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Flooding processes and recent trends in ice-induced high-water levels along rivers of Northwestern Canada

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Ice jams form in most cold region rivers on an annual basis. Through partial channel blockage and increased flow resistance, they generate high water levels. In some instances, most often during significant runoff events that follow a prolonged period of freezing temperatures, major flooding can result. This flooding process is relatively independent of, and therefore adds to, the probability of open water floods caused by spring snowmelt, glacier melt, as well as summer and fall rainstorms.

Climate change affects weather parameters that control hydrological and river ice processes. As a result, the frequency and intensity of floods is evolving, which may impact many aspects of our environment, from infrastructure design to land use planning, and from aquatic habitat health to traditional living. This paper explores and compares flooding processes at 11 Water Survey of Canada stations located in Northwestern Canada and reports on observed trends of three flooding processes over a maximum of 50 years. Results generally indicate that the frequency of ice-induced floods has remained stable or could not be confirmed because of gaps in hydrometric records. This research is part of a national effort to detect and foresee the impact of climate change on many aspects of river ice sciences and engineering.

1. Introduction

Most communities in Canada are established along large rivers and lakes that may respond to specific, short term and seasonal weather patterns by producing water levels that are higher than early settlers would have expected. In Northwestern Canada, several mining camps and villages were established by ambitious European descendants, seeking adventure, worried about surviving next winter, and largely ignorant about traditional ways of living and natural processes. Dawson City, Yukon, represents a classic example: It mushroomed on the banks of the Yukon River at the outlet of the Klondike River, home of the Tr'ondëk Hwëch'in, and it developed at such an exaggerated rate during the 1896-1899 Gold Rush than its population grew from a small fishing camp to a large mining city of 40,000 people in two years (the largest city in Canada west of Winnipeg at that time). Newcomers soon discovered about breakup ice jams, and the city, now a smaller community, had to adapt during the 20th century after being affected by several minor and major floods. Obviously, the development of Northwestern Canada was largely improvised, driven by resource exploitation, and urban planners were not among the first to live North of Sixty.

Statistically, it is a matter of time before the next flood happens. Therefore observations, acknowledgement of traditional knowledge, and a careful interpretation of western science all contribute to reducing flood risks. The Water Survey of Canada (WSC), the Federal agency responsible for the monitoring of rivers and lakes across the country, has been operating hydrometric stations at key locations in the north for decades. The early work to obtain water level and discharge measurements at remote locations involved great danger, from harsh weather conditions to rudimentary means of transportation and measurement equipment (e.g., Alford, 1985). The valuable data produced by the WSC, complemented by hydrometric networks operated by other agencies, is key to the development of statistical material that informs sustainable urban development and infrastructure design in the North.

However, global warming is affecting the range and frequency of weather conditions that drive hydrological processes, impacting flows, ice conditions, and water levels. This is especially true in the North, where climate change is occurring faster (Bush and Lemmen, 2019) in a land of thawing permafrost and melting glaciers, and where the production of continuous hydrological records remains a technological challenge. As a result, sustainable living in the North, and more specifically flood risk reduction, needs to account for something largely unknown: future hydrological conditions.

This paper explains river flooding processes at 11 locations in Yukon and Northwest Territories, and explores a simple approach to determine the impact of climate change on these processes. The following sections describe what has been reported in the scientific literature and explain the research methodology. Then, data sets, derived from recent historical WSC records, are presented and analyzed for different rivers. Results are discussed and possible research improvements are listed afterward.

2. Background

2.1 Research about the impact of climate change on ice-induced floods

The impact of climate change on river ice processes has been a fertile research topic since the end of the 20th century. Review papers (e.g., Beltaos and Prowse, 2001; Beltaos and Prowse, 2009; Burrell et al., 2021) and book chapters (e.g., Beltaos and Burrell, 2008) compiled and compared the results from various studies and addressed a number of winter-related subjects such as hydroelectric production, transportation (including winter navigation and ice roads), flood risk reduction, infrastructure design adaptation, and evolving aquatic and riparian habitats. A majority of studies focused on historical trends of simple river ice parameter and, as a result, review papers remained relatively conceptual, only provided general information, and could not establish explicit projections about future ice-induced floods. In other words, the river ice scientific community was still a few steps away from being able to quantify the probability or the risk of future ice-induced water levels at specific locations. Many reasons explain the lack of confidence in the projection of future ice-induced floods risk:

- There is a scarcity of river ice data: Winter hydrological parameters are often dangerous and costly to monitor on a continuous basis and some major historical events, especially in remote areas, were not documented.
- Climate change projections are largely uncertain, and their representativeness will continue to depend on scientific progress as well as on political decisions at a global scale. This affects our capacity to determine future weather conditions, especially specific parameters dictating and influencing hydrological processes.
- Guidelines for the development of flood maps that includes ice-jam floods, even those excluding the impact of climate change, have only recently been explored (e.g., NRCan, 2019) and techniques that have been applied recently are yet to be endorsed by a majority of river ice experts.
- Because of the complexity of interactions between weather, hydrology and morphology-related parameters that drive or influence ice-induced water levels (a diagram presented by Turcotte et al., 2019, provides an overview), investigating the impact of climate change on single, isolated indicators (such as maximum ice thickness, winter season duration, or discharge after the spring breakup) does not provide much insight about past or future ice jam flood frequencies and intensities.

Turcotte et al. (2019) summarized additional concepts to anticipate, and a few approaches to evaluate, the impact of climate change on river ice processes. A classic but complex approach, often referred to as the hydrotechnical approach, consists in relying on hydrological and river ice models, calibrated using recent historical weather data and ice observations, to simulate a range of future ice-hydraulic conditions, and then to compile the results into meaningful statistics. This approach was recently applied at specific sites (Das et al., 2020) and at a provincial scale (Turcotte et al., 2020). The authors clearly mentioned some limitations as well as future research needs, one of which was to develop and calibrate hydrological models that would adequately simulate snowmelt runoff and that would capture winter hydrological processes such as hydraulic storage release (e.g., Prowse and Carter, 2002) and flow-ice interaction at breakup (e.g., Jasek and Beltaos, 2008, She and Hicks, 2006).

In turn, the simplest and most direct approach to understand the impact of climate change on ice-induced floods involves the analysis of historical water levels. Keeping in mind that historical trends cannot simply be extrapolated into the future, this approach was adopted in this study and is described in Section 3.

2.2 Overview of ice-induced floods in Northwestern America

Ice-induced flood mechanisms and specific flood events in northwestern America has received significant attention (at least relatively to the population density) in recent decades, especially for these two large watersheds:

- Yukon River watershed (e.g., Jasek, 1997; Jasek 1999; McCreath et al., 1988; White, 1999)
- MacKenzie River watershed downstream of (and excluding) the Peace-Athabasca Delta (e.g., Goulding et al., 2009a; Hicks et al., 1995; Marsh et al., 1993; Oveisy and She, 2017; Parkinson and Holder, 1988; Watson et al., 2009)

In terms of climate change impact on ice processes, Janowicz (2010) suggested that a warming climate was already affecting river ice breakup severity and had led to the unprecedent occurrence of winter breakup events in Yukon (on the Klondike River in 2002). Janowicz (2017) also suspected that river ice breakup events may become more dynamic in the Porcupine River (northern Yukon) in the future.

A study by Von de Wall et al. (2010) presented 1969-2006 trends in maximum breakup water level for several rivers in Northwestern Canada, including tributaries and the main branch of the Yukon and MacKenzie Rivers. Results suggested that maximum breakup water levels were increasing or decreasing, depending on the site or hydrometric station, and that most trends were not considered statistically significant. Only the Frances River (Tributary of the Liard River that flows towards the Mackenzie) was confidently showing signs of reduced breakup water levels whereas historical trends from the Liard River at Fort Liard and the Liard River near Fort Simpson were suggesting an increased likelihood of ice jam flooding over time. Overall, the analysis did not state if identified trends, significant or not, would have an impact on the frequency of flooding, given that dominant flooding processes or flooding thresholds were not considered (ice jams may become more frequent, but they may generate relatively low water levels compared with open water floods).

Another interesting data set is provided by the USACE Ice Jam Database (Carr et al., 2015) for the Yukon River in Alaska. From 1970 to 1995, there was an average of 10 reported ice jams on an annual basis at different locations along the river. This average dropped significantly afterward, with several recent years reporting zero ice jams worth of mention. Although this excludes information about ice jam intensity, it tentatively suggests that ice jam floods are becoming less frequent and/or severe along the Yukon River downstream of Yukon, Canada.

Generally, the expected impact of climate change on ice-induced floods seems to largely vary depending on the authors’ interpretation, the adopted analytical approach, the period considered, and assumptions. This paper cannot realistically pretend to provide an accurate picture of the impact of climate change on high-water levels in all rivers of northwestern Canada, but it attempts to bring us, river scientists and engineers, closer to an answer.

3. Methodology

As mentioned earlier, the simplest and most direct approach proposed by Turcotte et al. (2019) to quantify the impact of climate change on ice-induced floods was selected in this study. It consists in extracting maximum water levels from historical records to determine if the impact of a warming climate, through a myriad of interconnected effects on weather, hydrological and ice-related parameters, on ice-induced floods can be detected. Maximum annual water levels (Y_{max}) were extracted from historical data sets (generally between 1970 to 2020) for three types of hydrological events:

- River ice breakup ($Y_{max\ B}$)
- Maximum open water discharge ($Y_{max\ OW}$)
- River ice formation ($Y_{max\ F}$)

Identifying $Y_{max\ B}$, either caused by the juxtaposition of ice floes, the formation of an ice jam, the superimposition of an ice jam with a jave (ice jam release wave) from upstream, or a jave accompanied by a high concentration ice run, was based on judgement, experience, analysis of satellite images (for recent years), notes left by WSC employees, and complementary weather indicators including cumulated degree-days of thaw (CDDT), air temperatures, and precipitation. The science of interpreting ice processes in water level signals is described in a companion paper (Turcotte and Nafziger, 2021). To extract the most accurate $Y_{max\ B}$ value, it was critical to use instantaneous (hourly or sub-hourly) water level data, not only because it provides more comprehensive information about ice conditions at, upstream and downstream of the hydrometric station, but also since the difference between instantaneous and daily-averaged water levels when an ice jam forms or releases is generally significant (e.g., a few tens of centimeters to more than two meters). The estimated discharge associated with each $Y_{max\ B}$ presented in this study is generally a daily-averaged value estimated by WSC, but in some instances, the discharge was re-evaluated based on the interpretation of the water level signal.

Maximum open water levels ($Y_{max\ OW}$) were included in the study with the purpose of comparing the intensity of different type of flooding processes for different river segments. The use of instantaneous data was not critical in this case, given the generally limited peak factor, but hourly or sub-hourly data was use for consistency. Most events were associated with spring snowmelt or a combination or residual snowmelt and summer rain, and were fairly easy to extract from historical records. In a few cases, a jave with an assumed low ice concentration (a wave of limited amplitude that would last several hours), and therefore falling on the open water rating curve, was identified as the highest open-water event of the year.

