than in 2023 (when the ice jam resisted to about 450 m^3/s).
Dempster Highway bridge (Km 46)	A minor ice jam forms against the piers of the bridge almost every year. However, a major ice jam was observed in 2003 at that location, and it flooded nearby properties. The occurrence of this jam would rely on the supply of fragmented ice cover from Km 46 to 49. This ice cover would need to be mobilized by a sharp rise in runoff associated with a sudden increase in air temperatures or a rain event.

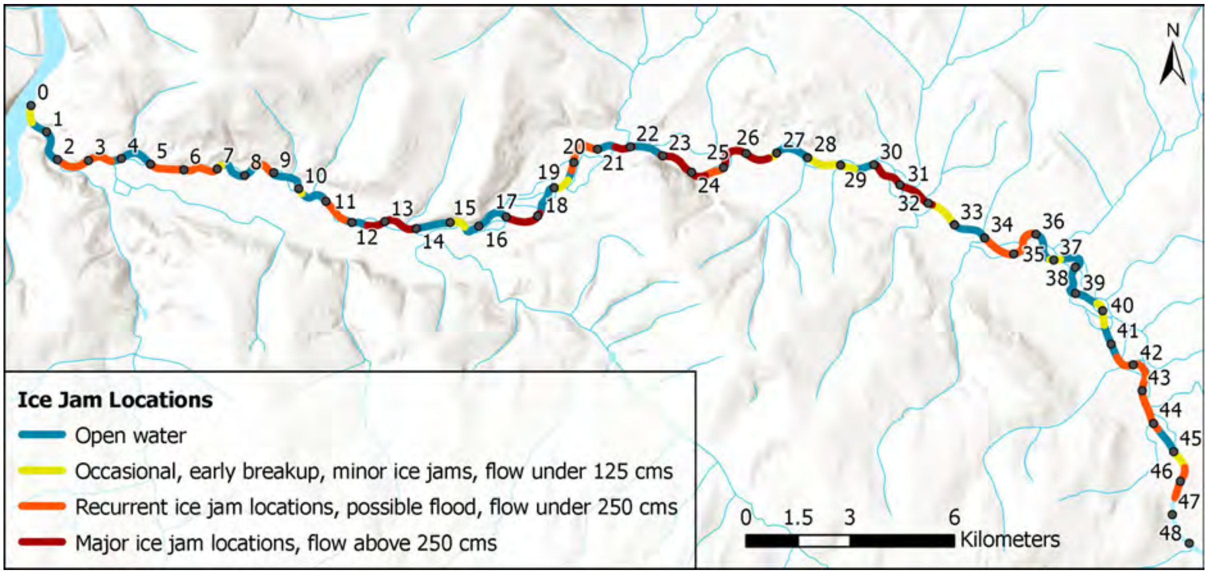

Figure 4.6.1. Map of the Klondike River showing where major ice jams (red and orange) and minor ice jams (yellow) have been reported in recent years. Blue segments have seen fewer or no ice jams, and this is where open water floods may be more frequent than ice jam floods.

5. Hydrometeorological aspects of breakup

5.1. Hydrometeorological envelope - station 09EA003

At the end of winter, the ice cover on Yukon rivers is usually at its thickest while the flow is at its annual minimum. The combination of these specific conditions results in an ice cover that is about ten times stronger than the hydrodynamic force acting on it. As the flow rate increases in response to snowmelt, and the ice cover degrades in response to thermal influences, the disparity between resisting and driving forces narrows, eventually leading to breakup conditions.

The timing and intensity of river ice breakup are controlled by weather conditions during the weeks and days prior to breakup, but also during the preceding fall and winter. As late-winter weather conditions start changing and snowmelt and ice cover degradation begins, flood forecasters need to assess several hydrometeorological factors that influence breakup, including:

- Intensity of the early-winter freeze-up process,
- Ice cover thickness (absolute or relative/anomaly) at different key locations,
- Snow cover conditions on the ice cover,
- Snowpack in the watershed.

The first three factors are considered to be indicators of the ice cover resistance whereas the fourth factor represents a runoff potential indicator. A fifth factor could be added: the winter or late-winter flow (compared to the historical average). However, this factor is probably not relevant for some rivers, including the Klondike, for two reasons: 1. The range of historical late-winter flows is comparable to the uncertainty associated with breakup and freshet flow estimations and 2. A higher-than-average late-winter flow may be the result of a thicker active layer resulting from permafrost thaw rather than an increased ground saturation with limited snowmelt absorption capacity. Nonetheless, a high late-winter flow usually means that the early-winter flow was also above average, and this would translate into an intense, or dynamic freeze-up process.

Regardless of late-fall and winter hydrometeorological conditions, breakup could still be very gradual and thermal. However, late-winter weather factors will inform forecasters about the possibility of a very dynamic breakup scenario with possible ice jam floods. For instance, at the end of the mild and record-dry winter of 2018-2019, even the worse weather conditions during breakup could not result in a 2003 or a 2023-equivalent flood. Once the pre-breakup assessment is completed and the range of possible breakup intensities is established, a close look at weather conditions starting in mid-April should inform the breakup timing and intensity forecast, with ranges of possible dates and scenarios that become narrower as breakup approaches.

As stated in companion reports (Turcotte et al., 2024a,b), breakup resisting and driving forces cannot be measured directly, and their evolution during the breakup period cannot be predicted with great certainty. This is why breakup forecast models need to rely on ice, hydrological, and weather parameters. Table 5.1.1 presents a list of such parameters with ranges associated with peak breakup levels at Water Survey of Canada station 09EA003. The timing of peak breakup water level at the station normally occurs at most 3 days before ice clearing, with a high probability of the peak level taking place a few hours to a few minutes before the release of the local ice jam.

TABLE 5.1.1. HYDROLOGICAL AND METEOROLOGICAL VARIABLES OR PARAMETERS THAT INFLUENCE BREAKUP TIMING AND INTENSITY ON THE KLONDIKE RIVER AT WATER SURVEY OF CANADA STATION 09EA003 NEAR DAWSON.

Parameters	Historical range	Historical average	Years of record
Peak breakup water surface elevation at station 09EA003 (GDVD2013e2010)	320.5 to 324.8 m	322.3 m	36 (1972-2024)
Date of breakup peak level	April 17 to May 15	May 1	36 (1972-2024)
Estimated peak flow during peak level at station 09EA003*	25 to 280 m^3/s	130 m^3/s	36 (1972-2024)
Effective cumulated degree-days of thaw** (ECDDT) at breakup at Dawson airport	120 to 215 °C-days	165 °C-days	36 (1972-2024)
April 1 snowpack averaged at 4 snow courses (water equivalent)***	100 to 300 mm	175 mm	50 (1975-2024)
Maximum cumulated degree-days of freezing (CDDF) at Dawson airport	2100 to 4600 °C-days	3350 °C-days	55 (1970-2024)
Estimated discharge before freeze-up at station 09EA003*	18 to 70 m^3/s	30 m^3/s	27 (1992-2024)
Peak freeze-up level at station 09EA003	320.5 to 323.1 m	321.5 m	27 (1992-2024)

* Based on a reassessment of WSC estimates

** Based on air temperatures roughly corrected for sun radiation

*** Snow courses 09EA-SC01, 09EA-SC02, 09EB-SC01, 09DD-SC01

The ranges and averages presented in Table 5.1.1 can significantly differ for other river reaches where historical ice processes have not been documented consistently. For example, the flow associated with peak breakup water levels at Km 24 must be higher than those of station 09EA003 because the Km 23 ice jam usually releases at a later date (Table 4.5.1). Different results would also be obtained for effective cumulated degree-days of thaw (ECDDT) as those tend to increase over time during the breakup period. More importantly, there are limited data about peak breakup levels (in the presence of ice jams or not) at other locations, including areas of high vulnerability like Rock Creek and Henderson Corner. Even though the WSC station 09EA006 has been operating for 10 years, it has not consistently monitored critical hydrological conditions (i.e., freeze-up levels, spring floods). Given the steepness of the Klondike River, even the date of peak breakup water level can change over a few hundred meters upstream or downstream of a monitored location, and Rock Creek represents a perfect example of this situation: In 2023, the ice jam that flooded the hamlet moved downstream where it continued to affect other properties, but its backwater was hardly detected at station 09EA006.

The data presented in the next sections will only refer to station 09EA003, which means that it mostly applies to a short reach of the lower Klondike River, between Km 1.5 and 3.5 (this includes Tr’ondëk [C-4] Subdivision, part of the Klondike Highway, the nearby gasoline station and RV campground, as well as the bridge). The lack of data at other sites prohibits the preparation of meaningful statistical assessments beyond Km 3.5, and this will be discussed in Section 5.4.

