CGU HS Committee on River Ice Processes and the Environment
20th Workshop on the Hydraulics of Ice Covered Rivers
Ottawa, Ontario, Canada, May 14-16, 2019.

The Impact of Climate Change on Breakup Ice Jams in Canada: State of knowledge and research approaches

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River-ice jams represent a major hazard for many Canadian communities as well as an essential natural process to support biodiversity along streams and rivers. When we consider the complex interconnectivity between the various spatial and temporal factors that control and influence ice jamming processes, it is not surprising that assessing whether ice jams could become more frequent and severe in a changing climate represents a major challenge. Nonetheless, identifying past and foreseeing future ice-jam frequency and intensity trends is important because it will contribute to the determination of the amount of resources that should be allocated to predicting and mitigating ice-jam floods as part of a larger flood damage reduction effort that Canada is currently undertaking.

This paper presents a review of recent research about past and future trends of river-ice breakup and ice jamming intensity in Canada, describes parameters that control or influence river-ice breakup and illustrate how they have been and will be evolving in decades to come. This paper also classifies different approaches to evaluate the impact of climate change on the frequency and severity of ice jams, and identifies research gaps and monitoring requirements needed to develop cold region-adapted flood-risk knowledge on which land-use planning and infrastructure design depend.

1. Introduction

Most Canadian communities are located close to major rivers and some of them are even situated at a transition in the river gradient (e.g., an unpassable rapid such as on the St. Lawrence River in Montreal) or at a major confluence (e.g., on the Athabasca River at Fort McMurray). Unsurprisingly, a number of those communities and cities are affected by ice jams every year. More than 20 years ago, Beltaos (1995) reported that about one third of all flood events in Canada were ice-related. Considering that ice-induced floods may affect smaller areas, but that they can generate more damage for a specific water level compared to open water floods, it is reasonable to assume that the flood damage caused by ice jams at the end of the 20th century was in the order of 25% to 40% of the total flood damage.

In recent years, there have been major open-water floods in southern Quebec in 2011, in Calgary and Toronto in 2013, in western Quebec in 2017 and in 2019 as well as southern New Brunswick in 2018 and 2019. These events have either been directly associated with the impact of climate change, or, at least, they have opened the eyes of political leaders about what the future of Canadian floods may look like. These costly events have initiated a movement towards private flood insurance services, generated unprecedented investments in academic research to foresee the impact of climate change on floods (e.g., FloodNet, Global Water Future, Ouranos), and initiated a national offensive to develop up-to-date flood maps for exposed Canadian communities. River-ice processes have been largely excluded from this national mobilization despite the fact major ice jams continued to affect Canadian communities and waterways before and during that period.

There seems to be a general lack of awareness about ice-induced floods in Canada, which is surprising considering that the vast majority of rivers are ice-covered between 2 to 8 months on an annual basis (de Rham et al. 2019), and are affected by at least one breakup event every year, generally in the spring, that can cause ice jams of varying magnitudes. This is certainly not because of a lack of understanding about ice processes that generate floods, the literature on the topic has produced key publications including textbooks by Beltaos (1995, 2008, 2013) and Hicks (2016), as well as a number of CRIPE workshop (www.cripe.ca) and IAHR symposia papers, not to mention key publications in scientific journals about the impact of climate change on ice (e.g., Beltaos and Prowse 2009) and about how to integrate ice-jams floods in flood mapping (Kovachis et al. 2017). This scarcity of acknowledgement may be a result of river-ice processes being mostly excluded from civil engineering courses at the bachelor level in this cold country, a status that is now changing. It may also be due to the fact that ice-induced floods are generally more complex and apparently chaotic compared to open-water floods. Finally, it could be associated with a mobilization deficiency by the river-ice scientific community.

Now, in 2019, with climate change impacts largely visible in Canadian watersheds, time has come for a blitz of research about the future frequency and magnitude of ice-induced floods. Recent research about the duration of the ice cover period along Canadian rivers (e.g., de Rham 2019, Lemmen et al. 2008, Magnuson et al. 2000, Prowse et al. 2011) is welcomed, but it is not enough. In a context where flood maps are being produced and where flood mitigation measures are being discussed and implemented, there is an urgent need to include ice jams into the national flood conversation in order to avoid costly mistakes associated with inappropriate land-use planning and inadequate infrastructure design. Is the 30% ratio of ice-jam floods to all floods in Canada still up-to-date? Will climate change reduce or increase the ice-jam flood risk across the country? Will some communities be affected more often by ice jams, including those caused by mid-winter river-ice breakup events?

The first objective of this paper is to present a preliminary literature review about the impact of climate change on the frequency and severity of ice jams in Canada. The second objective is to advocate a national research effort on the topic by proposing different approaches that can be applied to foresee what Canadian communities may expect in terms of ice-jam frequency and severity in decades to come. This paper mostly focuses on mid-winter and spring breakup ice jams, but also mentions the importance of other types of jams such as freeze-up congestion and hanging dams. Regulated rivers are indirectly included in this paper, but the interaction between ice jams and flow regulation represents a topic on its own. Although this paper mostly focuses on the negative impacts of ice jams, the authors acknowledge that ice jams are natural processes that can be beneficial to riparian and flood-plain environments (e.g., Prowse 2001).

2. Review of the Impact of Climate Change on Ice Jams in Canada

2.1 Overview of Climate Change

Anthropogenic changes to the land surface and to atmospheric composition are known to be the dominant cause of the observed warming since the mid-20th century (IPCC 2014). In 2017, human-induced warming reached approximately 1°C in terms of globally averaged surface temperature above 1850-1900 levels, used as an approximation of pre-industrial temperatures (IPCC 2018). National temperature estimates (from 1948 onward) reveal that the rate of warming in Canada as a whole has been more than double that of the global mean, and that warming in northern Canada (i.e., north of 60°N) has been roughly three times the global mean (ECCC 2016). Figure 1 presents an overview of how winter and spring temperatures have evolved since 1984. Clearly, central and northwestern Canada have been the most impacted regions.