Finally, the maximum water level associated with river ice formation processes ($Y_{max\ F}$), either dynamic (frazil ice congestion and freeze-up jams) or passive (border ice migration and gentle ice flow juxtaposition), was included in the study. The analysis of water level signals to extract the maximum early-winter (or mid-winter in some cases) water level rarely gave room to interpretation, and results were sometimes surprising. The estimated daily-averaged discharge at the time of $Y_{max\ F}$ was obtained from the WSC records.

4. Studied sites

Table 1 presents a summary of the studied rivers, including simple hydroclimatic data. It also shows that mean flows have either been rising (↗) or remained constant (≈) since 1970, and that average maximum annual cumulated degree-days of freezing (CDDF) have been declining in recent decades (e.g., -13 CDDF per year (y) indicates that each winter, a day with an average temperature of -13°C is replaced by a day at 0°C or any equivalent combination). Figure 1 presents a map showing the location of each WSC station included in the study.

Table. 1. Studied rivers and locations (community) with additional information of approximate drainage basin area, mean annua flow, and average annual maximum cumulated degree-days of freezing (CDDF).

River	Community	Basin area	Mean flow	Max CDDF
Porcupine	Old Crow, YK	55,400 km^2	320 m^3/s (↗)	4300 (-21/y)
Yukon	Dawson, YK	264,000 km^2	2,200 m^3/s (↗)	3400 (-13/y)
Klondike	Dawson, YK	7,800 km^2	65 m^3/s (↗)	3400 (-13/y)
Stewart	Mayo, YK	~ 30,000 km^2	~ 300 m^3/s (↗)	2900 (-11/y)
Pelly River	Pelly Crossing, YK	48,900 km^2	400 m^3/s (≈)	3100 (-16/y)
Nordenskiold	Carmacks, YK	6,410 km^2	15 m^3/s (≈)	2800 (-13/y)
Yukon	Carmacks, YK	81,800 km^2	750 m^3/s (≈)	2800 (-13/y)
Liard	Upper Liard, YK	32,600 km^2	380 m^3/s (≈)	2700 (-9/y)
Liard	Fort Liard, NWT	222,000 km^2	~ 2000 m^3/s (≈)	ND
Hay	Hay River, NWT	51,700 km^2	105 m^3/s (≈)	2880 (-12/Y)
MacKenzie	Fort Simpson, NWT	1,300,000 km^2	6850 m^3/s (≈)	3300 (-11/Y)

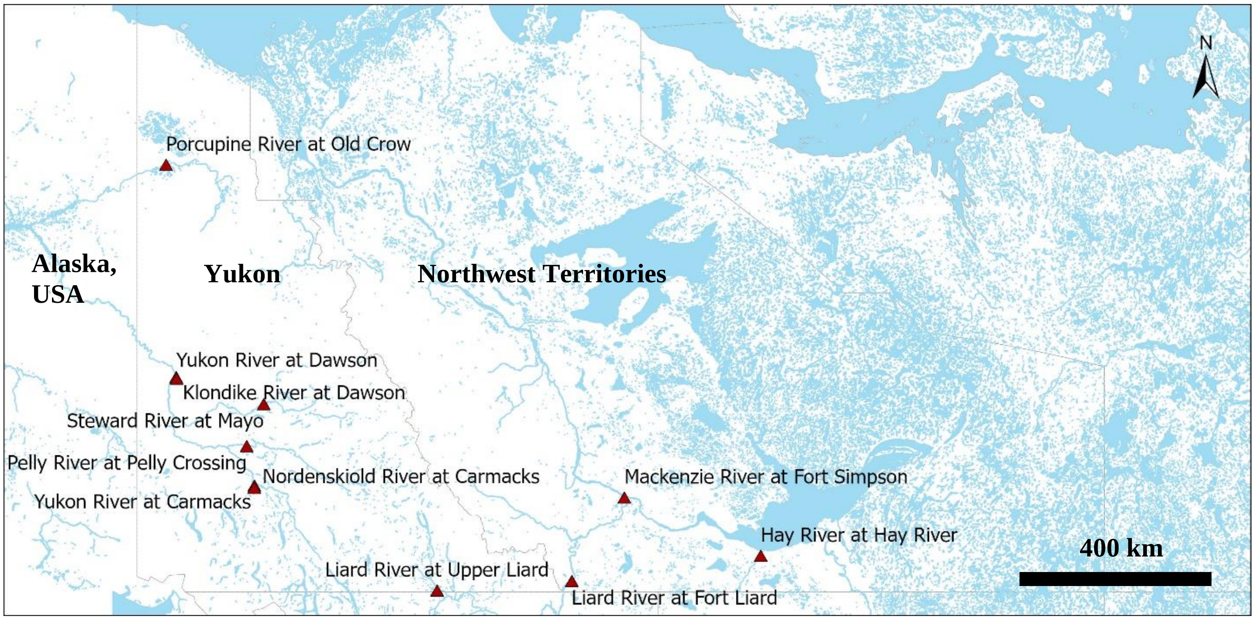


Figure 1. Map presenting studied rivers and sites in Northwestern Canada (prepared by Stephanie Saal, Yukon University Research Center).

5. Results

5.1 Porcupine River in Old Crow

The Porcupine River watershed is home of the Vuntut Gwitchin First Nation; its Government is based in Old Crow, the northern-most and only fly-in community of Yukon. The river flows northward from the Ogilvie Mountains before turning west and meeting the Yukon River at Fort Yukon, Alaska. This river is known for its significant ice jams (Jasek, 1997); the most intense event in recent history was recorded in 1991 when Old Crow was significantly flooded (Figure 2). Figure 3 presents Y_{max} for three flooding processes from 1970 to 2021. The WSC hydrometric station in Old Crow (09FD003) changed location in 1995 (used to be 09FD001, downstream of Old Crow), and only some maximum ice jam water level elevations prior to 1995 could be transposed successfully to Old Crow. Moreover, the station is usually turned off before winter, therefore the limited $Y_{max\ F}$ record.

Figure 2. 1991 Old Crow ice jam flood (ice jam head located downstream of the community, to the left, a small portion of the airport runway is visible in the middle of the picture to the right below the ice-covered pond). Photo taken by the Federal Government.

From this partial data set, it can be alleged that the highest annual water level is often associated with the spring breakup period (about 6 out of 10 years), that ice jams and impeded ice runs generate water levels that are, on average, 1 m higher than maximum open water flows, and that freeze-up events are not impressively dynamic. Based on an analysis made by Jasek (1997), given that the 1991 flood occurred upstream of the ice jam equilibrium section (Beltaos, 2008) and actually upstream of the ice jam head (Figure 2), and considering the local river valley and flood plain topography (Old Crow is located on the lower bank of the river), ice jams have the potential to produce even higher water levels in Old Crow.

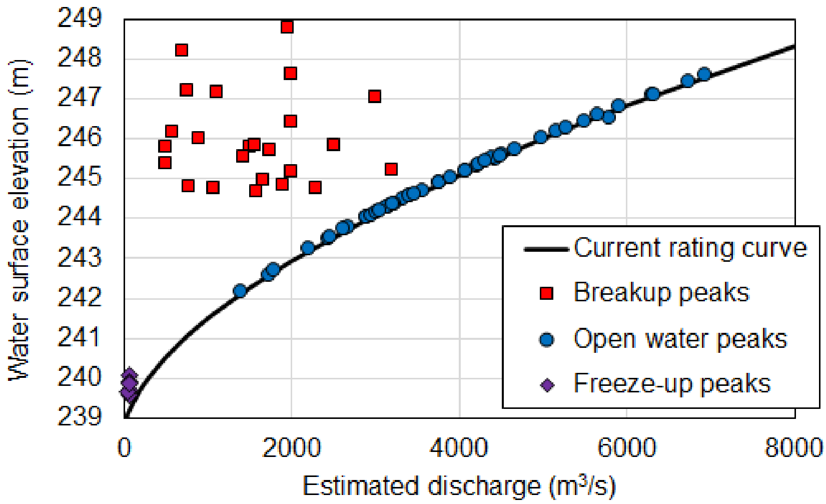


Figure 3. Approximate current rating curve, maximum breakup water levels, maximum open water levels and maximum freeze-up water levels between 1970 and 2021 (with several gaps) expressed as a function of the estimated discharge at station 09FD003 on the Porcupine River in Old Crow, Yukon

The short record and gaps (Figure 4) preclude attempting to distinguish a climate-change trend in $Y_{\text{max B}}$ and $Y_{\text{max F}}$ elevations (a comparable conclusion had been obtained by Janowicz, 2010). In turn, the 50-year trend analysis reveals that $Y_{\text{max ow}}$ (some of which were reconstructed using flow data from station 09FD002 located further downstream) have remained fairly stable over time (linear interpolation), with a rising trend in the last 20 years (polynomial interpolation).

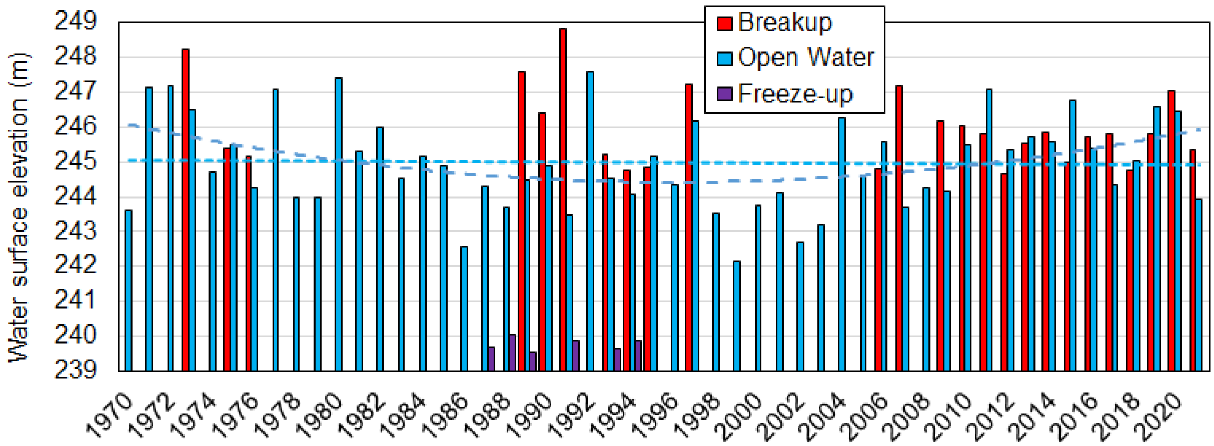


Figure 4. Historical annual maximum water levels at breakup, during the open water season, and at freeze-up between 1970 and 2021 (with several gaps) at station 09FD003 on the Porcupine River in Old Crow, Yukon. Linear and second order polynomial interpolation presented for open water data only.