5.2. Influence of different breakup indicators

This section of the report explores the significance of different theoretical indicators as they would apply to the lower Klondike River breakup regime, mostly in terms of intensity (here represented by peak water surface elevation), but also in terms of timing. As mentioned at the end of the previous section, peak water levels reported in the following graphs are measured at station 09EA003 and may significantly differ at other sites along the river. Moreover, the timing and intensity of breakup at other points along the river could be controlled by other indicators.

Before diving into the existence or absence of logical trends and correlations, it is necessary to list important breakup years associated with either anomalous peak water levels or hydrometeorological parameters (often plotted in different colours in the following graphs):

- 1986: Breakup that year generated the highest absolute water level on record (324.8 m). One could presume that ice levels were slightly higher and that some ice floes came in contact with the Klondike Highway bridge soffit. Breakup conditions, in terms of winter coldness, earliness of breakup, and late-winter snowpack, were not particularly uncommon. Freeze-up conditions (in 1985) were not documented, but it seems that late-winter snow and some rain could have influenced the breakup process.
- 1994: This was the latest breakup on record, not in terms of date, but in terms of effective cumulated degree-days of thaw (ECDDT of 213°C-days). It was associated with a fairly low peak breakup water level (321.4 m).
- 2003: This is the second highest breakup water level on record (324.3 m), and it is largely attributed to a well-documented freeze-up jam (water level of 323.1 m) that formed in December 2002 following a significant warming in air temperatures (Janowicz, 2010). It was a relatively late breakup, in terms of ECDDT (194°C-days), and it followed a mild winter with a below-average snowpack.
- 2004: This is the third highest breakup water level on record (323.9 m). It occurred after a slightly colder and snowier winter than average. Unfortunately, there is a data gap in the hydrological record during the preceding season of river ice formation.
- 2016: This was the warmest winter on record with only 2100 cumulated degree-days of freezing (CDDF). Interestingly, the breakup peak water level in that year was slightly above average (322.6 m), potentially because freeze-up had also been more dynamic than usual.
- 2019: This winter was the driest on record at many nearby snow courses and the breakup peak water level was also the lowest on record (320.5 m). It was an extremely thermal breakup scenario along the Klondike River as well as on other rivers in the Yukon.
- 2022: This winter was characterized by a record-high snowpack in the central Yukon, and it is also the earliest breakup on record from an ECDDT perspective (120°C-days). This combination, on top of a winter with average temperatures, would logically mean that breakup was dynamic, but the peak breakup water level was actually below average (321.9 m).
- 2023: This event caused the fourth highest ice-affected water level on record (323.8 m). It followed a relatively dynamic freeze-up (322.4 m) and a wet winter (20% higher-than-normal snowpack in early April).

The intention behind this list, as the following graphs will show, is to depart from a standard statistical analysis and from significance tests (only a few clear trends were obtained in this study, partly because of the uncertainty associated with some of the data sets used). Instead, we propose to focus on anomalous breakup events (either causing high and low water levels) and extreme breakup driving and resisting indicators by examining specific data points (years) that seem to support or contradict expected trends. From our point of view, this is the best way to understand the physics of breakup in the Klondike River and advance the development of forecast tools. The following sections investigate the influence of different parameters on peak breakup water levels at station 09EA003, starting with recent conditions.

5.2.1 Spring air temperatures

ECDDT represents a breakup resistance parameter: the higher its value, the more degraded and less resistant the ice cover is expected to be. Therefore, it is anticipated that a high ECDDT would be associated with a low range of peak breakup water levels (as resisting and driving forces would meet at a lower value). Figure 5.2.1 presents a graph showing no correlation between these parameters and a trend that defies the theory (a downward interpolated trend from the 2013 data point to the 1994 data point would have appeared more logical). Breakup years 2003, 2004, and 2022, among others, represent anomalies from the expected, theoretical behaviour of the Klondike River. This suggests that other, more influential breakup parameters exist, and it questions the representativeness of ECDDT (as currently calculated) as an ice cover resistance indicator for the Klondike River.

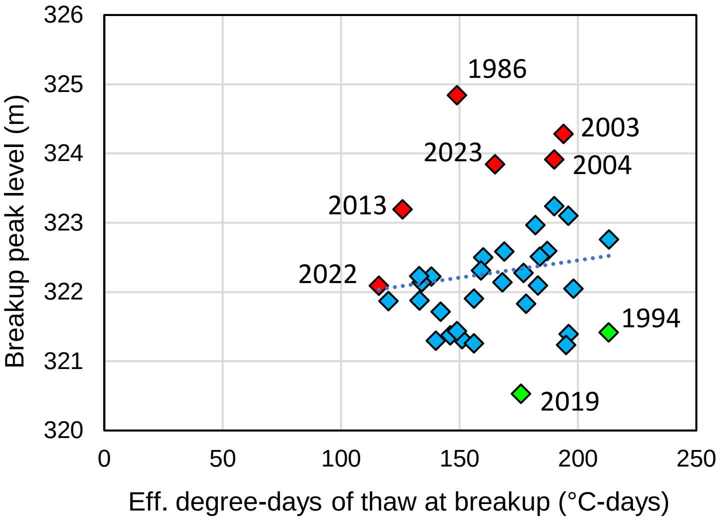

Figure 5.2.1. Annual peak breakup water levels (surface elevation) at station 09EA003 expressed as a function of effective cumulated degree-days of thaw (ECDDT) at Dawson Airport on the same date (data from 1972 to 2024 with several gaps).

5.2.2 Discharge during breakup

Discharge during breakup is known to represent a direct breakup driving indicator. It is only roughly estimated at station 09EA003 by the Water Survey of Canada during the breakup period. For this assessment, a reanalysis of the flow was performed using a judgement- based approach inspired by Turcotte (2022) to improve the accuracy of this record.

Figure 5.2.2 presents annual peak breakup water levels expressed as a function of this re-estimated (daily average) discharge during the corresponding date. The rising trend between these parameters was expected and the correlation is fair even if it is expected that the nature of the ice cover (thickness and roughness as well as blockage) would influence this relationship. The residual uncertainty in discharge rates precludes over-analyzing the results, including regrouping data points in families of comparable late-winter ice conditions (freeze-up jam, thick ice cover, thinner-than-average ice cover). However, among the highest water levels, it is confirmed that breakup in 2003 occurred in the presence of an unusually resistant freeze-up jam.

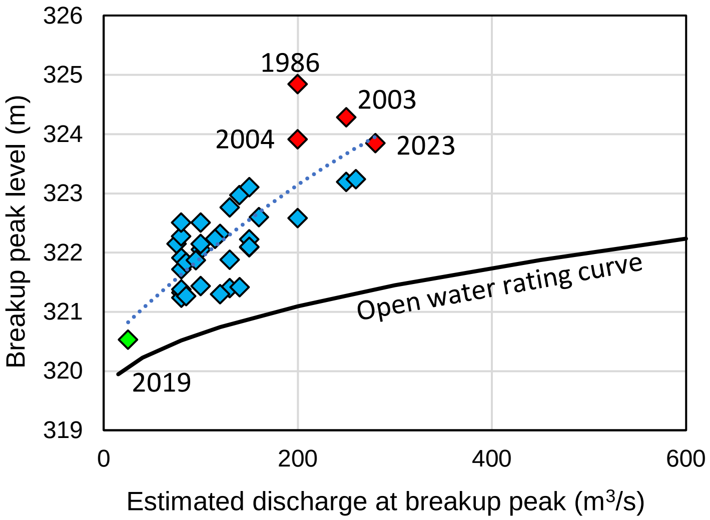

FIGURE 5.2.2. ANNUAL PEAK BREAKUP WATER LEVELS (SURFACE ELEVATION) EXPRESSED AS A FUNCTION OF CORRESPONDING ESTIMATED DISCHARGE AT STATION 09EA003 (DATA FROM 1972 TO 2024 WITH SEVERAL GAPS). AUTOMATIC POLYNOMIAL INTERPOLATION (BLUE DOTTED LINE) WAS EXPECTED TO DEPART FROM THE OPEN WATER RATING CURVE AS FLOW INCREASES.

Since the discharge can be difficult to estimate in real-time from ice-affected hydrometric data (the authors had access to post-breakup discharge data for their analyses), it does not represent an easily available breakup indicator when it is needed. Forecasters would benefit from having access to measurable, alternative parameters that influence snowmelt runoff, even if such parameters represent indirect indicators of breakup driving forces.