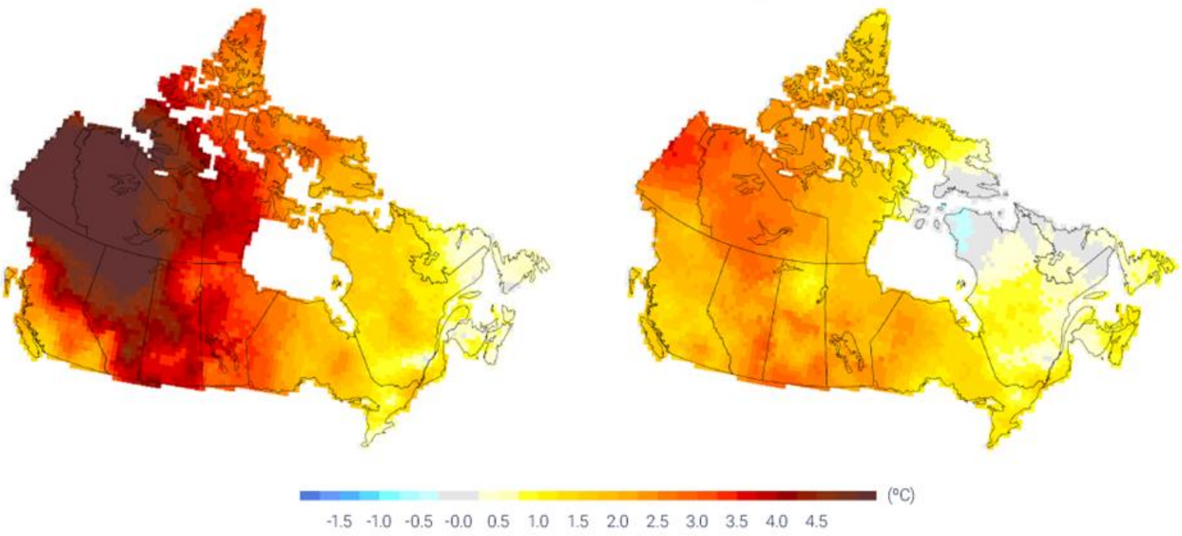

Figure 1. Winter (left) and spring (right) observed changes in temperatures between 1984 and 2016 (Figure 4.4 in Bush and Lemmen 2019, originally from Vincent et al. 2015).

Annual precipitation totals also changed in Canada, with most of the country (particularly the North) having experienced an increase in precipitation over the past century, but a decreasing trend in past winter precipitation in the southwestern part of the country (ECCC 2016). These trends are clearly visible in Figure 2.

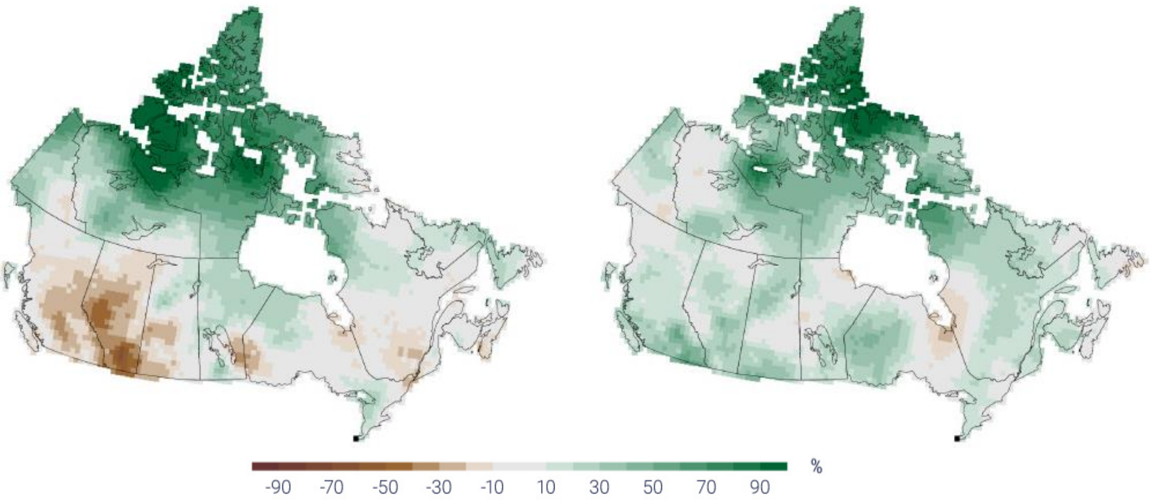

Figure 2. Winter (left) and spring (right) observed changes in precipitation between 1984 and 2012 (Figure 4.16 in Bush and Lemmer 2019, originally from Vincent et al. 2015).

Projections of future greenhouse gas emissions vary over a wide range, depending upon the readiness of human populations to modify their life-style in response to the impending crises. Surface temperature is projected to rise over the 21st century under all assessed scenarios. Projected changes for Canada are roughly 50% greater than for the global land area. Projected winter (December-February average) precipitation change for the period 2046–2065 in Canada range from 9% to 18% compared with the 1986–2005 baseline period (ECCC 2016), but as presented in Figure 3 for maximum snow water equivalent, there is a large spatial variability and still significant uncertainty about future precipitation trends. Additional information with respect to observed trends and projected changes in temperature and precipitation can be found in ECCC (2016) as well as in Bush and Lemmer (2019).