It is expected that the hydrological regime of this watershed will continue to change profoundly because of a combination of permafrost thawing (increased ground absorption capacity), expected increased snowpack (e.g., Bush and Lemmer, 2019), more extreme melting conditions, and more intense summer precipitation. A possible first indicator of this evolution is that breakup patterns observed in recent years have been significantly different from what Jasek (1997) had described. Moreover, in May 2020, the Porcupine River was close to flooding Old Crow during an impeded ice run; had the run stalled to form an ice jam downstream of Old Crow, significant flooding would have resulted. The annual probability of flooding for Old Crow (minor flood elevation corresponds to about 247.0 m, but the WSC datum may need to be corrected by almost 2 m to match LiDAR-derived elevations), currently estimated at 10% to 20%, is expected to increase in the future, but the data only partially supports this statement.

Note that at the downstream station 09FD002, located in a steeper reach at the border with Alaska and operated year-round, $Y_{\mathrm{max\ OW}}$ slightly but consistently dominate $Y_{\mathrm{max\ B}}$. This illustrates that flooding processes can vary over short distances along the same river.

5.2 Yukon River at Dawson

Dawson is home of the Tr'ondëk Hwëch'in and has a unique history (see introduction). The Yukon River is the largest water course in Yukon, it drains about 55% of the territory and generally flows northward before turning northwest and entering Alaska. The Yukon River at Dawson has one of the longest, continuous breakup records in the region, with breakup dates and estimated water levels starting back in 1898 (McCreath et al., 1988). Dawson is known for its dynamic river ice breakup events and a siren informs the population when the first sustained ice cover movement takes place, generally early in May. People then gather on the dike and take pictures of large, blue ice floes left on the banks as the ice run continues. The most significant flood in recent history happened in 1979. The ice jam formed at midnight and it remained in place for several days. This motivated the construction of a higher dike in the mid-1980s (McCreath et al., 1988).

Figure 5 presents Y_{max} for the three flooding processes from 1970 to 2021 expressed as a function of the calculated or estimated discharge at station 09EB001 (operated by WSC and by Yukon Government for several years, but not consistently during winter until recently). The record shows that ice jams only cause Y_{max} 35% of the years, but they have the potential to generate the most significant floods. In turn, it seems that most freeze-up events, generally consisting in a dynamic interception and packing of incoming ice pans (Turcotte, 2020), do not have the potential to generate high water levels. The freeze-up event of 2020, which happened relatively early in the fall after a wet summer, only caused the water level to rise to an elevation of 314.7 m (not presented in Figure 5 because the discharge had not been estimated yet).

Figure 6 presents the 1970-2021 Y_{max} record based on the data from station 09EB001 as well as breakup data elevation collected by the Government of Yukon (detailed in Janowicz, 2010). Some open water record gaps were filled using data from a station operated by WSC at Eagle, Alaska, and available on the Alaska Pacific River Forecast Center website. This data suggests that $Y_{\mathrm{max\ OW}}$ seems to be declining, which is in line with what is detected along several large rivers in Yukon (see subsequent site analyses). In turn, the red linear trend in Figure 6 suggests that $Y_{\mathrm{max\ B}}$ remained fairly stable over 50 years, with significant variability, with some low values in recent years, but ending with a dynamic breakup event in 2021.

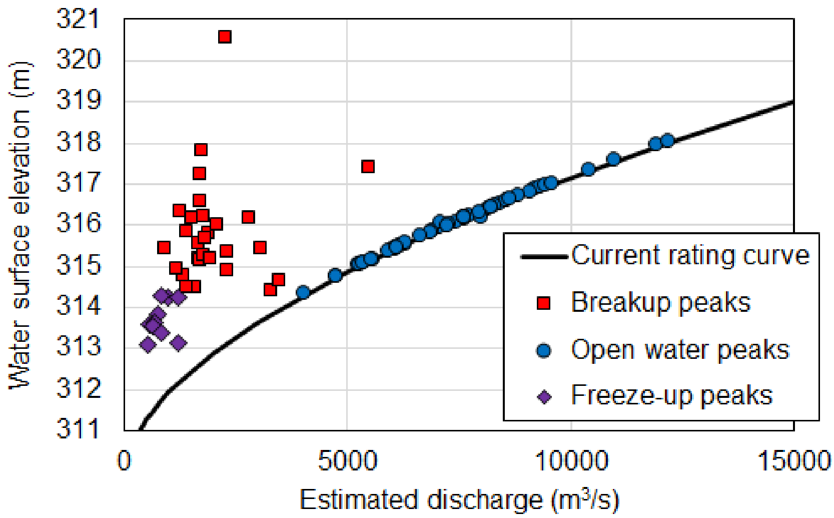


Figure 5. Approximate current rating curve, maximum breakup water levels, maximum open water levels and maximum freeze-up water levels between 1970 and 2021 (with several gaps) expressed as a function of the estimated discharge at station 09EB001 on the Yukon River at Dawson, Yukon.

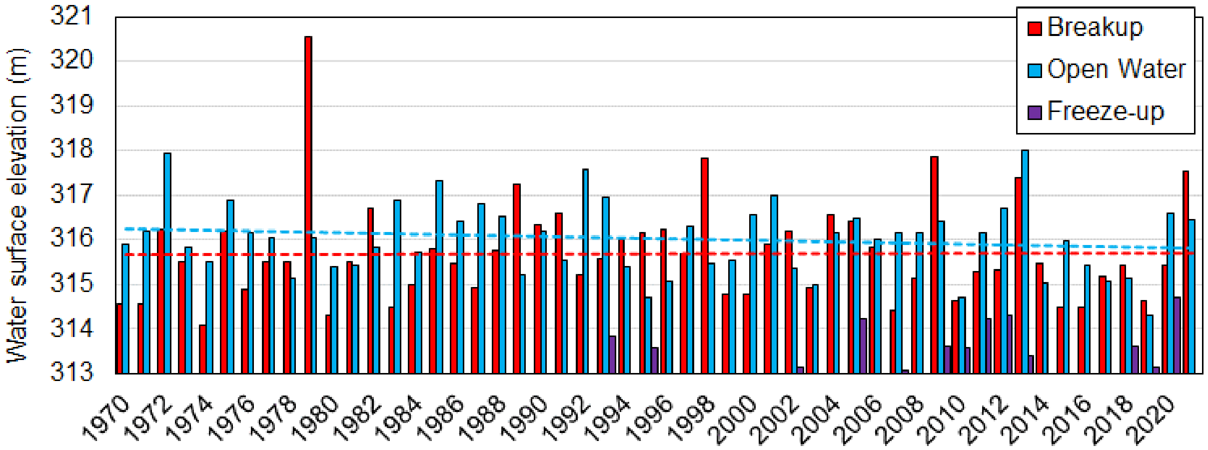


Figure 6. Historical annual maximum water levels at breakup, during the open water season, and at freeze-up between 1970 and 2021 (with several gaps) at station 09EB001 on the Yukon River at Dawson, Yukon. Linear interpolation not presented for freeze-up water levels.

It is important to mention that the five highest ice-jam flood elevations in Dawson have been recorded prior to the construction of the dike that is still in place nowadays. It is uncertain if an event comparable to the 1979 ice jam is still possible. Several factors would need to be considered:

- There has not been a winter as cold since then and this is in line with long-term projections.
- Air temperatures in late April appear to be decreasing, but air temperatures during the second week of May have been rising since 1979 (a similar result was presented by Janowicz [2017] for the Porcupine River).

- Snowpack trends in upstream watersheds, that are known to play a role in the Yukon River breakup at Dawson (White River, Steward River, Pelly River), are uncertain, but the variability seems to be increasing (2019 was a record dry winter, but 2020 and 2021 were record snowy winters).
- Freeze-up conditions have not been documented in detail over the years, but freeze-up patterns are apparently changing (Turcotte, 2020). Moreover, the river ice formation event of November 2020 (that preceded the highest breakup water level in several years) was particularly dynamic.

Regardless if interpolated and perceived maximum breakup water level trends are due to climate change, to the construction of the dike, or to other processes, the frequency of intense river ice breakup events on the Yukon River at Dawson seems to be declining.

5.3. Klondike River at Dawson

The Klondike River watershed has a significant cultural meaning for Tr'ondëk Hwëch'in as well as an important value for the territory's economic sector. The river flows west towards Dawson on the south side of the Ogilvie Mountains and its profile along lower reaches is relatively steep (refer to Turcotte and Nafziger, 2021). This characteristic, and the general morphology of the river, affect the intensity of river ice processes. Indeed, an ice cover that forms in rapids and riffles is generally more fragile and can be mobilized by a small rise in discharge or by a weak ice push from upstream, which may result in the formation of several small ice jams early during the river ice breakup sequence. The Klondike River has been monitored (09EA003) on a continuous basis since 1966, but this record includes several winter gaps, mostly during the river ice formation period.

Figure 7 presents Y_{max} expressed as a function of the estimated discharge from 1970 (1996 for freeze-up) to 2021. It is of interest to note that the discharge range that produces $Y_{max\ B}$ seems restricted to a maximum 200 m^3/s, and this may represent an approximate ice cover evacuation threshold. Most importantly, ice-induced water levels, especially at breakup, are significantly higher than $Y_{max\ OW}$; they are associated with the six highest Y_{max} since 1970. It is also of interest to note that if the current rating curve for that site was extrapolated, a discharge that represents 2.5 times the highest discharge on record would be needed to match the ice jam water surface elevation of 1986 at the WSC station (Figure 8). This shows how important it is to consider ice jams in the design of infrastructure and how engineers and land-use planners can benefit from continuous hydrometric records at that site. Furthermore, $Y_{max\ F}$ represents the absolute Y_{max} for 4 out of the 22 years where all three flooding processes were monitored (see Klondike River hydrographs presented in Turcotte and Nafziger, 2021, for a description of freeze-up processes).

Figure 9 reveals several hydrometric gaps prior to 1996. Linear interpolations suggest, with reserve, that $Y_{max\ F}$ and $Y_{max\ B}$ are relatively constant. However, given the small size of the watershed and its sensitivity to weather warming in the spring, it is expected that $Y_{max\ B}$ could increase in the future, especially considering that the WSC station reach is constricted to a single channel (no floodplain for water to by-pass an ice jam) with a dominant ice jam formation location downstream. For similar reasons, $Y_{max\ F}$ could rise in the future as climate change brings more extremes and warmer weather, which would promote the occurrence of early-winter and mid-winter breakup events (Janowicz, 2010). The linear $Y_{max\ OW}$ trend, based on a complete and reliable record, is also relatively stable (Figure 9). This is hypothetically related to an equilibrium between permafrost thaw (causing a groundwater lamination effect of runoff events) and more intense snowmelt rates and rainfalls (creating more intense runoff events).