5.2.3 Late-winter snowpack

The quantity of snowmelt runoff over time can be evaluated directly using upstream (or tributary) flow data, or indirectly through the use of flow forecast models. Unfortunately, hydrometric stations in tributaries (e.g., 09EA005) or in an upstream reach (e.g., 09EA006) of the lower Klondike River are also affected by ice (breakup at those sites rarely happens early), and flow forecast models rarely perform optimally during snowmelt (the ripeness and presence of snow on different terrains within the watershed, as well as the capacity of the ground to absorb snowmelt, is hard to assess).

One could assume that the amount of snow on the ground would correlate with snowmelt flows in the Klondike River. Reported measurements from four Government of Yukon snow courses (King Solomon Dome [09EA-SC01], Midnight Dome [09EB-SC01], Grizzly Creek [09EA-SC01], and Calumet [09DD-SC01]) within or near the Klondike River watershed were averaged to generate an estimated late-winter snowpack dataset. The correlation between peak breakup water levels and both the April 1 and May 1 (for breakup events taking place after May 1) snowpack were tested and are reported in Figures 5.2.3 and 5.2.4. In both cases, the trend makes sense, but the correlation is very low (see R^2). When considering the April 1 snowpack, years 1986, 2003, and 2022 appear as anomalies. The data point from 2019 makes sense, but it is important to keep in mind that spring conditions in that year came very early and gradually (in addition to the record low snowpack). For the May 1 snowpack (Figure 5.2.4), the years 1986 and 2022 still represent outliers. Overall, assuming that snow course data are representative of the watershed average, this indicates that 1. In most years, there is enough snow in the watershed to generate a dynamic breakup scenario leading to severe ice jams and 2. Even with a significant snowpack, breakup could still be thermal (with consequent low water levels).

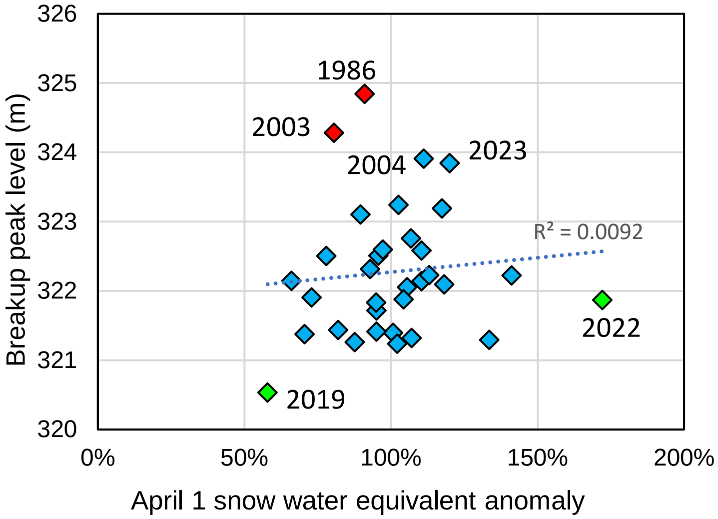

FIGURE 5.2.3. ANNUAL PEAK BREAKUP WATER LEVELS (SURFACE ELEVATION) AT STATION 09EA003 EXPRESSED AS A FUNCTION OF AVERAGE SNOWPACK (SWE ANOMALY) ON APRIL 1 AT FOUR SNOW COURSES (DATA FROM 1975 TO 2024 WITH SEVERAL GAPS).

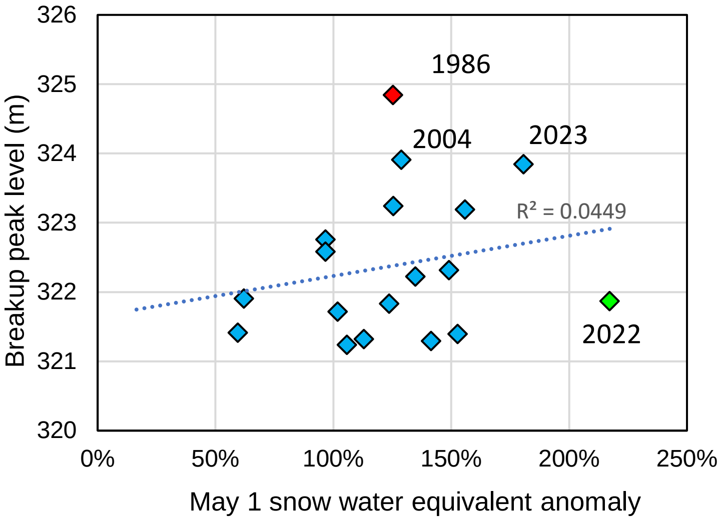

FIGURE 5.2.4. ANNUAL PEAK BREAKUP WATER LEVELS (SURFACE ELEVATION) DURING THE MONTH OF MAY AT STATION 09EA003 EXPRESSED AS A FUNCTION OF AVERAGE SNOWPACK (SWE ANOMALY) ON MAY 1 AT FOUR SNOW COURSES (DATA FROM 1975 TO 2024 WITH SEVERAL GAPS).

It is interesting to note that for 15 of the 35 breakup events where the peak water level happened in April, the average snowpack around April 1 was only 90%. This either suggests that a thin snowpack would melt sooner and generate enough runoff to cause an early breakup or that dry winter patterns are often followed by early spring conditions (i.e., warm conditions). Also of interest is that the average, residual snowpack for those April breakup peak events was 95 mm on May 1 compared with 160 mm on April 1. This suggests that, on average, only 65 mm (ranging from 0 mm to 140 mm) of the snowpack would contribute to ice clearance at station 09EA003 (balancing the role of sublimation, rainfall, snowfall, and the breakup peak date during the month of April).

5.2.4 Spring air temperature thresholds influencing breakup timing

Beyond late-winter snowpack data, the rate of snowmelt is also an important factor controlling freshet flows. Since Figures 5.2.3 and 5.2.4 suggest that the amount of snow on the ground rarely represents a limitation to breakup intensity, the influence of air temperatures on breakup peak water levels was investigated. Figure 5.2.5 shows that most high breakup water levels occur after a day with an average temperature of 8°C at Dawson Airport once at least 80 ECDDT is reached (making the snowpack isothermal and ready to melt). In these cases, high temperatures caused high runoff rates pushing against a competent ice cover near station 09EA003. Only 1986 stands as an anomaly, but 1985 also represents an extreme scenario. Since both breakup events are associated with similar known parameters (e.g., ECDDT, snowpack), it appears that freeze-up conditions (unknown) or rain (known to have occurred in 1986) could have played a role, therefore explaining the distance between both data points in Figure 5.2.5.

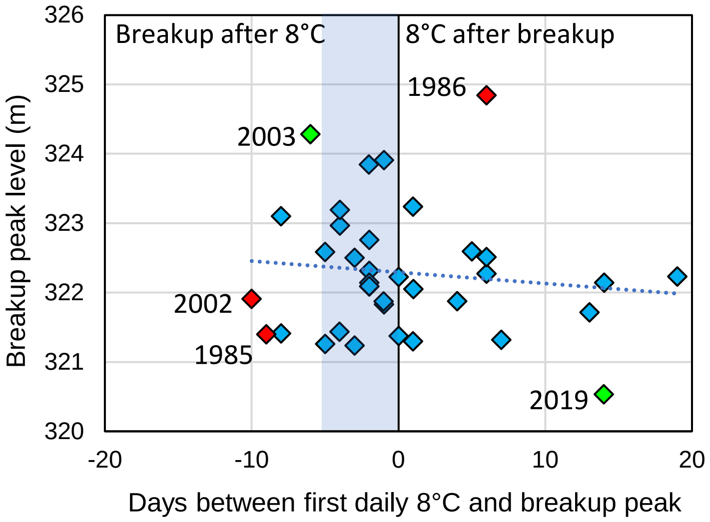

FIGURE 5.2.5. ANNUAL PEAK BREAKUP WATER LEVELS (SURFACE ELEVATION) AT STATION 09EA003 RELATIVE TO THE DIFFERENCE IN DATES BETWEEN BREAKUP PEAK AND THE FIRST DAILY-AVERAGE AIR TEMPERATURE ABOVE 8°C AT DAWSON AIRPORT (DATA FROM 1972 TO 2024 WITH SEVERAL GAPS).

The threshold of 8°C in Figure 5.2.5 was selected because it is often associated with a maximum air temperature of about 15°C, clear sky conditions, and significant snowmelt potential. It also means that the night temperature could be above 0°C, which would translate into continuous snowmelt runoff for more than 24 hours in a row. Rather than speculating, the influence of the timing of the first night above 0°C on breakup intensity was tested directly (Figure 5.2.6).