The cryosphere (global elements of the Earth system that contain water in its frozen state) provides useful indicators of climate change and in return, changes in the cryosphere also affect global climate (Key et al. 2015). An important part of the cryosphere is snow and its future distribution will have an impact on global climate. Cryosphere-related hazards include river-ice breakup events that affect transportation and the occurrence of ice-related flooding and structural damage. As more winter precipitation falls as rain, mid-winter breakup events are becoming more frequent and there is still a significant potential for large snowmelt flows in many regions. As for mean temperature and precipitation, changes in climate extremes are not uniform across Canada (ECCC 2016) and those extremes are often responsible for all types of floods. The next subsections present some observed and foreseen weather and ice process trends for different regions of Canada.

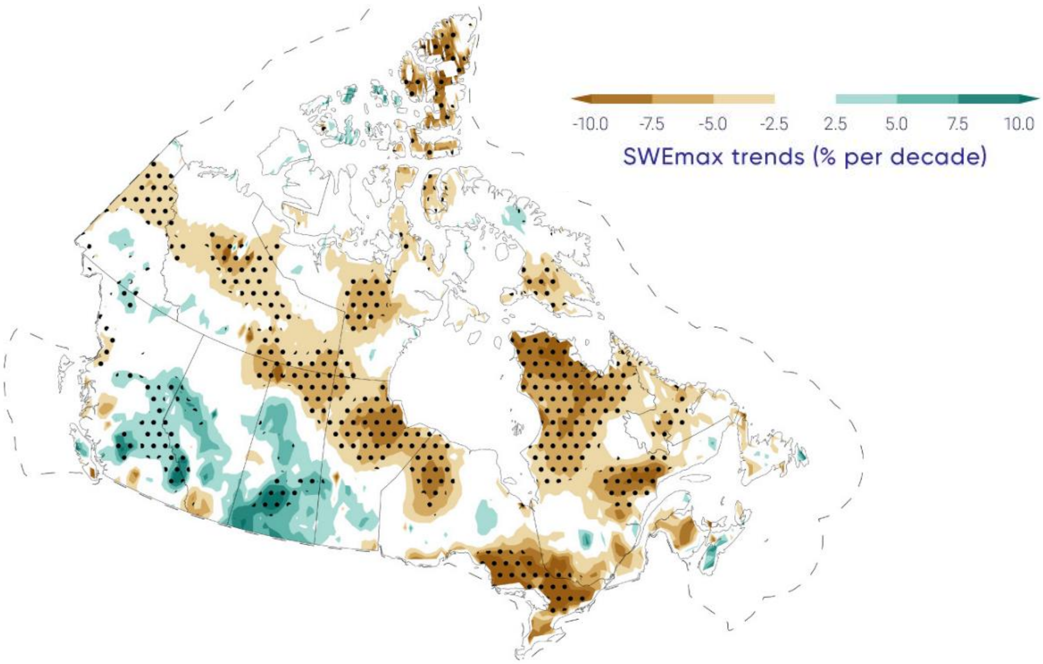

Figure 3. Maximum Snow Water Equivalent (SWEmax) trends from 1981 to 2015 (dotted areas indicate statistical significance, Figure 5.3 in Bush and Lemmer 2019, originally from Mudryk et al. 2018).

2.2 Observed Changes in Breakup Patterns and Ice-Jam Frequency and Severity

This sections only covers some regions of Canada.

Atlantic Provinces

From 1981 to 2010, widespread and increasing temperature trends were detected during winter (Thistle and Caissie 2013). Swansburg et al. (2003) predicted temperature increases up to 6°C in maximum spring air temperature and minimum winter air temperature, a result that compares with what has been proposed for the Maritime Provinces for 2050 by Vasseur and Catto (2008). Coastal areas would see lesser changes in temperature than would interior Nova Scotia and western New Brunswick (Vasseur and Catto 2008), which is somewhat visible in Figures 1 and 2.

Thistle and Caissie (2013) found that some weather stations showed a significant decrease in total precipitation during winter months in the Maritimes and a significant increase in precipitation during the fall in both the Maritimes and Newfoundland over the 1980-2010 period. Precipitation in Maritime Canada is also projected to increase in the future (Vasseur and Catto 2008). Swansburg et al. (2003) suggested that this trend would apply to winter throughout New Brunswick. Hare et al. (1997) stated that one-day heavy rain or snowfall events had increased in intensity over the Saint John River Basin, and proposed that amounts of precipitation might occur during the period of spring ice breakup and flooding. The present and projected climate of Newfoundland and Labrador differ from Maritime Canada because of the Labrador Current as well as the variations associated with the North Atlantic Oscillation (NAO) (Vasseur and Catto 2008).

With respect to river ice, a shorter season and thinner freshwater ice covers are foreseen. Over the period from 1950 – 2009, the number of days per year with river ice decreased at an average rate of ~ 6 days per decade at streamflow stations in New Brunswick, but increased at an average rate of ~ 8 days per decade on Nova Scotia and Newfoundland rivers (Thistle and Caissie 2013). These results compare with what was presented by Arisz et al. (2011) and Brimley and Freeman (1997). Also, Thistle and Caissie (2013) mentioned that recent years trends seem to level. Stations in Labrador showed few significant or spatially consistent trends.