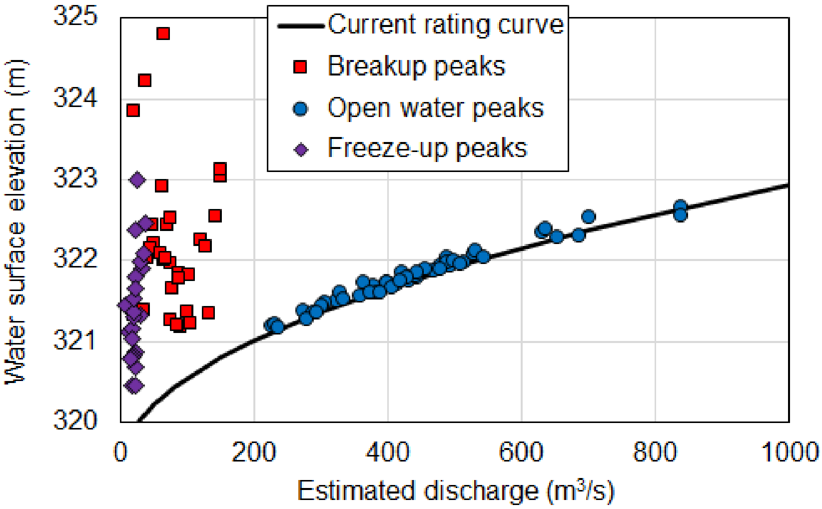


Figure 7. Approximate current rating curve, maximum breakup water levels, maximum open water levels and maximum freeze-up water levels between 1970 and 2021 (with several gaps) expressed as a function of the estimated discharge at station 09EA003 on the Klondike River at the Klondike Highway, Yukon.

Figure 8. 1986 ice jam on the Klondike River at the Klondike Highway bridge. Photo taken by the Federal Government.

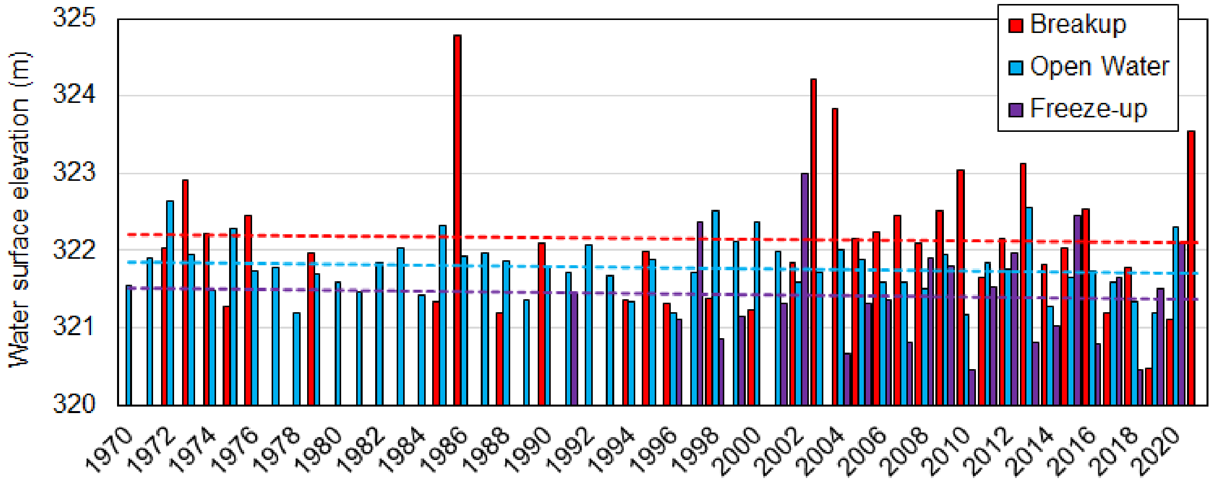


Figure 9. Historical annual maximum water levels at breakup, during the open water season, and at freeze-up between 1970 and 2021 (with several gaps) at station 09EA003 on the Klondike River at the Klondike Highway, Yukon. Linear interpolation for freeze-up is presented for visual purposes only.

5.4 Stewart River at Mayo

The Stewart River watershed, home of the First Nation of Na-Cho Nyak Dun, flows west towards the Yukon River from the MacKenzie Mountains. The most important community along the Stewart River is Mayo (WSC station 09DC006, water level only), located about 300 km upstream from its outlet (WSC station 09DD003, water level and discharge). Figure 10 reveals that Y_{max} (with transposed discharge from outlet) is virtually always caused by high open water flows, 90% of which happen during the spring freshet season (from mid-May to late-June).

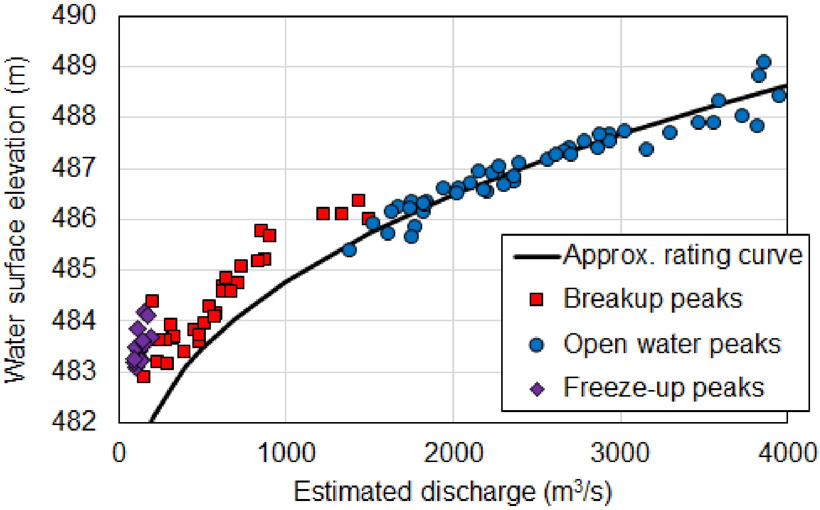


Figure 10. Approximate rating curve (based on transposed discharges), maximum breakup water levels, maximum open water levels and maximum freeze-up water levels between 1970 and 2021 (with several gaps) expressed as a function of the transposed estimated discharge from station 09DD003 to station 09DC006 on the Stewart River at Mayo, Yukon.

Ice jams are known to form along the Stewart river (including at the outlet station 09DD003), but breakup scenarios in the Mayo reach are most often thermal with a limited backwater effect (small departure from approximate local rating curve). This statement is supported by satellite images from various springs showing an extended open water lead downstream of town, in part caused by the regulated Mayo River. This open water area provides freedom to the local ice cover to move far downstream of town once it gets mobilized, which significantly reduces the probability of any local ice jam. The few monitored river ice formation events on record suggest a gentle process causing an anemic rise in water levels. Satellite images again confirm that the Mayo River and the local Stewart River morphology impose initial ice bridging conditions to take place far downstream and immediately upstream of Mayo, therefore explain low $Y_{\text{max F}}$.

Figure 11 reveals, from a different angle, that $Y_{\text{max OW}}$ is, on average, 2.5 m higher than $Y_{\text{max B}}$. It also suggests that maximum annual flows are following a weak declining trend, as detected along other large rivers of Yukon, a potentially consequence of permafrost thaw that would not be compensated by more extreme runoff conditions (the size and the heterogeneous topography of the watershed promote peak flow attenuation), or at least no recent extreme flow has managed to change the observed trend. Finally, it can be safely stated that ice jams should not become a recurrent source of flooding concern in a near future at Mayo.

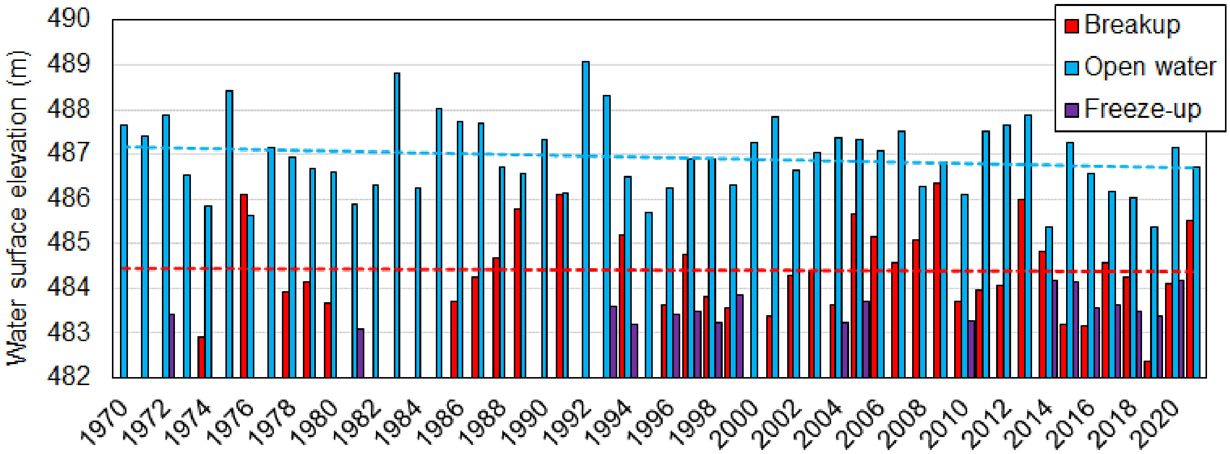


Figure 11. Historical annual maximum water levels at breakup, during the open water season, and at freeze-up between 1970 and 2021 (with several gaps) at station 09DC006 on the Stewart River at Mayo, Yukon. Linear interpolation not presented for freeze-up water levels.

5.5 Pelly River at Pelly Crossing

The Pelly River watershed is the Traditional Territory of the Selkirk First Nation (western part) and the Ross River Dena Council (eastern part). Like the Stewart River, the Pelly River flows west from the MacKenzie Mountains towards the Yukon River. The WSC station 09BC001, located in Pelly Crossing, the downstream most community along the river, was used for this analysis. Continuous (12-month) water level records were only initiated in 2001, but older historical records also include several breakup events.

The highest ice jam-induced water level in recent years happened on April 30, 1991, at 463.9 m (Figure 12). Breakup scenarios vary from year to year, alternating between strictly thermal (no rise in water level during breakup) and ice jam event of minor to moderate intensity. Overall, $Y_{\text{max B}}$ represents the annual Y_{max} on average every 10 years whereas high open water flows are the dominant flooding process. This hydrological behavior is also apparent upstream at Faro (09BC004) and Ross River (09BC002), through shorter water level records. Figure 12 also reveals that the ice evacuation threshold, in terms of estimated discharge, is relatively low compared with peak spring and summer flows. This suggests that the discharge during breakup could represent a limiting factor to the frequent occurrence of high ice jam-induced water levels. Finally, freeze-up events are only associated with a small (1 to 2 m) stage rise (although the freeze-up event of 2020 was the most dynamic on the record, refer to Turcotte and Nafziger, 2021).