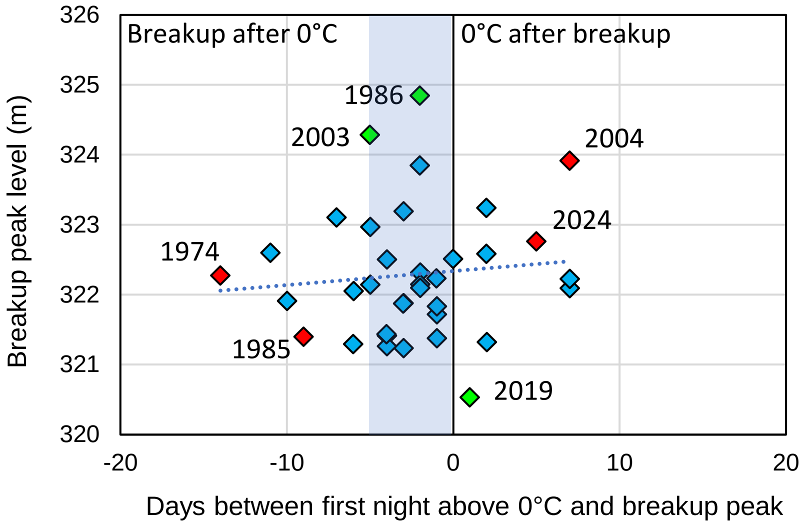

FIGURE 5.2.6. ANNUAL PEAK BREAKUP WATER LEVELS (SURFACE ELEVATION) AT STATION 09EA003 EXPRESSED AS A FUNCTION OF THE DIFFERENCE IN DATES BETWEEN PEAK BREAKUP AND WHEN THE FIRST NIGHT ABOVE 0°C OCCURRED AT DAWSON AIRPORT (DATA FROM 1972 TO 2023 WITH SEVERAL GAPS).

The scatter in Figure 5.2.6 is as high as in Figure 5.2.5, and the interpolated trend does not make sense, in part because of data points from 1974 (first warm night at 80 ECDDT followed by cold weather), 1985 (first warm night at 112 ECDDT followed by cold weather), 2004 (daily freeze-thaw cycles consistently occurred from April 2 to May 8), and 2024 (daily freeze-thaw cycles consistently occurred from March 19 to May 4). However, the breakup event of 1986 is now on the left side of the graph (compared with Figure 5.2.5), implying that high snowmelt rates played a role in that flood as well. Even if breakup intensity is not predicted by the occurrence of a rise in snowmelt rates driven by high air temperatures, the timing of breakup seems to be remarkably predicted by this rather simple parameter alone: Between the data series presented in Figure 5.2.5 and 5.2.6, one or both air temperature indicators predict breakup within 5 days (see light blue areas) for 25 of the 35 breakup events and in only 3 of the remaining 10 cases (including thermal breakup year 2019), both indicators fail to anticipate breakup.

5.2.5 Winter air temperatures

Considering the vertical spread in Figure 5.2.2, as well as the poor correlations presented in Figures 5.2.3 to 5.2.6, it appears that breakup intensity at station 09EA003 is largely controlled by breakup resistance. Since ECDDT does not represent a reliable breakup intensity indicator (Figure 5.2.1; peak breakup water levels appear relatively independent of ice cover degradation), the influence of other ice resistance parameters needed to be explored.

The theory of lake and river ice suggests that colder winters lead to thicker ice covers. Based on the well-used Stefan equation (e.g., Michel, 1971), ice cover thickening is a function of the square root of cumulated degree-days of freezing (CDDF), which means that an ice cover exposed to 4000°C-days of freezing (common near Old Crow) is only twice as thick as an ice cover exposed to 1000°C-days of freezing (common in northern British Columbia). Figure 5.2.7 explores the relationship between maximum CDDF (an expected proxy of ice cover thickness, and therefore, resistance) and breakup intensity at station 09EA003 for 36 years. Not only is the interpolated linear trend horizontal (it would be expected to rise), but the scatter is high.

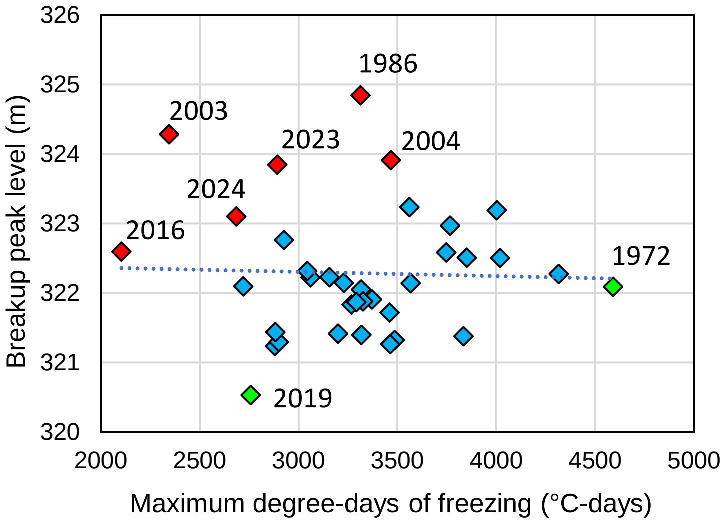

Figure 5.2.7. Annual peak breakup water levels (surface elevation) at station 09EA003 expressed as a function of maximum cumulated degree-days of freezing at Dawson Airport (data from 1972 to 2024 with several gaps).

In Figure 5.2.7, the four highest peak breakup water levels (1986, 2003, 2004, and 2023) occurred after a mild or normally cold winter. In addition, the coldest winter in this data set (1972) was associated with a peak water level during breakup that was close to average. In contrast, the mildest winter on record at Dawson occurred in 2016 and resulted in a higher-than-average peak water level (i.e. higher than the level in 1972). Multiple reasons can explain the noisy results of Figure 5.2.7, including the intensity of the freeze-up process near or immediately downstream of station 09EA003, or the effect of snow insulation, both of which are currently unaccounted for in this assessment. In the Yukon, low-density snow offers significant insulation against heat loss.

5.2.6 Freeze-up intensity

Figure 5.2.8 presents 23 peak breakup water levels expressed against peak freeze-up water levels at station 09EA003. In this case, the expected rising trend is nicely captured by the interpolation, and the correlation is reasonable, with only a single serious anomaly (1998) plotting below the 1:1 line. Generally, results show that a peak breakup water level in the spring will remain within a 1.5 m-range (average of 0.8 m) above the corresponding maximum peak freeze-up water level. Moreover, breakup events in 2016, 2019, and 2024 followed mild winters and were gradual and thermal, which validates the boundary role of the 1:1 line for predicting minimum peak breakup water levels. Note that the river ice theory (e.g., Beltaos, 2008) proposes that an ice cover would only be mobilized once the water level rises above the freeze-up level.

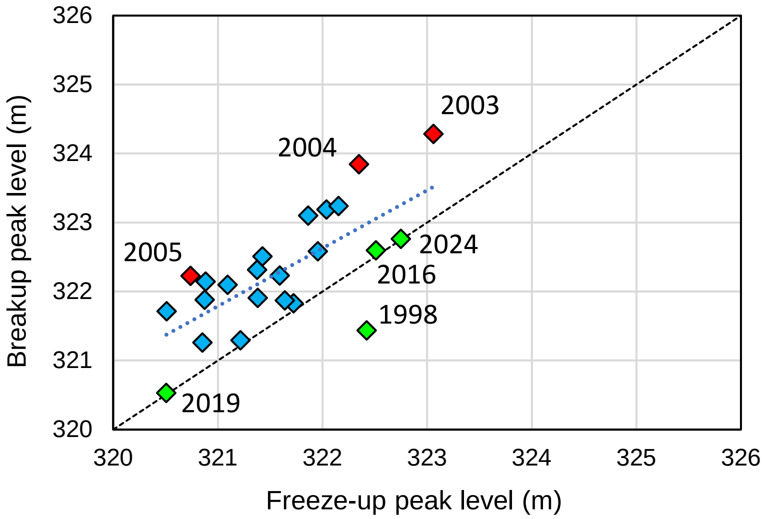

FIGURE 5.2.8. ANNUAL PEAK BREAKUP WATER LEVELS (SURFACE ELEVATION) EXPRESSED AS A FUNCTION OF CORRESPONDING PEAK FREEZE-UP WATER LEVELS AT STATION 09EA003 (DATA FROM 1998 TO 2024 WITH SOME GAPS). THE DOTTED LINE IS THE 1:1 LINE.

A dynamic freeze-up process is often associated with high flows that can cause consolidation events, frequently referred to as freeze-up jams. The correlation between pre-freeze-up flows and peak freeze-up water levels was tested. Unfortunately, the scatter was significant. Since estimating the discharge of the Klondike River prior to the formation of a complete ice cover is challenging (the large uncertainty is in part associated with the freeze-up flow depression), and since maximum water levels are relatively easy to measure, investigating the correlation between fall flow and spring level was discarded.