Several rivers in the Atlantic Provinces experience occasional mild spells throughout the winter and early spring, resulting in several freeze-up and breakup events per ice season. Beltaos et al. (2003) suggested that the increased frequency of mid-winter breakup along the upper Saint John River within the last 40 years could be a regional indicator of a changing climate. Significant ice-jam floods have occurred in recent years within Atlantic Canada; e.g., the 1987, 1993 and 2012 ice-jam floods at Perth-Andover, New Brunswick, and the 2015 ice-jam flood in Badger, Newfoundland. With respect to Perth-Andover, climate change may aggravate ice problems over the next few decades but temper ice problems afterward (Beltaos and Burrell 2015). Generally, ice breakup and flooding in Atlantic Canada may become more frequent and unpredictable.

Quebec

While the general trend seems to lead the province towards warmer winters (Desjarlais et al. 2010), those of 2013-14, 2014-15, and 2018-19 have been largely colder than average, somewhat in agreement with what is presented in Figure 1. Ice jams on the St. Lawrence River, occurring during intense cold spells, have been reported during those winters. In terms of precipitation, winters have generally been associated with more precipitation over time (Desjarlais et al. 2010), with record snowpacks and total precipitation in the Quebec City regions during winters 2007-08 and 2018-19. However, on average, studies suggest that winters in the south should be drier (Figure 2).

Major dynamic spring breakup events have occurred in 2012 and 2014 in southern and central Quebec (e.g., Pigeon et al. 2015) and it has been observed that mid-winter rain-on-snow events are generating breakup more frequently in southern and central Quebec. In January 2018, a railway bridge on the St. François River was destroyed by an ice jam. Severe damage and extensive flooding are nowadays reported almost every winter on many rivers flowing north into the St. Lawrence River and significant mid-winter rain events (generally 30 mm of rain or more over 24 hours) occur further north than they used to. The presence of mid-winter jams has been the source of increasing concern in preparation for spring breakup.

A study on the frequency and intensity of dynamic river-ice breakup events on 7 rivers of Quebec under 9 climate change scenarios has been recently completed (Morse and Turcotte 2018). Results reveal an eventual reduction in river-ice-jam damage in the south as a consequence of very frequent winter runoff events alternating with cold periods that would not be long and intense enough for significant ice to form. In turn, in the center and north, the new occurrence of mid-winter breakup events would tend to increase ice-jam flood damage. From 1972 to 2000, the annual damage associated with ice-jam floods along those seven rivers was estimated to $2 000 000 (representing about 50% of the flood damage), a number that would increase to about $3 000 000 on average during the period of 2042-2070 (for an unchanged infrastructure and exposition to floods).

Ontario

McDermid et al. (2015) summarized comprehensive climate change projections for the province of Ontario under different climate scenarios defined in the Intergovernmental Panel on Climate Change's Fifth Assessment Report. The Hudson Bay Basin is likely to experience the highest degree of warming (2.6 to 10.3 °C above the 1971–2000 baseline by the 2080s). This can be compared to 2.6 to 8.8 °C in the Nelson River Basin and 1.5 to 7 °C in the Great Lakes Basin. In all cases, winter warming is likely to exceed summer warming. Precipitation is projected to be more variable across climate scenarios. The province could experience up to 240 mm more precipitation annually than historical levels. All three basins are likely to experience more precipitation in the winter.

Ice-jam floods occur frequently in rivers of densely populated southwestern Ontario, typically as a result of mid-winter thaws and rain-on-snow melt. Runoff increases sharply, causing ice breakup in portions of local rivers, such as the Grand and Thames; broken ice is arrested by intact ice cover to form major jams that occasionally result in flooding. In recent years, major mid-winter floods occurred in Feb. 2018, followed by less extensive flooding in Feb. 2019. The expected winter warming would tend to reduce the thickness of the ice cover and thence limit the frequency of ice jams. On the other hand, the expected increase in winter precipitation would enhance mid-winter thaw hydrographs, rendering water levels higher than before when ice jams do form.

Spring flooding caused by ice jams often affects First Nation communities of the Hudson Bay Basin, such as Fort Severn, Winisk, Attawapiskat, Kashechewan (a decision was recently made to relocate the entire community), Fort Albany, and Moosonee, which are located next to large northern rivers. Evacuation is often the result of such flooding (Shaw et al. 2013, Abdelnour 2013). Statistical analyses have only identified weak breakup-related changes during past decades. However, traditional First Nations knowledge indicates that potentially drastic and rapid changes have occurred in the very recent past (15 to 20 years), involving earlier and more damaging ice breakup patterns (Ho et al. 2005, Khalafzai et al. 2019).

Alberta

Figure 1 shows that winters have been warming up significantly in recent decades, especially in the northern part of the province and during winter months. Overall, the province has also been receiving less winter precipitation over the years, especially in the south (Figure 2). Interestingly, a statistically significant increase in snowpack has also been detected in that region (Figure 3).

The most studied unregulated river in Alberta from an ice processes perspective is undoubtedly the Athabasca River. Based on data shared by Alberta Environment (Jennifer Nafziger, unpublished data), the snow water equivalent in the basin over the years has been relatively stable. At Fort McMurray, the Athabasca has caused 14 major ice-jam floods since 1835, the last one occurred in 1997. Summer precipitation has declined over the years on the basin, which is thought to increase the capacity of snowmelt absorption during the following spring, thus reducing the potential for fast snowmelt runoff. Winters are also becoming less severe, and the trend in the date of breakup shows earlier breakups by about 4 days in 55 years. The net impact of these hydrometeorological trends is producing a global drop in maximum ice-induced water levels in the spring (Figure 4). However, the linear trend is largely influenced by low-water-level years from

1998 to 2012. In 2018, some communities (Athabasca, Whitecourt) were affected by ice jams caused by the early melt of a higher-than-average snowpack. Fort McMurray was spared, the intense ice run observed on the Athabasca River continuing its way downstream.