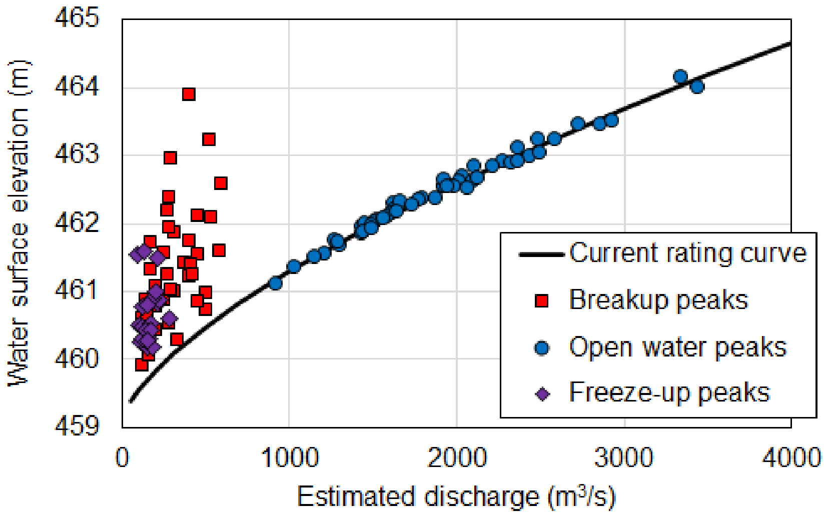


Figure 12. Approximate current rating curve, maximum breakup water levels, maximum open water levels and maximum freeze-up water levels between 1970 and 2021 (with several gaps) expressed as a function of the estimated discharge at station 09BC001 on the Pelly River at Pelly Crossing, Yukon.

Given the number of gaps in the $Y_{\text{max B}}$ record (and this is the most complete data set between the three active WSC stations on the Pelly River), the slight rise in the linear interpolation presented in Figure 13 must be taken with a grain of salt. Indeed, had the 2021 spring breakup been a low $Y_{\text{max B}}$, this trend would be horizontal. In turn, a decreasing trend in $Y_{\text{max OW}}$ is detected between 1970 and 2020, in line with what is reported in most watersheds from central Yukon.

5.6. Nordenskiold River upstream of Carmacks

The Nordenskiold River drains one of the driest areas in Yukon (as inferred by the ratio of average annual discharge to watershed area in Table 1), a vast plain surrounded by small hills. It flows through the Traditional Territory of the Little Salmon/Carmacks First Nation. The main channel becomes steeper (evolving from meandering to an incised riffle-pools and rapids with an average gradient of 0.35%) in its last 10 km before reaching the Yukon River at Carmacks. The WSC hydrometric station 09AH004 is located at the upstream end of that steep reach.

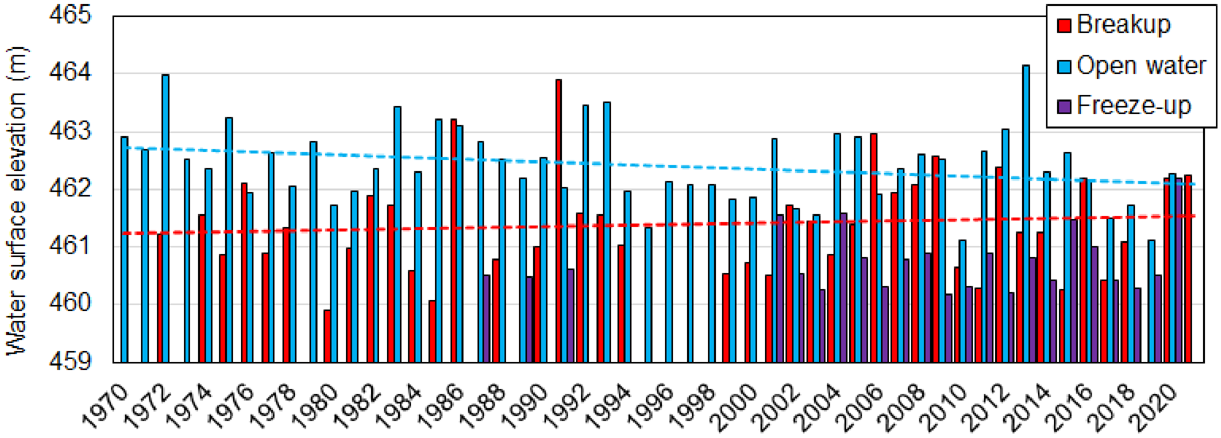


Figure 13. Historical annual maximum water levels at breakup, during the open water season, and at freeze-up between 1970 and 2021 (with several gaps) at station 09BC001 on the Pelly River at Pelly Crossing, Yukon. Linear interpolation not presented for freeze-up water levels.

Figure 14 presents $Y_{max\ OW}$ starting back in 1983 as well as $Y_{max\ B}$ and $W_{max\ F}$ since 2005. Interestingly, $Y_{max\ F}$ has been higher than $Y_{max\ OW}$ and $Y_{max\ B}$ about 80% of the last 15 years of year-round hydrometric record. A careful analysis of freeze-up conditions reveals that the water level during ice cover formation is rising at a rate of 0.5 to 1.0 cm/h, independently of the air temperature (as long as it remains well below freezing). This rate corresponds to the formation of anchor ice and ice dams, as documented in Dubé et al. (2015), in line with expected freeze-up processes in steep channels (Turcotte and Morse, 2013) and as supported by observations of the undulating surface of the channel during winter.

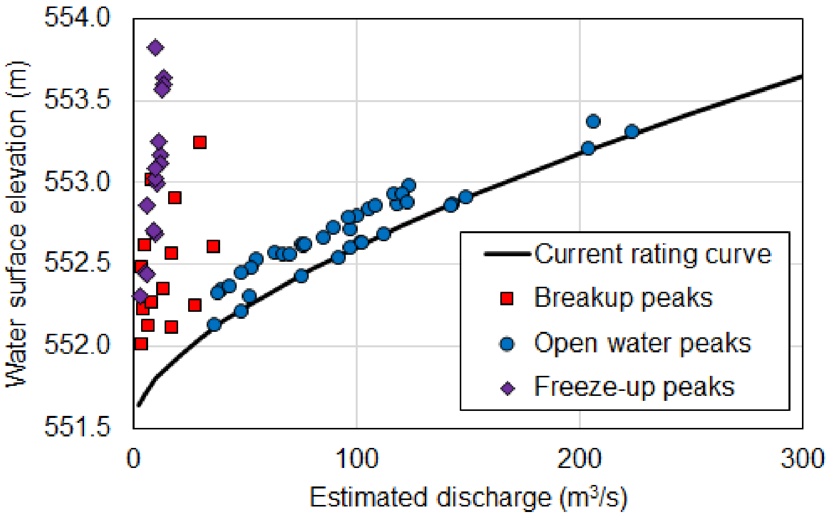


Figure 14. Approximate current rating curve, maximum breakup water levels, maximum open water levels and maximum freeze-up water levels between 1983 and 2021 (with several gaps) expressed as a function of the estimated discharge at station 09AH004 on the Nordenskiold River upstream of Carmacks, Yukon.

Breakup processes at or just downstream of the stations are moderately dynamic and involve minor ice jams (more significant ice jams form further downstream as breakup progresses). The most significant breakup ice jam in recent years occurred in April 2021, it was preceded by the highest freeze-up level on record (Nov. 2020). Figure 14 also reveals a sharp shift in the station 09AH004 rating curve in 2009. This indicates that the channel is unstable from a morphological point of view, an interpretation also supported by the observation of large trees falling in the river and the presence of wide, vegetation-less gravel bars. This condition may influence local river ice processes in the future.

No defendable trend analysis can be obtained from the short record of ice-induced water levels on the Nordenskiold (Figure 15), especially if the channel is unstable. This also applies to $Y_{\text{max OW}}$ because of the rating curve shift from 2009 (this trend is presented in Figure 15 for qualitative purposes only, the linear interpolated trend in maximum annual flows over that period is essentially horizontal). An examination of hydrometric records from 1983 to 2020 reveals a rise in late summer flows in the Nordenskiold River and a positive correlation between the discharge during the river ice formation period and $Y_{\text{max F}}$. It is therefore possible that freeze-up will continue to dominate other flooding processes at that location in a changing climate, especially because the floodplain (that can impose a limitation to ice-induced flood levels) is narrow.

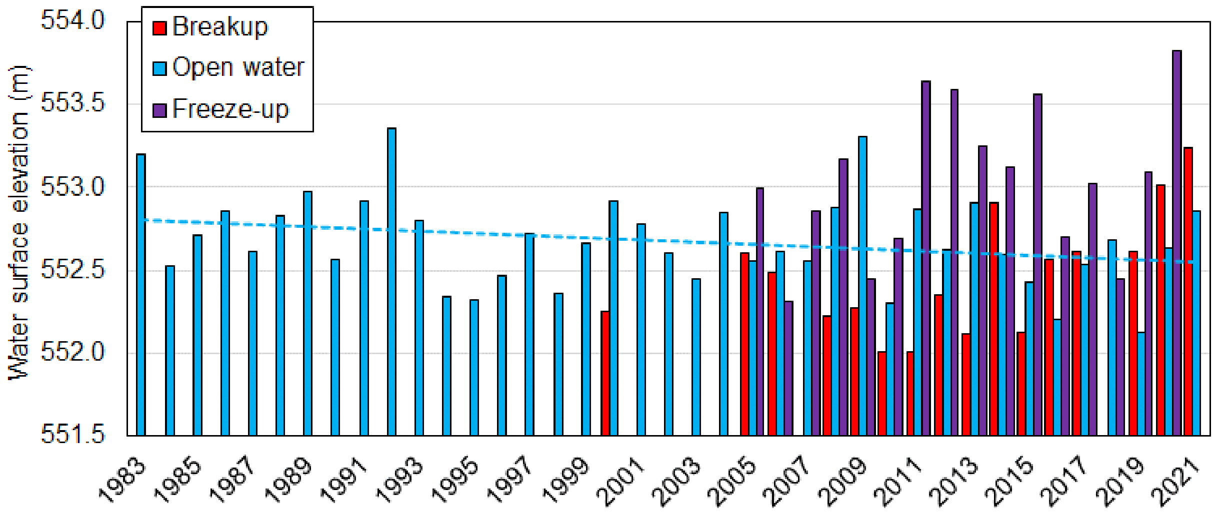


Figure 15. Historical annual maximum water levels at breakup, during the open water season, and at freeze-up between 1970 and 2021 (with several gaps) at station 09AH004 on the Nordenskiold River at Carmacks, Yukon. Linear interpolation for maximum open water levels presented for visual purposes only.