5.3. Breakup indicators at station 09EA003

Based on the material presented in Section 5.2, it seems that river ice breakup at the Klondike Highway bridge near Dawson can evolve quickly following a sharp rise in snowmelt runoff. Results from Figures 5.2.5 and 5.2.6 suggest that, once the snowpack is ready to melt (80 effective degree-days of thaw), above-freezing conditions over more than 24 consecutive hours may generate enough runoff to cause significant ice movements in that segment of the lower Klondike River during the following days. From the information provided in Section 4, peak breakup water levels may occur during the formation, the consolidation, or the release of the local, annual ice jam. Its formation and consolidation are generally caused by the mobilization of the ice cover over a relatively short upstream distance (less than 3 km) whereas the clearance of the local ice jam is likely caused by the release of an upstream ice jam (and its associated ice run or its wave/jave).

As a summary, the timing of peak breakup water levels at Water Survey of Canada station 09EA003 would occur:

- Within a few days after a single day with an average air temperature above 8ºC or a single night above freezing after 80 ECDDT at Dawson Airport (easy to forecast or measure)
- As soon as there are more than 120 ECDDT at Dawson Airport (easy to measure)
- Because of a large ice run from upstream (very hard to predict or detect, even a few hours in advance)

In terms of breakup intensity, the dominant breakup indicators identified here are the discharge (Figure 5.2.2, a driving force parameter) and the freeze-up level (Figure 5.2.8, a resisting force parameter), the latter being much easier to assess than the former. In turn, any parameter associated with winter or spring weather conditions seems to have poorer ability to predict peak breakup water levels. The most intense breakup events at station 09EA003 would be associated with:

- A freeze-up jam (water levels above 322.0 m, Figure 5.2.8)
- A sufficient snowpack in the watershed (above 75% of normal in early April, Figure 5.2.3)
- A sudden rise in air temperatures or a rain event causing runoff and the flow to increase relatively quickly (predictive power to confirm, refer to breakup events from 1986, 2003, and 2023). Note that long sequences of thaw-freeze cycles would have the opposite effect.

To further understand the factors and conditions leading to severe ice jams and occasional ice jam floods near station 09EA003, more information about breakup sequences in 1986, 2003, 2004, 2023, and 2024 (high freeze-up level in 2023) should be obtained, including from local residents. The presence of fresh snow on the ice cover prior to spring breakup, which is assumed to contribute to maintaining the structural integrity of the ice as mobilization forces are rising, has not yet been investigated. This could partially explain the unexpected trend presented in Figure 5.2.1. The occurrence of significant ice jams after mild (2003, 2023) or normally cold (1986, 2004) winters could be attributed to a relatively weak ice cover upstream of a freeze-up jam, which also deserves scientific attention. Finally, the role played by sublimation (dry conditions) and rainfall events (wet conditions) in the watershed should be analyzed, starting with the weather record from the Dawson Airport weather station.

5.4. Breakup indicators at other Klondike River sites

Ice jam flooding at Henderson Corner was reported in 2006, 2012, 2013, and 2023. Out of these years, only 2023 produced above-average ice jam water levels some 22 km downstream at station 09EA003. A similar situation is reported for Rock Creek, where ice jam floods occurred in 2006, 2009, 2013, 2015, and 2023 whereas peak breakup water levels at station 09EA003 in 2009 and 2015 were also close to average. Furthermore, ice jam floods occur frequently at TH Farm, which is not the case at most other locations along the lower Klondike River. This is a reminder that ice jam flooding is highly site specific and often hard to predict with great accuracy. Since all sites are affected by similar hydrometeorological conditions during winter and spring, the significant spatial variation in breakup intensities demonstrates that freeze-up conditions and year-specific breakup sequences play a major role in the occurrence of ice jam floods.

The influence of freeze-up jams, among other breakup intensity factors, needs to be consistently documented near vulnerable sites. In addition, the timing of local ice cover mobilization as well as nearby ice jam formation, consolidation, and release events need to be adequately monitored in order to improve the predictability of ice jam floods and design reach-adapted flood risk reduction measures. These aspects are discussed in the next section.

6. Summary and recommendations

6.1 Spatial aspects

Information from different sources of data, including aerial photos and satellite imagery, was compiled to create knowledge about the breakup regime of the lower Klondike River, from the North Klondike River confluence (Km 50) to the outlet in the Yukon River (Km 0). Based on 8 to 15 years of data and observations, several assessments about the spatial aspect of breakup were completed and are presented in Section 4.

Our confidence in the results of these analyses mostly varies from moderate to low, and our understanding is therefore considered incomplete. For instance, the location of weak and strong ice cover segments (Figure 4.1.1), the role of tributaries (Table 4.2.1), as well as the location of minor and major ice jams (Figure 4.4.1) are known with a moderate level of confidence; The Klondike River could still cause surprises in future years, but our understanding is probably fairly representative of the actual breakup regime. In turn, the distribution of freeze-up jams (Figure 4.3.1), the location of dominant ice jams (Figure 4.4.2), the spatial distribution of the flood risk (Figure 4.6.1), and the description of a typical breakup sequence (Table 4.5.1) are likely representative of approximately half of all breakup events.

Recommendations to improve our knowledge about the spatial aspect of breakup in the lower Klondike River are:

- Produce a highly accurate surface profile of the Klondike River to identify steeper and flatter reaches that would partially explain the location and resilience of breakup ice jams.
- For the next 3 to 5 springs, document ice coverage conditions during breakup, identify the location and timing of breakup ice jams and confirm the occurrence and timing of ice runs in the lower Klondike River. This work can be performed through aerial surveys, drone surveys, water level data records from different instruments, and observations from the ground using portable and automated cameras.
- For the subsequent 3 to 5 falls, dedicate resources to the investigation of freeze-up processes and patterns, including the determination of the location of early-winter congestion points.
- Consult residents and knowledge holders to identify sites where ice jams form or never seem to form and about historical floods. Any information can be useful.

6.2 Timing and intensity aspects

Through analyzing 23 to 36 years of available data, Section 5 has explored the parameters that seem to influence and control the timing and intensity of river ice breakup at the Water Survey of Canada station 09EA003. In terms of timing, it can be stated with confidence that breakup (peak ice jam water level and subsequent ice clearance) at Water Survey of Canada station 09EA003 happens between 120 and 220 effective cumulated degree-days of thaw (ECDDT), for a discharge below 250 m^3/s. Moreover, it generally occurs after the first night above freezing (Figure 5.2.6) or the first day with an average air temperature above 8°C (Figure 5.2.5), once more than 80 EDDT have been cumulated.

In terms of breakup intensity at station 09EA003, a higher discharge (Figure 5.2.2) and a higher freeze-up water level during the preceding fall (Figure 5.2.8) generally lead to higher breakup water levels, especially if the April 1st snowpack is above approximately 75% of normal (Figure 5.2.3). In turn, long periods of daily freeze-thaw cycles or a return to cold temperatures promote a thermal breakup. Most other air temperature indicators (e.g., maximum cumulative degree-days of freezing, CDDF, Figure 5.2.7) showed a low predictive capacity of breakup intensity during the following spring.

There were not enough available data to investigate hydrometeorological controls on breakup timing and intensity at other river locations. Although it can be expected that they compare to those identified for station 09EA003, this needs to be confirmed. Moreover, the conditions that led to the ice jam floods of 2023, beyond an atypical freeze-up and a sudden rise in spring air temperatures, are still unknown.

Recommendations to improve our ability to forecast the timing and intensity of river ice breakup on the lower Klondike River include:

- For station 09EA003, develop a physics-based empirical model comparable to the prototype model of the Yukon River (Turcotte et al., 2024a), emphasizing hydrometeorological controls identified in Section 5. This model could promote further knowledge development about the local breakup regime and inform its own future optimization.
- Investigate the historical hydrological role of rain events in the Klondike River valley during the river ice breakup period (e.g., using ERA5 simulation results).
- Reconstruct hydrographs of historical breakup events (both dynamic and thermal) and freeze-up events (both dynamic and gradual) using the methodology developed by Turcotte (2022) and adopting a sub-daily time step,
- For the next 3 to 5 winters, measure maximum water levels and/or record the timing of dynamic ice events at several sites, including Km 5-6 (Eureka Drive), Km 12 (former swimming area), Km 17 (TH Farm), Km 22 (Rock Creek), Km 23-24 (dominant ice jam location between Rock Creek and Henderson Corner), Km 25-26 (Henderson Corner), Km 30-32 (potential location of the most resilient ice jam in the river), and Km 46 (Dempster Highway bridge). Since ice jam formation and release events between these locations seem to significantly influence maximum water levels along the river and therefore flood probabilities, it would be important to better understand how they are related in time.
- Compile hydrological and ice-related statistics (e.g., Table 5.1.1) for the same targeted sites as mentioned above.