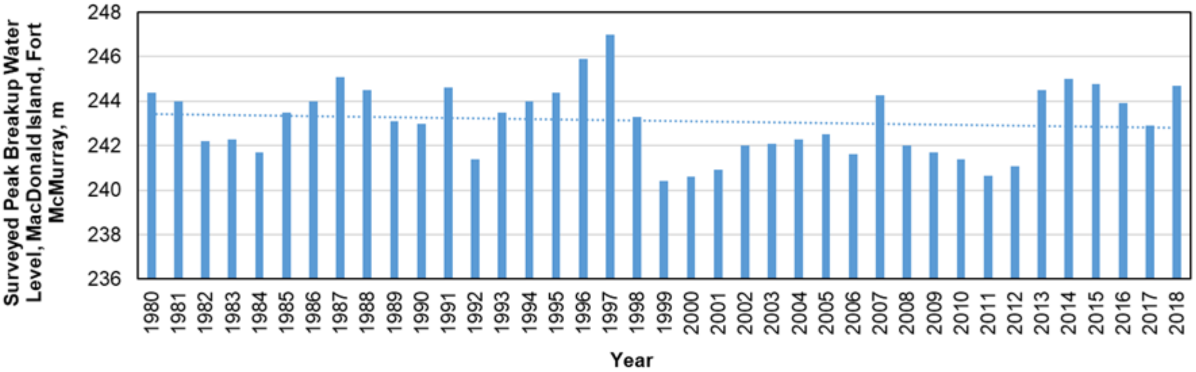

Figure 4. Annual maximum ice-induced water level in the Athabasca River at Fort McMurray from 1980 to 2018 (Data source: Alberta Environment).

Based on climate simulations, Das et al. (2017) suggested that the future ice season on the Athabasca River at Fort McMurray will be lengthened by one to two weeks, because of earlier river freeze-up and later ice cover breakup. They also proposed that an extended breakup period would reduce the chances of mechanical breakup, thereby reducing the severity of ice jamming along the river. In turn, Eum et al. (2017) reported an increasing spring flow and earlier freshet scenario over the years. It is therefore prudent to state that further research is needed.

Yukon

Based on Figure 1, northwestern Canada is the region most affected by a change in winter temperature. Winter and spring precipitation has also been increasing, especially in the north part of the Territory (Figure 2). Historically, the communities that have been impacted by ice jams are Dawson and Old Crow, located along the Yukon River and Porcupine River, respectively. The flood of record in Dawson happened in 1979 (prior to the construction of a dike) whereas the largest event in Old Crow happened in 1991.

Recent trends on six different rivers of Yukon indicated a reduction rate in late-winter ice thickness of 0.8 to 1.8 centimetres per year over 13 to 23 years. This is consistent with maximum cumulated degree-days of freezing (CDDF) trends, different weather stations in the Territory losing between 5 (south) to 25 (north) CDDF annually in the last 30 to 60 years.

Dawson's river-ice breakup lottery has been held since 1896 and as a result the exact time and date of first ice movement have been documented for more than a century. Since the mid-1970s, the date of the first ice movement (breakup onset) has happened 4 days earlier. Interestingly, the last B date (end of ice effect on water level) as documented by Water Survey of Canada upstream of town has only advanced by 2 days and there is a poor agreement between the two datasets (Jasek 1999, mentioned that there was no more stationary ice in reaches upstream of Dawson on May 7th 1998, whereas the last B date was May 15th 1998). A longer breakup period and a reduced winter CDDF could suggest that breakup in Dawson is becoming more thermal over the years, with a reduced potential for ice-jam floods.

Figure 5 presents annual maximum ice-induced water levels at Dawson. Although not statistically significant, the trend seems to support this evolution towards more thermal breakup scenarios with a reduced frequency of high ice-jam water levels. Neighbouring Alaska is also expecting more frequent thermal breakup events in a changing climate (Beck et al. 2013). Interestingly, large ice-jams floods were reported in Alaska in 2013 (Kontar et al. 2018).

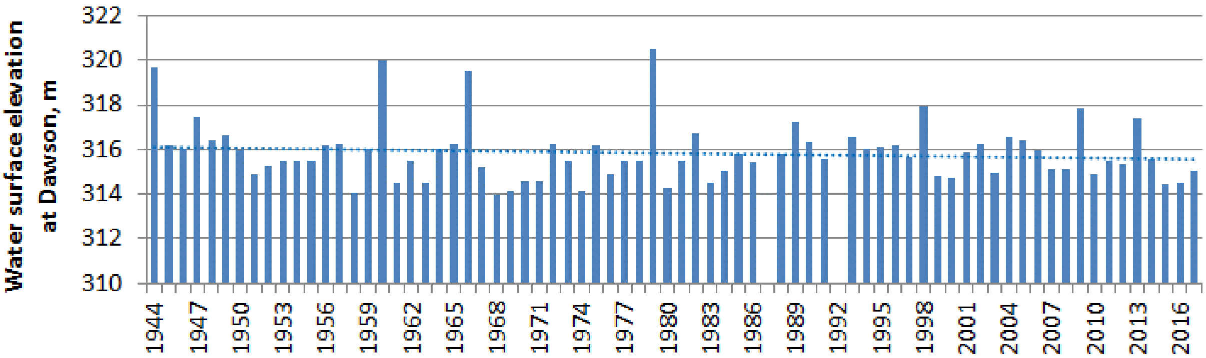

Figure 5. Measured and estimated annual maximum ice-induced water level in the Yukon River at Dawson from 1944 to 2017.