5.7 Yukon River at Carmacks

Flooding processes have been presented and described on the Yukon River at Dawson (5.2). This site is located further upstream (it excludes the contribution of 3 major tributaries of the Yukon River basin) and its discharge is significantly laminated by several large lakes. The WSC hydrometric station 09AH001 has been operated prior to 1995 and after 2015, which represents a significant gap that disqualifies the analysis of historical trends. However, it is worth mentioning that $Y_{\text{max OW}}$ is, on average, 1 m higher than $Y_{\text{max B}}$. (as suggested in Figure 16). This is in part caused by the presence of Lake Laberge (200 km upstream of Carmacks) that imposes a largely thermal breakup regime to the Yukon River, with a gradual upstream to downstream ice cover melt that rarely generates any shear wall (direct indicators of breakup intensity). It is also of interest to note that freeze-up has generated Y_{max} three years in a row since year-round hydrometric recording started (2018), including the third highest water level since 1970 in November 2020 (the highest Y_{max} presented in Figure 16 occurred in June 2021). This illustrates the importance of monitoring all the hydrological processes for the development of reliable flood maps and the design of resilient hydraulic structures.

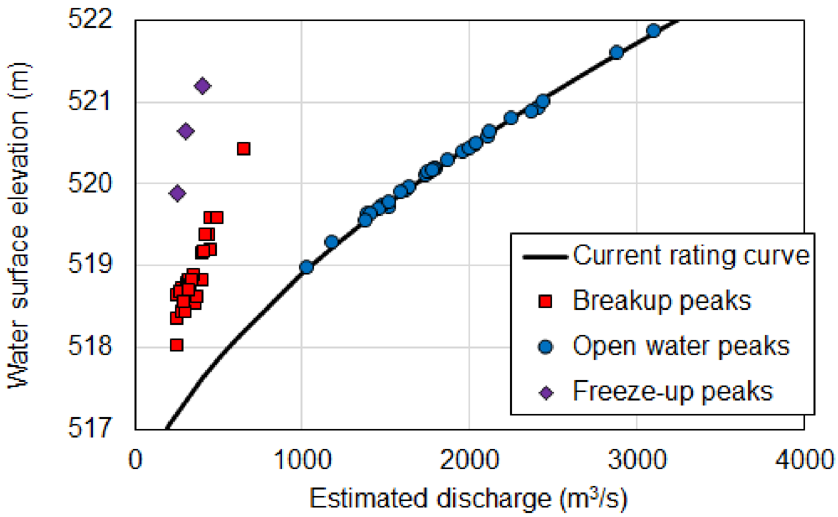


Figure 16. Approximate current rating curve, maximum breakup water levels, maximum open water levels and maximum freeze-up water levels from 1970 to 1995 and from 2015 to 2021 (early winter conditions only from 2018) expressed as a function of the estimated discharge (empirically calculated after 1995) at station 09AH001on the Yukon River at Carmacks, Yukon.

5.8 Liard River at Upper Liard

The Liard River drains the eastern portion of Yukon. It flows towards British Columbia before turning northeast to meet with the MacKenzie River at Fort Simpson. The watershed is part of the traditional territory of the Liard First Nation. Station 10AA001 is located just west of Watson Lake, the first community in Yukon along the Alaska Highway. Its southern orientation has been promoting thermal spring breakup scenarios as far as the record goes. Figure 17 confirms that open water events generate Y_{max} most of the years (85%) whereas freeze-up and breakup events are only associated with Y_{max} during relatively dry years. Moreover, the highest water level on record is, by far, the combined rain and snowmelt event of 2012 (almost 4000 m^3/s).

Trend analyses reveal that all flooding processes have generated water levels that are, overall, stable since 1993 (Figure 18). Ice-induced Y_{max} trends could not be extended prior to that year because of several record gaps. It has been proposed that this watershed could receive less precipitation during future winters (Bush and Lemmen, 2019). However, this projection would only align with the observed stable maximum flow trend starting back in 1960 if snow melting was occurring faster as a compensation for thinner snowpack. If observed tendencies towards higher fall and winter (estimated) flows continue, this could support more intense freeze-up events (and a thicker early-season ice cover) and potentially affect breakup scenarios.

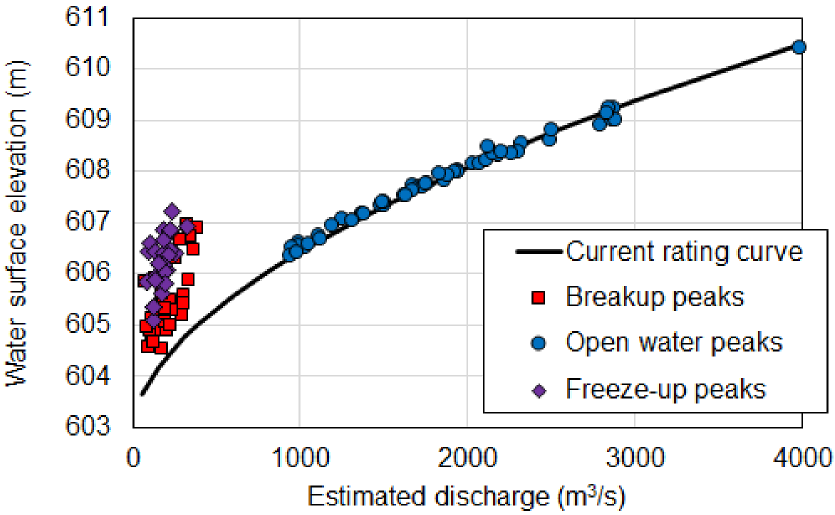


Figure 17. Approximate current rating curve, maximum breakup water levels, maximum open water levels and maximum freeze-up water levels between 1972 and 2021 (with several gaps) expressed as a function of the estimated discharge at station 10AA001 on the Liard River at Upper Liard, Yukon.

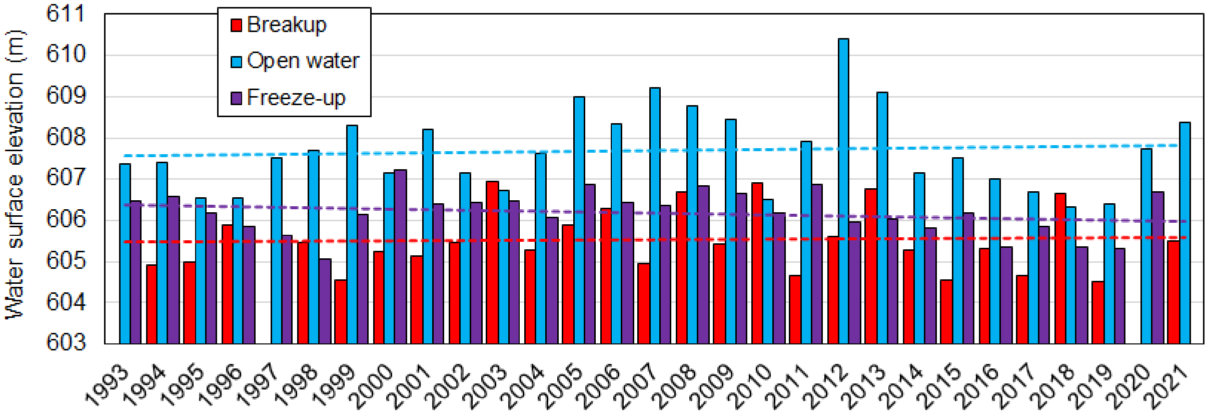


Figure 18. Historical annual maximum water levels at breakup, during the open water season, and at freeze-up between 1993 and 2021 at station 10AA001 on the Liard River at Upper Liard, Yukon.

5.9 Liard River at Fort Liard

Almost 600 km downstream of Upper Liard, after flowing through different morphologies including canyons and anastomosed reaches, the Liard River at Fort Liard (10ED001) is a distinct water course. The data presented in Figure 19 suggests that the Liard River has a dynamic ice regime in the Traditional Territory of the Acho Dene Koe First Nation, with the highest water levels since 1970 associated with breakup ice jams. Overall, $Y_{max\ B}$ dominates Y_{max} four years out of five.

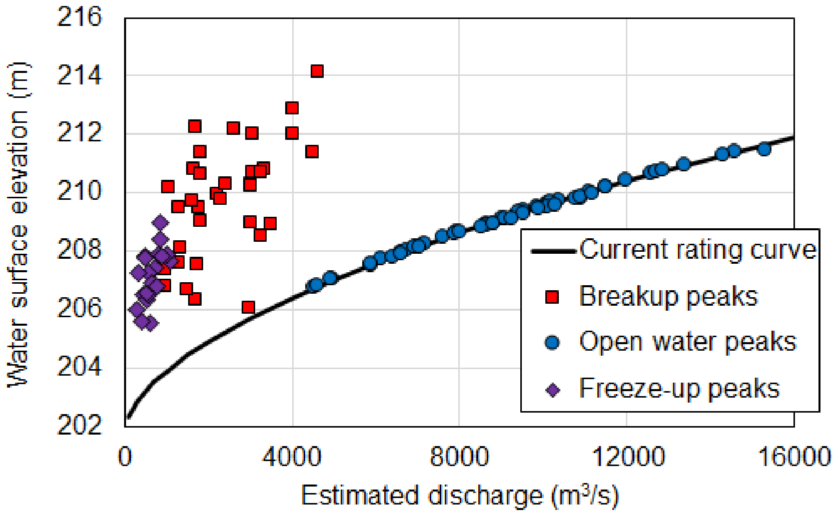


Figure 19. Approximate current rating curve, maximum breakup water levels, maximum open water levels and maximum freeze-up water levels between 1970 and 2021 (with several gaps) expressed as a function of the estimated discharge at station 10ED001 on the Liard River at Fort Liard, Northwest Territories.

The trend analysis starting back in 1981 (the period with fewer spring breakup gaps) reveals no significant change that could be attributed to a warming northern Canada (Figure 20). Independently of the period considered, this stability seems to remain. However, any additional significantly weak or intense event could generate a slight shift in the recent history tendency. The 2021 spring breakup event was probably dynamic, but the associated data was not available at the time of publication.