6.3 Other recommendations

In addition to the material presented in Sections 6.1 and 6.2, general recommendations from this study are:

- Improve the reliability of station 09EA006 or relocate the station to a different site. Furthermore, clarify the role of this station (it is currently of limited use for flood forecasting or flood risk reduction planning).
- Perform assessments comparable to the following preliminary analyses (Figure 6.3.1) as they would support the development of predictive tools for other river locations.

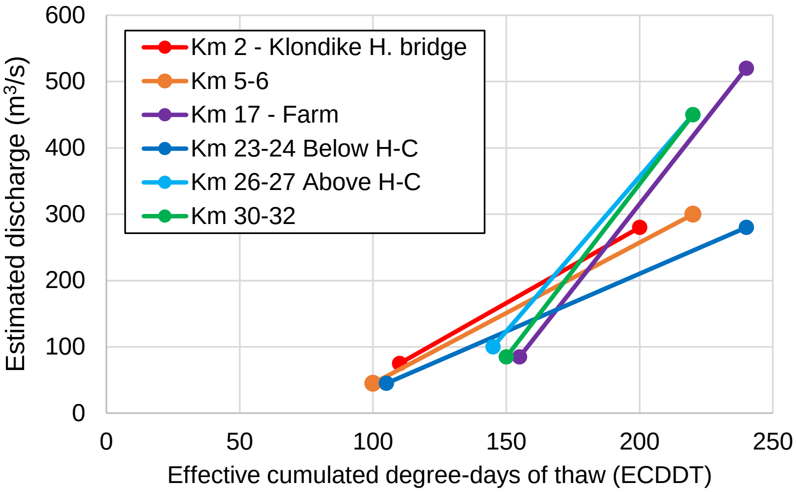

FIGURE 6.3.1. PRELIMINARY ASSESSMENT OF DISCHARGE AND ECDDT THRESHOLDS FOR THE FORMATION AND RELEASE OF HISTORICAL ICE JAMS AT DIFFERENT LOCATIONS ALONG THE LOWER KLONDIKE RIVER.

- Using data already collected as well as future observations, explore the development of simple, threshold-based breakup forecast models for multiple locations along the lower Klondike River.
- Complete a pre-feasibility study about implementing light ice jam mitigation measures (e.g., temporary monitoring stations, ice cover weakening, morphological adaptation, ice booms). These measures could impose a certain level of predictability on breakup sequences and directly reduce the risk of ice jam floods at vulnerable locations. This could also inform infrastructure design and the safe development of subdivisions in the Klondike River valley.

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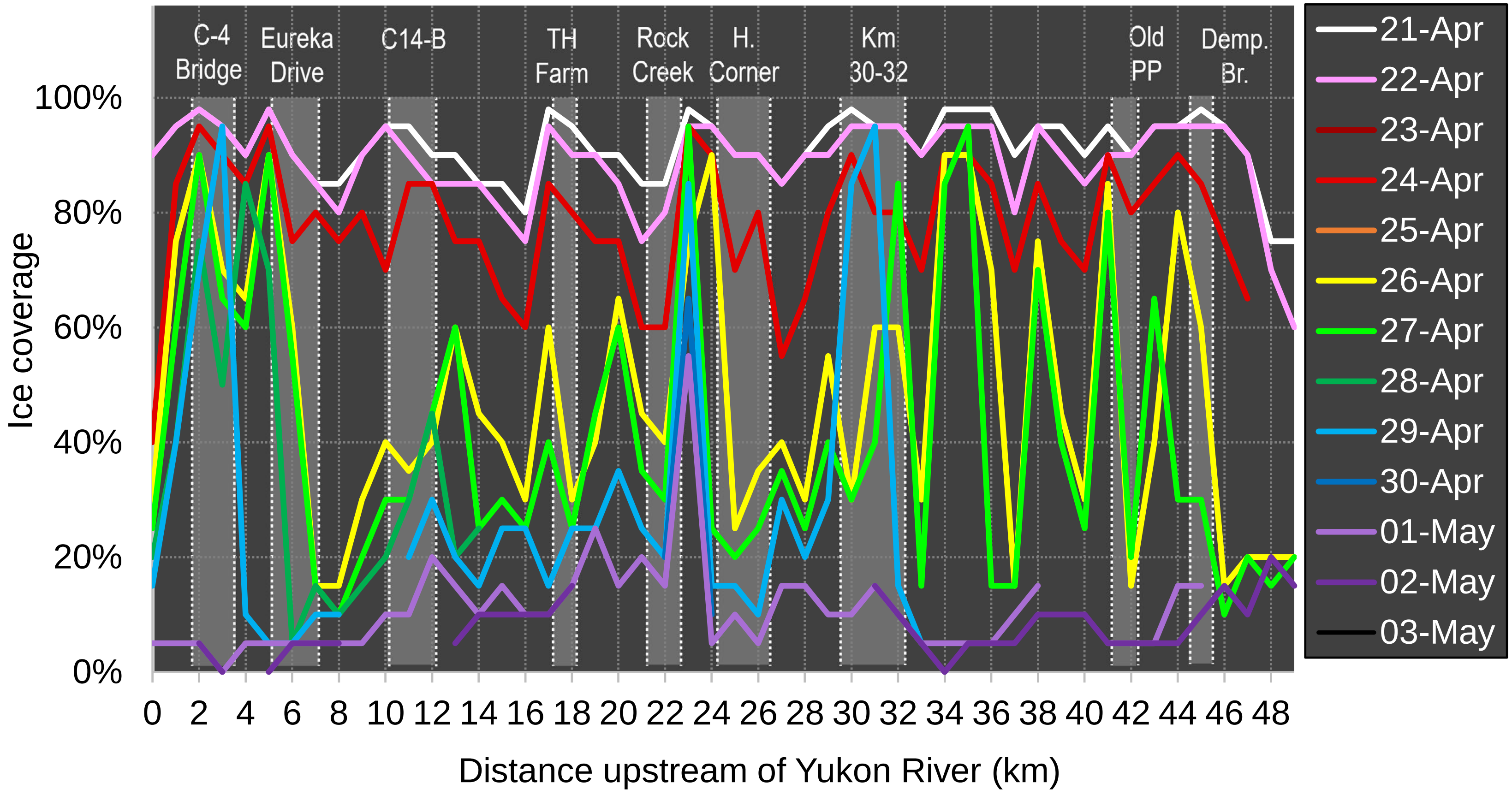
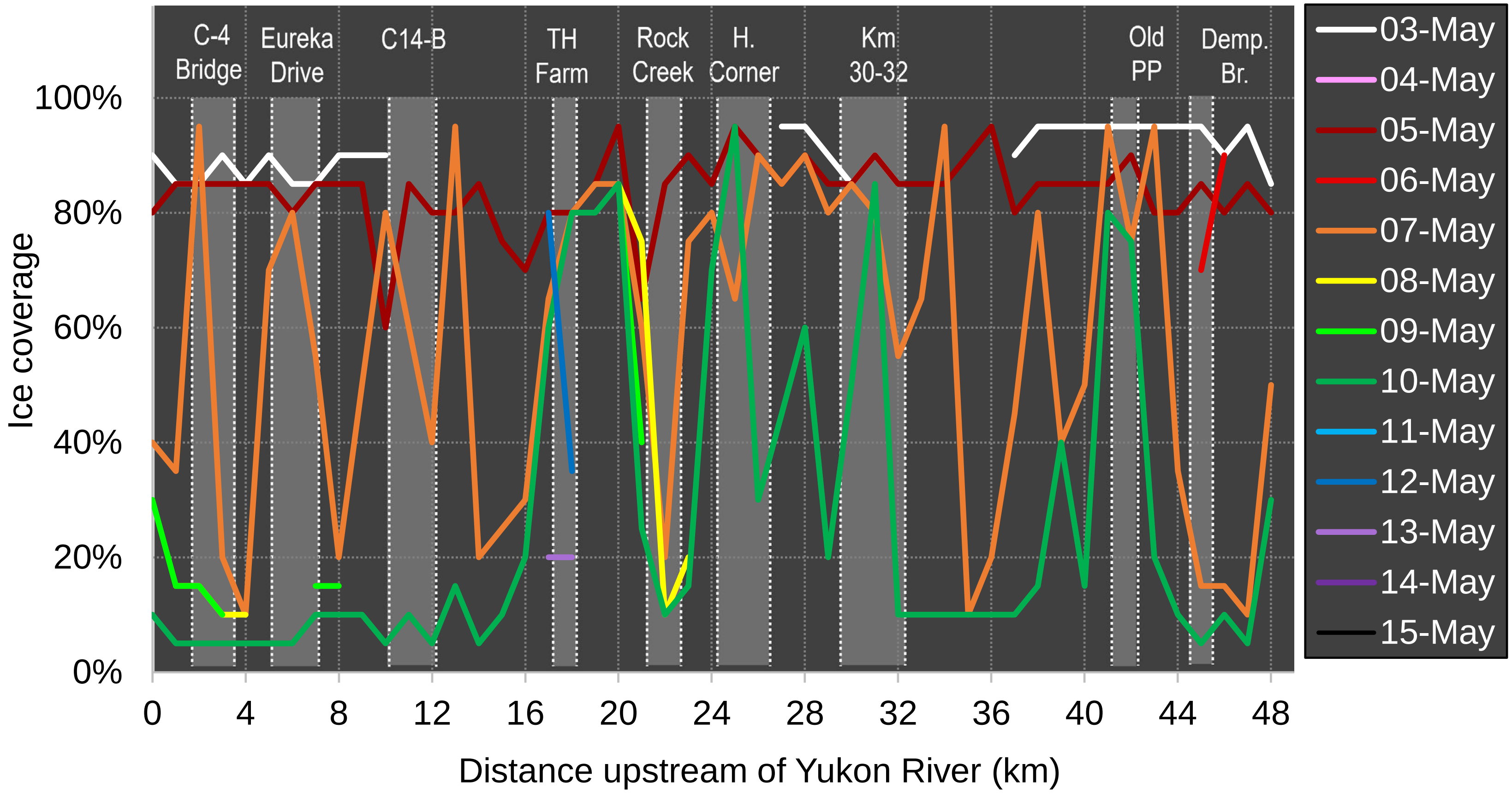
Appendix A:

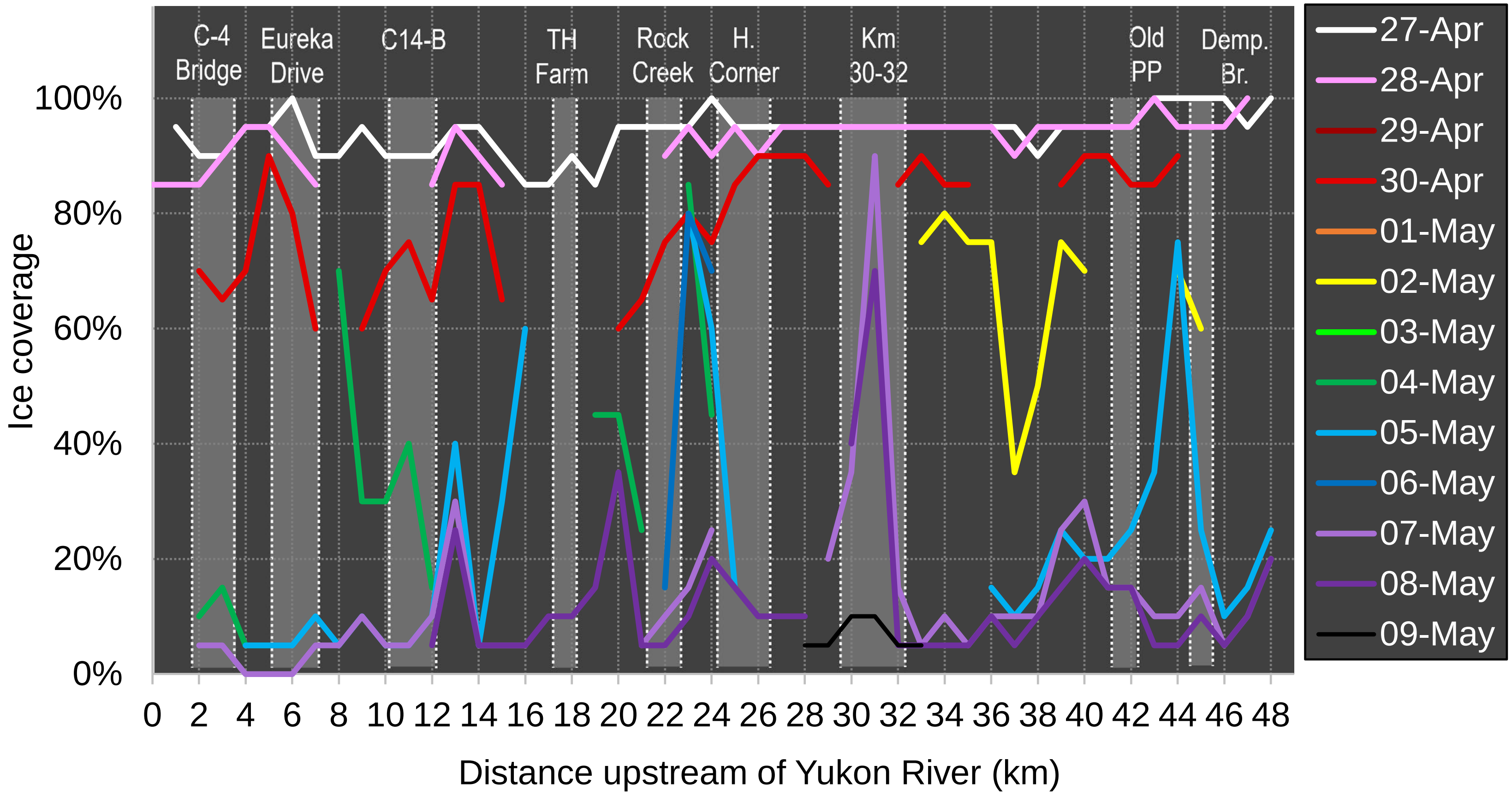
Cryograph from spring 2024.



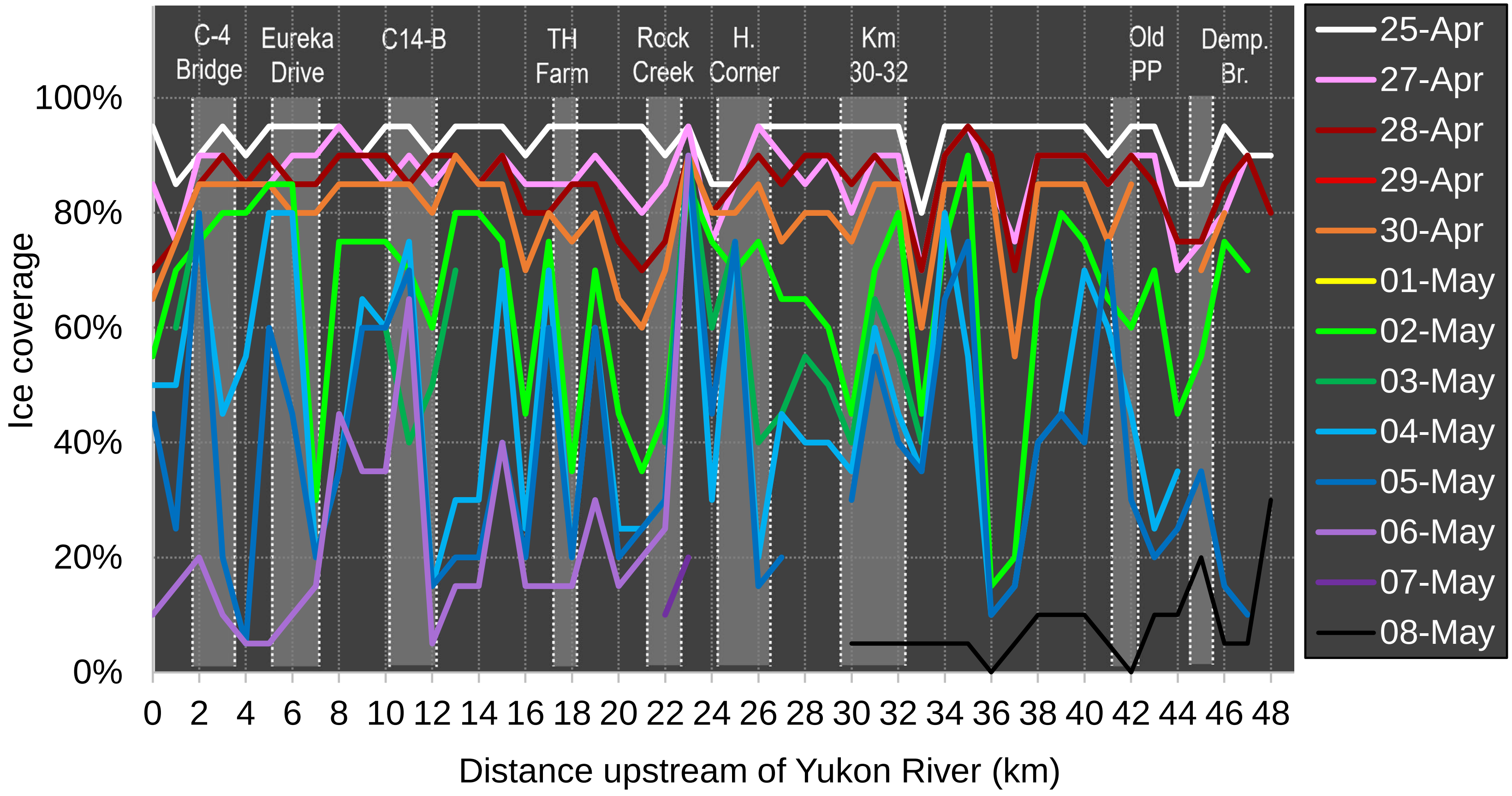
Cryograph from spring 2023.