Moreover, Janowicz (2010) noted that dynamic breakup ice jams seem to occur more frequently in some parts of Yukon. On the Porcupine River, Janowicz (2017) documented a trend towards earlier, shorter and peakier freshet hydrographs that are more likely to cause large ice jams. In turn, it seems that the major icing accumulation, which varies in severity from year to year, at the Bluefish River outlet located 45 km downstream of Old Crow is largely responsible for high ice-induced water levels in the First Nation community. This icing accumulation process is largely independent of runoff rates in the spring. In summary, more investigation is needed to establish a clear trend in ice-jam frequency and magnitude in Yukon.

3. Parameters Dictating Ice-Jam Occurrence and Severity

To demonstrate their relative complexity, ice-jam-induced floods can be compared with other types of floods. Open-water floods, which are not influenced by ice, are generally simple to monitor and simulate because they mostly depend on a single parameter, the channel discharge. At a defined channel cross-section, a given discharge generates a nearly unique water level based on a site-specific stage- discharge relationship (rating curve, green line, Figure 6), as long as the channel geometry and morphology do not change and the rate of flow rise or fall is moderate. Therefore, forecasting a high water elevation may be as simple as applying a forecasted discharge to a rating curve or, for longer river reaches, to a calibrated hydrodynamic model.

In the presence of a stationary ice cover, a specific discharge may be associated with a relatively broad range of possible water levels (blue area, Figure 6) simply because (1) the ice occupies a portion of the water column and (2) it adds a roughness boundary that reduces the water velocity, therefore (based on continuity) generating a rise in water level (for more information about the impact of a newly formed ice cover on water levels, readers are referred to Beltaos 2013, chapter 7). As a result, simulating or forecasting a water level does not only depend on discharge, but also on ice-cover characteristics such as the ice-cover thickness and roughness, which, as opposed to the discharge, can vary over short distances.

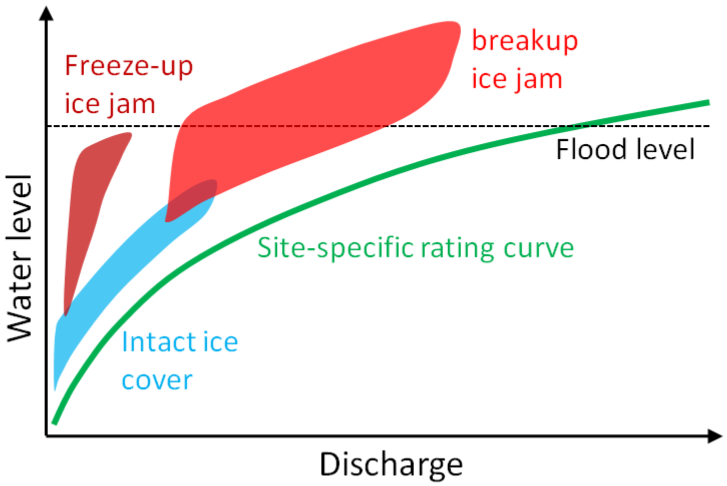

Figure 6. Conceptual water level – discharge relationship for different hydrological and ice processes. The flood level, or flood plain elevation, is presented as a reference.

Water levels caused by ice jams are even more challenging to monitor or simulate because they depend on additional parameters including ice strength, channel width, ice-jam toe location, grounding conditions, length of ice contributing reach, and dynamic mobilization thresholds. Many of these parameters are difficult to document and to forecast, and as a result, only complex models and a thorough knowledge of ice processes along the channel reach may yield representative simulation results and accurate forecasts. Because ice jams are composed of a single to multiple layers of broken ice sheets and floes, their impact on the water level is greater than that of a monolithic ice cover, and because there are more potential combinations of parameters involved, the possible water level range for a given discharge is also greater. This applies to both freeze-up and breakup ice jams (red areas, Figure 6).

The onset of breakup, or initial ice-cover mobilization, and the formation and release of ice jams depend on a balance between driving and resisting forces. If resisting forces are greater than mobilization forces, the ice cover or ice jams remains in place (Figure 7). In turn, for dominating driving forces, the ice cover or jam is set in motion and washed out of the reach, or it may form an ice jam further downstream where the force balance is different. Dynamic river-ice processes that generate significant impacts on water levels are associated with a significant value of these forces, as opposed to passive or thermal processes. A detailed quantitative discussion of driving and resisting forces is presented in Chapters 5 and 6 in Beltaos (2008). The following subsections present breakup and ice-jam driving and resisting forces as well as the parameters and indicators on which they depend, and describe how climate change in Canada is affecting those parameters and indicators.

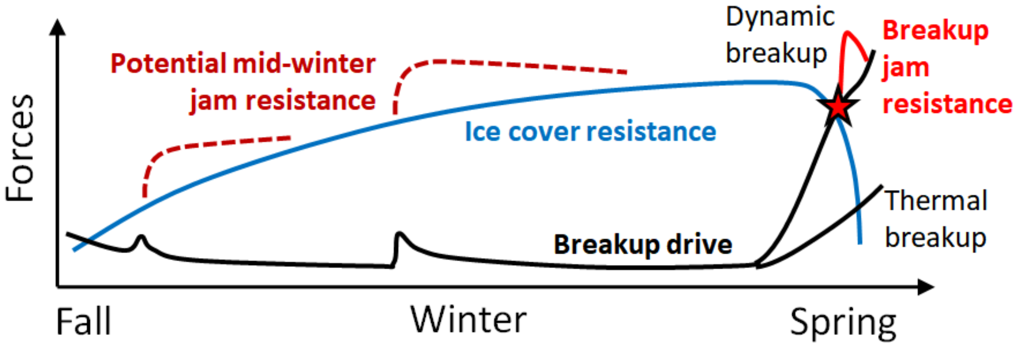

Figure 7. Conceptual graph showing how resisting (blue for intact ice cover, red for ice jams) and driving forces (black lines) may evolve under a specific winter scenario characterized by minor mid-winter runoff events, if any. A single ice-jam event is presented by a red star.