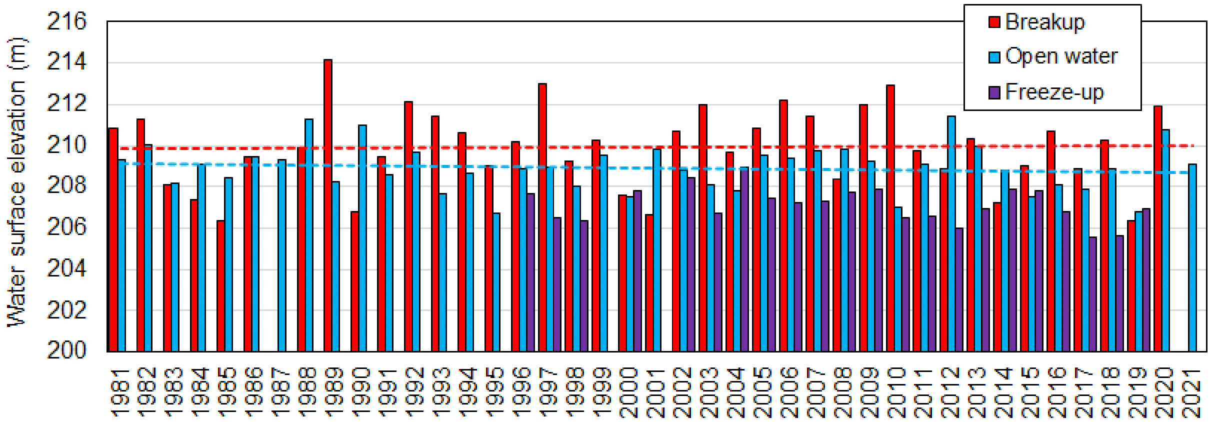


Figure 20. Historical annual maximum water levels at breakup, during the open water season, and at freeze-up between 1981 and 2021 at station 10ED001 on the Liard River at Fort Liard, Northwest Territories. Linear interpolation not presented for freeze-up stage.

5.10 Hay River at Hay River

Hay River, situated in the Traditional Territory of the K'atl'odeeche First Nation, has been affected by several ice jams in the past (e.g., Oveisy and She, 2017). Part of the community was relocated because of major historical ice-jam floods. Station 07OB001 measures water levels year-round about 12 km upstream of the community. This site is not significantly hydraulically influenced by Great Slave Lake during open water conditions, but the most significant ice jams in the Hay River delta are captured by the sensor (satellite observations suggest that the equilibrium section of ice jams rarely extends to the station) and the lake level probably has an influence on ice jamming processes. Figure 21 presents Y_{max} for three flooding processes from 1972 to 2020 (with a partial record of $Y_{max\ F}$ before 1996). It shows that spring breakup ice jams generate the most significant water levels on an annual basis (85% of the time) under a wide range of estimated discharges. In turn, freeze-up is not associated with significant water levels.

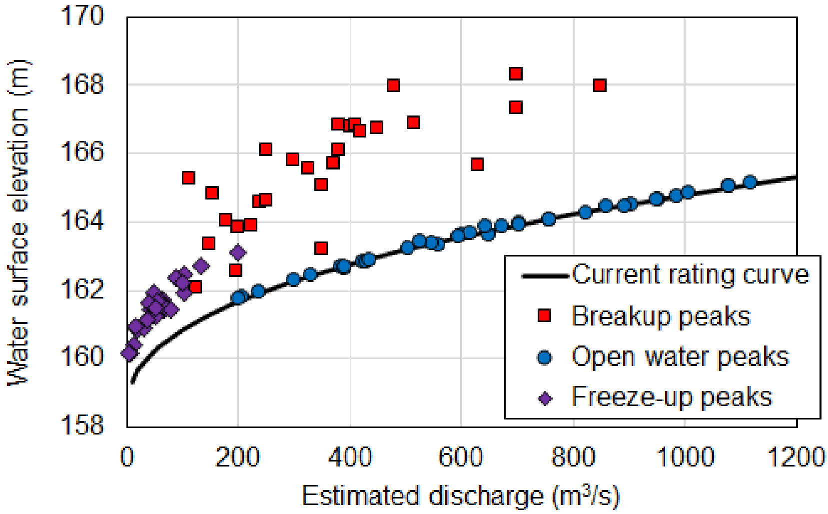


Figure 21. Approximate current rating curve, maximum breakup water levels, maximum open water levels and maximum freeze-up water levels between 1972 and 2021 (with several gaps) expressed as a function of the estimated discharge at station 07OB001 on the Hay River upstream of Hay River, Northwest Territories.

The trend presented in Figure 22 is influenced by high water levels early in the record (1985-1997) and ending with several consecutive years (2015-2019) of low water levels. As a result, both $Y_{max\ B}$ and $Y_{max\ OW}$ show strong declining interpolations. The $Y_{max\ OW}$ downward trend seems more resilient to a change in the period considered whereas the $Y_{max\ B}$ downward trend flattens if the period considered begins in 1970 or in 1998. The high water level in Great Slave Lake during winter 2020-21 probably played a role in the high $Y_{max\ B}$ of 2021, and this illustrates that breakup intensity at the station cannot be solely attributed to changes in the ice and hydrological regime of the watershed: downstream boundary conditions must be taken into account.

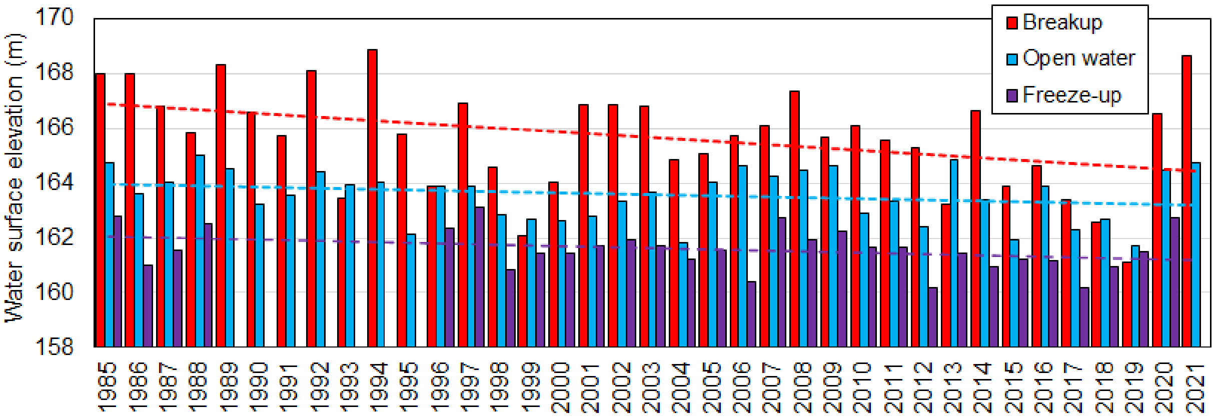


Figure 22. Historical annual maximum water levels at breakup, during the open water season, and at freeze-up between 1985 and 2021 at station 07OB001 on the Hay River upstream of Hay River, Northwest Territories. Linear interpolation for freeze-up is presented for qualitative purposes.

5.11 Mackenzie River at Fort Simpson

The Mackenzie is the largest river included in this study about the impact of climate change on flooding processes. Its ice regime has been studied by numerous authors and its river ice breakup behavior is known to generate spectacular ice jams. Fort Simpson is home of the Liidlii Kue First Nation, which name means “the place where the two rivers come together” (Liard and Mackenzie Rivers).

Figure 23 confirms that $Y_{\text{max B}}$ dominates, by far, other flooding processes at Fort Simpson (station 10GC001). Estimating the discharge during breakup, especially in the presence of ice jams, is challenging (Turcotte and Nafziger, 2021). This, in combination with other factors that affect breakup water levels (location of the ice jam toe, ice cover thickness, freeze-up level, degradation state of the ice cover, etc.), may explain why there is no apparent correlation between $Y_{\text{max B}}$ and the estimated discharge (Figure 3 also shows a significant scatter for the Porcupine River, where ice jams are known to form at different locations downstream of Old Crow).

Fort Simpson was affected by record high water levels in the spring of 2021 because of a severe ice jam that has been, at least in part, caused by extreme high flows in the Mackenzie River during fall and winter (with record high water levels in Great Slave Lake). This event is pulling the interpolated $Y_{\text{max B}}$ trend upward (Figure 24), almost independently of the period considered, and it is tentatively associated with extreme conditions that align with the expected impact of climate change. In turn, $Y_{\text{max OW}}$ appears to be relatively stable since 1996. Finally, $Y_{\text{max F}}$ is usually 4 to 5 m lower than Y_{max} and it also appears to be stable (the data was only available starting in 1996), despite the high freeze-up level in December 2020.

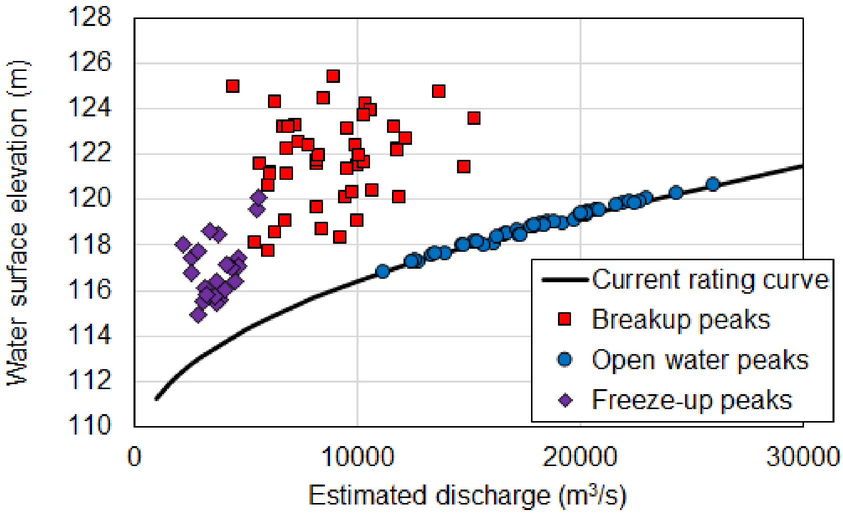


Figure 23. Approximate current rating curve, maximum breakup water levels, maximum open water levels and maximum freeze-up water levels between 1972 and 2021 (starting in 1996 for freeze-up) expressed as a function of the estimated discharge at station 10GC001 on the Mackenzie River at Fort Simpson, Northwest Territories.