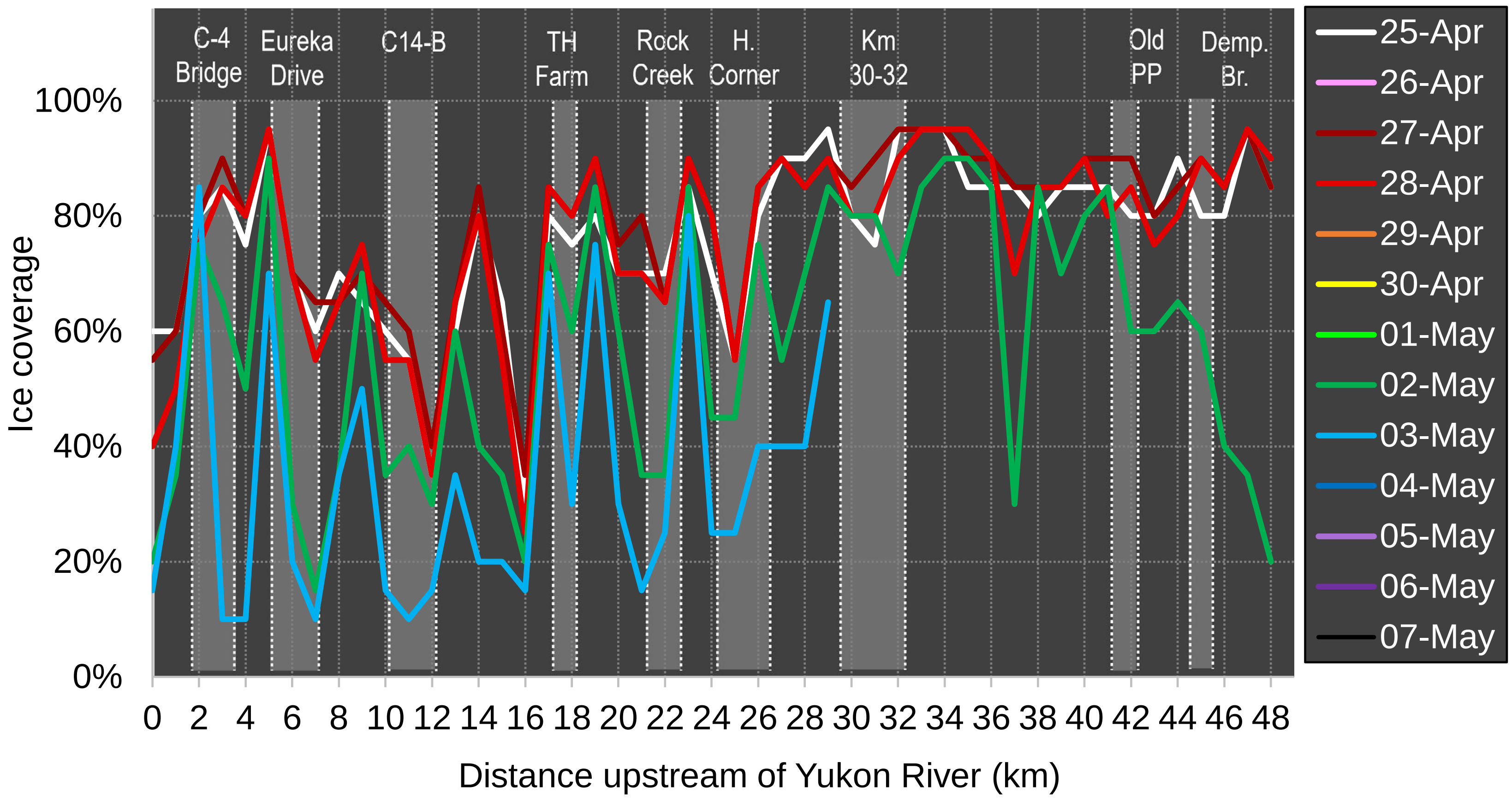
Cryograph from spring 2022.



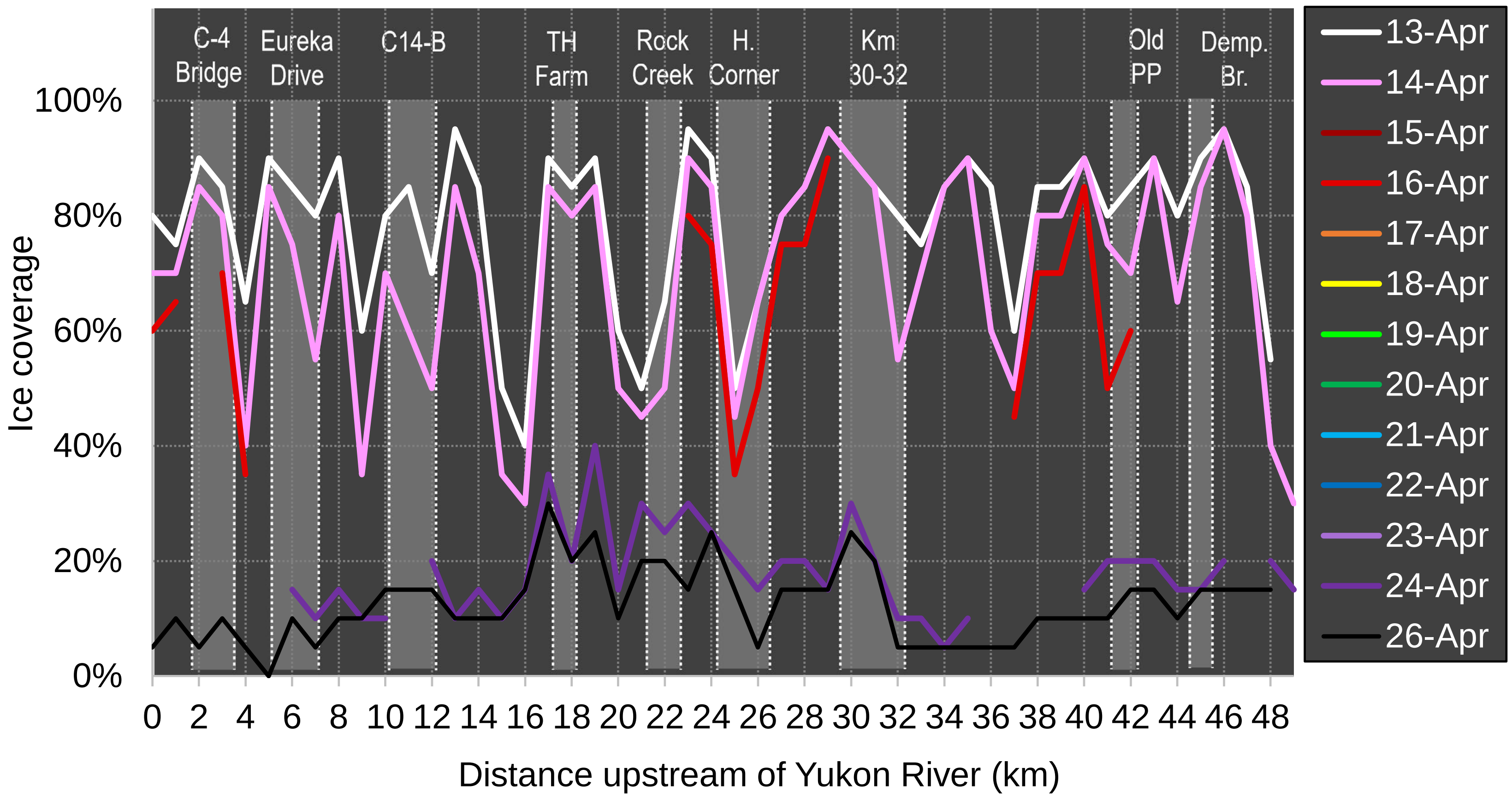
Cryograph from spring 2021.



Cryograph from spring 2020.



Cryograph from spring 2019.



Cryograph from spring 2018.