3.1 River-Ice Breakup and Ice-Jam Driving Forces

For stationary ice to be mobilized, hydrodynamic forces are required. The action of moving water at the underside of the ice cover and the downslope component of the weight of ice itself represent the two main forces acting on the ice cover or on an ice jam in the downstream direction (Figure 8). These forces depend on water velocities and on ice conditions immediately upstream. These parameters are relatively difficult to measure (any monitoring may put instruments and people in peril) and simulate (as represented by grey boxes in Figure 8), and they can vary significantly over time and space (as represented by dash-contoured boxes in Figure 8).

One relatively direct indicator of driving forces is the channel discharge, or flow. It is more versatile and spatially representative than shear stress or flow velocity, and it is also possible to evaluate it prior to breakup. Weather parameters (presented in black boxes in Figure 8), mainly associated with rainfalls and snowmelt rates, represent the most important indirect indicators of potential ice cover mobilization forces, as rainfall and snowmelt produce runoff and affect channel flow. They can be used to evaluate the timing and severity of ice-cover breakup in specific cases, but can hardly be used to forecast the timing of an ice- jam release because each ice jam is unique. Although snow melting rates are dictated in part by air temperatures, it is not recommended to use degree-days of thaw as an indicator of discharge or driving forces because their impact on ice-resistance parameters (section 3.2) is more direct.

Once breakup is initiated in a drainage system, sporadic ice movements generate water level and discharge instabilities, or waves that propagate downstream. Local ice-induced water-level fluctuations can be very hard to distinguish from ice-induced discharge variations. Therefore, it may be helpful to rely on multiple instruments or on hydrological simulations to estimate the discharge in ice-jam-affected reaches. It is not uncommon that an ice jam is set in motion by an increase in flow shear and downslope force (push) originating from a wave. These waves, or javes (Jasek and Beltaos 2008), are very difficult to track and forecast and therefore, it can be very challenging to forecast the maximum water level along an ice jam prior to its mobilization. In terms of location, it may be easier to rely on historical observations or on ice-mobilization-resistance parameters (section 3.2), including geomorphic features, to identify potential jamming sites.

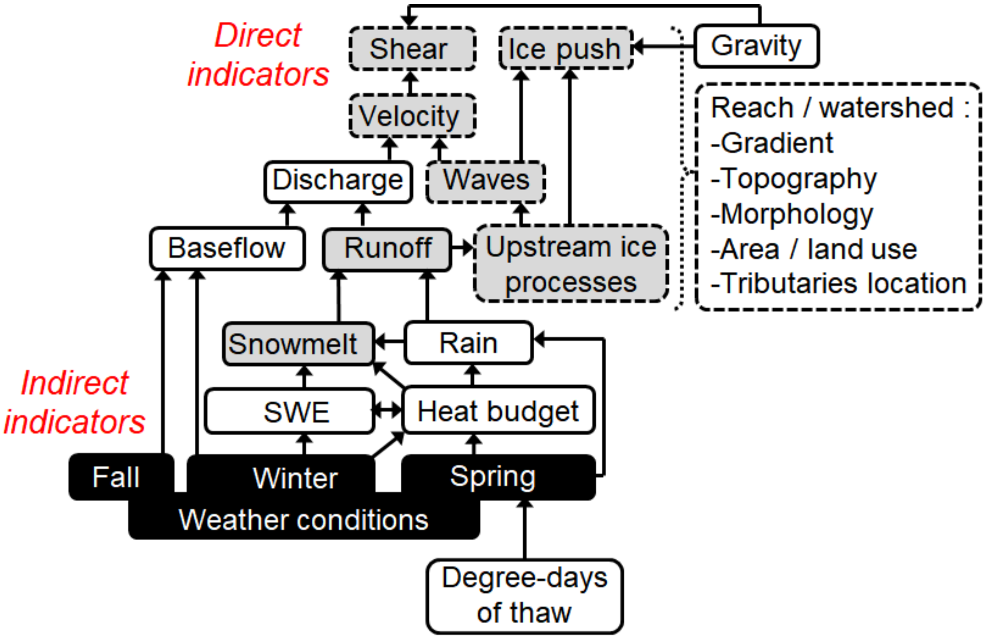

Figure 8. Parameters that can be used to directly calculate *or indirectly evaluate* ice cover and ice-jam mobilization forces. These parameters are presented from more direct (upper part of diagram) to indirect (lower part of diagram) (modified from Turcotte and Morse 2015).

3.2 River-Ice Breakup and Ice-Jam Resisting Forces

The ice cover resistance often reaches its maximum at the end of winter, prior to the first mild and sunny days (Figure 7). Initially, the ice cover is strong (links between ice crystals are intact), it can be grounded at the channel bed at some locations, frozen against the banks, and confined by river width constrictions, bends, and meanders (Figure 9). At a specific location (morphology-related parameters being constant) the timing and intensity of breakup from a resisting perspective will be a function of the ice cover strength, which depends on initial ice cover thickness and composition, and on its degradation state.