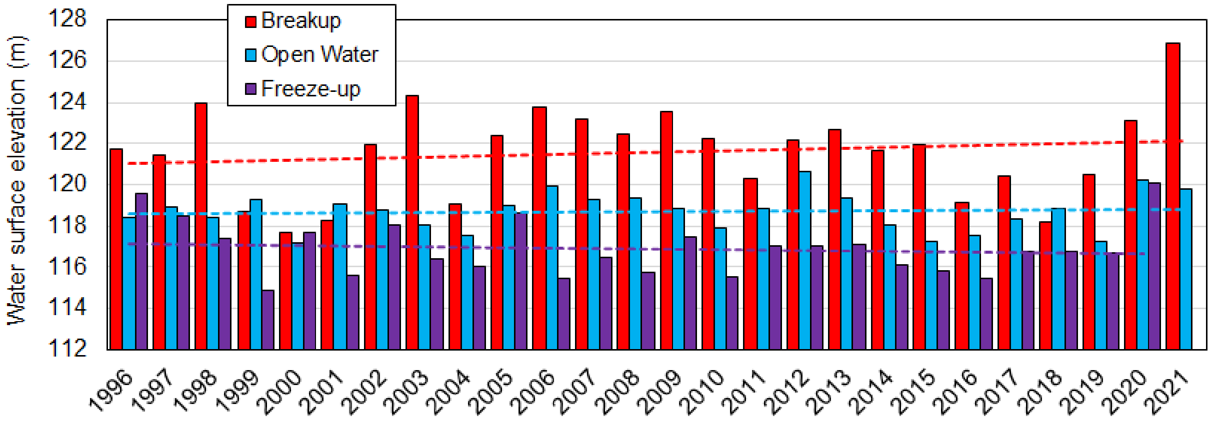
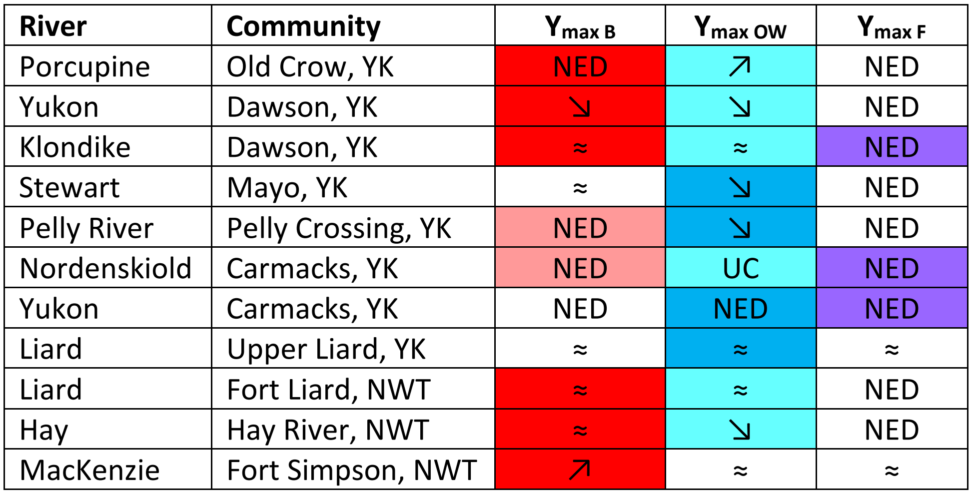


Figure 23. Historical annual maximum water levels at breakup, during the open water season, and at freeze-up between 1996 and 2021 at station 10GC001 on the MacKenzie River at Fort Simpson, Northwest Territories.

6. Summary of results and discussion

The approach adopted to investigate the impact of climate change on flood processes and focusing on ice-induced water levels is relatively simple: it uses direct results and generally excludes any attempt to answer questions about the potential origin of observed tendencies (e.g., does extreme weather compensate for ice cover thinning resulting from warmer winters?). Research results are summarized in Table 2.

Table 2. Flooding processes and tendencies for 11 river sites in Yukon and Northwest Territories. The dark color (red, blue, and purple) means that this flooding process is dominant, light colors mean that flooding process is not the dominant one and white cells indicate a process that is very unlikely to generate flooding. NED stands for “Not Enough Data” whereas UC means “Unstable Channel”.



River	**Community**	$Y_{max\ B}$	$Y_{max\ OW}$	$Y_{max\ F}$
Porcupine	Old Crow, YK	NED	↗	NED
Yukon	Dawson, YK	↘	↘	NED
Klondike	Dawson, YK	≈	≈	NED
Stewart	Mayo, YK	≈	↘	NED
Pelly River	Pelly Crossing, YK	NED	↘	NED
Nordenskiold	Carmacks, YK	NED	UC	NED
Yukon	Carmacks, YK	NED	NED	NED
Liard	Upper Liard, YK	≈	≈	≈
Liard	Fort Liard, NWT	≈	≈	NED
Hay	Hay River, NWT	≈	↘	NED
MacKenzie	Fort Simpson, NWT	↗	≈	≈

Within the 11 studied sites, three are mainly affected by open water floods, seven are most often affected by ice-induced floods (one of which seems to be mostly affected by freeze-up events) and one is probably affected by both open water and freeze-up events (Yukon River at Carmacks, based on a very short and partial record). Overall, it seems that maximum open water levels have been decreasing (↘) or have remained stable (≈) in recent years, apart from what has been observed in the last 20 years on the Porcupine River. In turn, maximum ice-induced water level trends appear stable (≈), besides a 2021-driven rising trend on the Mackenzie River at fort Simpson as well as a long-term declining trend on the Yukon River in Dawson, and most of them remain uncertain because of insufficient record lengths or several record gaps.

The fact that several ice-induced water level trends appear stable does not mean that climate change has no impact on ice jam floods in Northwestern Canada. Indeed, it could be that, at this point in the climate warming and precipitation pattern alteration evolution, tendencies favoring more dynamic breakup events (e.g., faster snowmelt) are compensated by others that promote thermal breakup events (e.g., higher freeze-up levels). A comparable interpretation was offered by Goulding et al. (2009b) about climatic drivers of river ice breakup in the Mackenzie delta.

The approach to identify Y_{max} trends in historical records is scientifically robust, in part because it is based on limited assumptions. However, since history only produces one data set per site and that only one data point is added to the record every year, given the large number of parameters that influence or control ice-induced floods, it is not surprising that some results do not reveal a clear recent-past and, by continuity, near-future tendency. Moreover, the presence of only one extreme event, and its year of occurrence within the considered period of record, can significantly pull the linear trend upward or downward. This is the reason why careful result interpretation is often required to establish conclusions.

What is more striking is that there are several "Not Enough Data" (NED) labels in the results presented in Table 1. This status is associated with:

- Too many gaps in historical records
- Periods during which stations were not operated or stations that only started to be operated consistently throughout winter in recent years.

Gaps in historical records could have different causes, including instrument failure or limited resources to re-establish water level recording prior to spring breakup. Indeed, instruments (e.g., air lines connected to water level recorders, compressors, solar panels, or simply instrument shelters) have more chances to fail because of extreme cold conditions or because of unanticipated high ice runup levels. Historically, some hydrometric stations have failed during dynamic river ice breakup events, a limitation that has been reported several times in the literature (e.g., Beltaos and Prowse, 2009). Station operators usually attempt to document maximum ice jam levels, and maximum water levels at breakup often appear on old hydrometric summaries, at least when they represented the annual maximum water level.

Periods during which stations are not operated also need to be addressed. Since flooding processes, that are independent (or only partially dependent) from one another, are evolving differently over time, it is not impossible that future floods will not be caused by the same hydrological process. When the Yukon River station at Carmacks started to be operated year-round in 2018, there was no record about high freeze-up levels at that location. Yet, recent data revealed that freeze-up significantly influences water level-frequency analyses. There is a logical tradeoff between maximizing hydrometric station operation periods for the benefit of data users and maintaining reasonable operational costs for taxpayers. In a context of increasingly reliable and available technologies as well as evolving data needs, the annual operational scheme of critical stations could be reassessed, and redundancy could be added.

Readers may wonder why it is important to consider each flooding process separately rather than only keeping a record of Y_{max}, independently of the process involved. Beyond the potentially very different mitigation strategy for each flooding process, the cumulative probability of each process may introduce a statistical subtilty. Table 3 presents frequency analysis results from the Yukon River at Dawson between 1970 to 2021. Clearly, at least at sites affected by more than one flooding process, a notable difference may exist between flooding return periods derived from Y_{max} alone and flooding return periods obtained by summing the probability of those independent flooding processes ($Y_{max\ combined}$).

Table 3. Water surface elevations at station 09EB001 located on the Yukon River at Dawson City, Yukon, expressed in terms of three return periods based on maximum annual water levels (Y_{max}), on breakup maximum water levels ($Y_{max\ B}$), on open water maximum water levels ($Y_{max\ OW}$), and on the combination of the probability of ice-jam and open-water maximum water levels ($Y_{max\ combined}$).

Return Period	**Y_{max}**	**$Y_{max\ B}$**	**$Y_{max\ OW}$**	**$Y_{max\ combined}$**
2 years	316.21 m	315.47 m	315.96 m	316.44 m
20 years	318.22 m	317.85 m	317.44 m	318.09 m
200 years	320.02 m	320.43 m	318.31 m	320.43 m

The author considers that the results presented in this paper, although imperfect, are satisfying. Beyond continuing to populate the database for each studied site on an annual basis, there are ways to improve and enrich the approach presented in this paper:

- Each river has a story to tell and each Y_{max} data point has its own origin. Although the analytical power of statistics is not questioned, it imposes a degree of separation between the research and the subject matter and, as a result, some valuable information might be lost or overlooked. In this context, to better quantify the impact of climate change on cold region floods, it is beneficial to document ice processes for each station. This may include the spatial (streamwise) stability of the initial freeze-up congestion (location of early winter ice bridges) or the location of (the toe of) breakup ice jams. Satellite images and local observations represent advantageous sources of visual information.
- A parallel point would be to identify tangible ways to include Traditional Knowledge in scientific studies. Not only does it represent a form of respect towards First Nation people who have been living form the land and rivers for thousands of years, but it can positively influence research outcomes. This is not a simple task, partially because this information rarely relies on fixed benchmarks and specific dates. Nonetheless, scientists and practitioners are encouraged to dedicate efforts in building trust relationships with First Nations as this represents one of many steps towards Reconciliation (e.g., Wong et al., 2020)
- Besides the Canadian River Ice Database (de Rham et al., 2020) that contains valuable winter hydrology information on a number of rivers in Canada (this database was not used for the present study as one of the author's goal was to complete his own analysis before comparing the results obtained by recognized experts) and historical hydrological and meteorological data available on the website of Environment and Climate Change Canada (ECCC), researchers are encouraged to contact ECCC specialists when seeking complementary information that can support research projects on climate change. The data may be available to the public, but experts can provide valuable complementary information.
- It would be of interest to compare historical Y_{max} trends with the results obtained from other approaches that attempt to foresee future flooding processes. As briefly mentioned in the introduction, the performance of these approaches would depend on (1) reliable estimated discharges in the presence of ice as this represents initial conditions in hydrological models, (2) improved snow water equivalent (SWE) and snowmelt rate products, (3) adapted hydrological models that take river ice processes into account in flow routing, and (4) representative river ice models operated by experienced geoscientists and forecasters.

This research has not considered all the possible flooding processes that are happening in different watersheds of Yukon and Northwest Territories (or in cold regions in general). At some point in the future, there would be interest in considering the impact of climate change on:

- The intensity of ice-induced floods in regulated rivers (e.g., Morrissette et al., 2017)
- The frequency and intensity of aufeis (icing) driven floods, especially along highway corridors (e.g., Ensom et al., 2020)
- The occurrence of mid-winter breakup events that will likely become more frequent in the future (e.g., Janowicz, 2010), partially because of the winter weather phenomenon referred to as "atmospheric rivers" that brings heat and moisture from the Gulf of Alaska to Yukon.

7. Acknowledgments

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