Since the air temperature is the dominant parameter affecting ice-cover thickening during winter, the ice thickness, h, produced by static ice formation is commonly estimated using the Stefan equation:

$$h_i = Ꝁ * \sqrt{CFDDs} \qquad [1]$$

where h_i (mm) is the ice thickness, Ꝁ (mm/(°$C^{0.5}$ $day^{0.5}$)) is an empirical coefficient that varies from site to site depending on local conditions such as the snow cover, wind, and exposure to solar radiation, and CFDDs (°C day) is cumulative freezing degree-days. The theoretical value for Ꝁ is 35, but values of Ꝁ may vary between 7 and 27 (Michel 1971, Beltaos 1995). An additional level of complexity and representativeness to estimate h_i consists in including other winter parameters that have a direct impact on ice cover thickening, insulation and heat deficit: presence of snow or water on the ice, short and long wave radiation, friction, groundwater heat, shading from riparian vegetation and surrounding topography, etc. (refer to Ashton and Beltaos 2013, for thermal and snow-ice thickening equations).

The degradation state of the ice cover, which is often associated with the weakening of links between ice crystals via absorption of solar radiation, is usually difficult to quantify. It depends on a very complex heat budget and on changing ice properties (Bulatov 1970, Hicks et al. 2008). The warming and the rate of warming of the ice cover may also introduce internal stresses that contribute to breakup. Cumulated degree-days of thaw are often used as an indicator of residual ice-cover resistance (Figure 9). Sunny conditions (short-wave radiation) accelerate ice-cover degradation rates while recent snowfalls may reduce it. Therefore, cumulated degree-days of thaw are often calculated above a temperature that is colder than 0°C, -5°C being a common assumption (Bilello 1980), while recent snow falls or cloudy conditions may be accounted for by manually reducing the amount of cumulated degree-days of thaw. Though this approach only considers part of the heat budget, it tends to provide a reasonable estimate of residual ice cover resistance over time, which contributes in evaluating the timing and intensity of breakup.

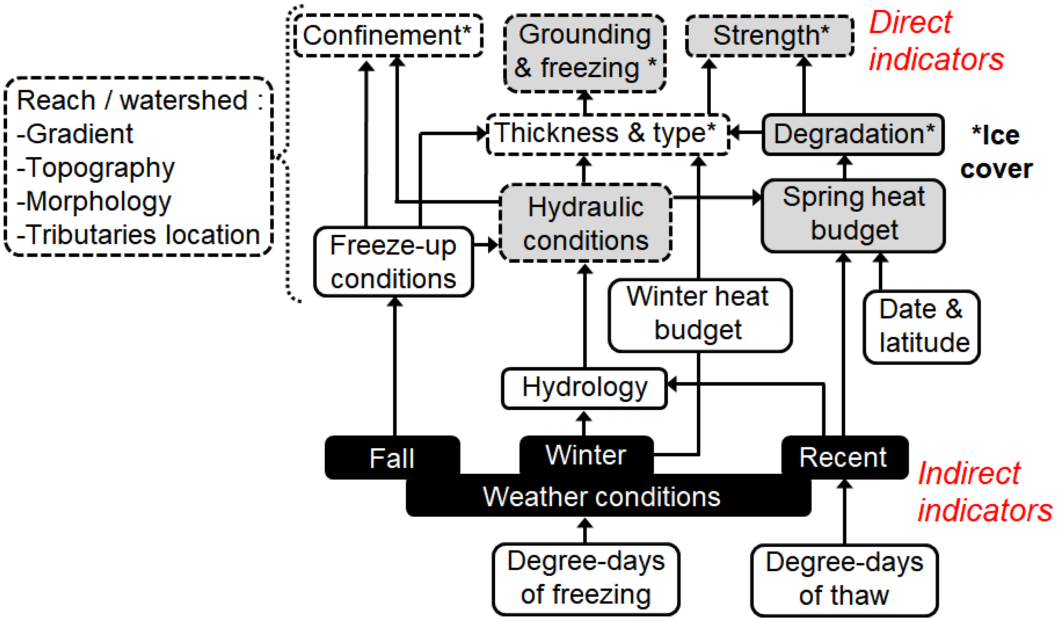

Figure 9. Parameters that can be used to directly calculate or indirectly evaluate ice cover and ice-jam resisting forces. These parameters are presented from direct (upper part of diagram) to indirect (lower part of diagram) (modified from Turcotte and Morse 2015).

Once river-ice breakup has initiated, the resistance of ice jams, if any, depends on similar groups of parameters as described in Figure 9. In theory, as an ice run becomes arrested by an obstacle (often a strong ice cover) or as the moving ice rubble becomes congested at a channel constriction, it will shove and thicken until the driving forces are compensated by the resisting forces. Note that because of inertia and because of discharge variations (waves) during the ice-jam formation process, the final resistance of the fully formed ice jam may be locally significantly greater than the post-formation driving forces. Cohesion also develops over time as ice blocks and potential snow slush are pressured together. Grounding and freezing (if air temperatures drop below freezing) may further explain why an ice jam can stay in place for several hours or days, even under an increasing discharge (i.e., driving force).

For a given channel reach (morphology-related parameters being constant), what determines the final thickness of the ice jam is the prevailing driving force (indirectly associated with the channel discharge), and ice-rubble strength and roughness (at the ice-water interface). Fortunately, the roughness is often correlated with the ice-jam thickness (e.g., Beltaos 2001), but it can also be estimated by looking at the aspect of the jam surface (more angularity means a higher roughness). In steady-state models in which the ice jam is static (unchanging), the location of the ice jam needs to be specified, and the maximum water level along the ice jam will depend on the following resisting parameters and indicators:

- Initial ice cover thickness (h)
- Ice-jam roughness, or "manning's n" (see Beltaos 1995 for typical values)
- Ice specific gravity (approximately 0.92)
- Ice-jam porosity (0.4 for ice jams consisting of large and thick ice blocs, lower values for ice jams made of thinner ice and slush)
- Angle of friction between ice blocs (internal strength of the ice jam as a granular material, between 56° and 59°, from Beltaos 2010)
- Ice-jam resistance ratio (transferring longitudinal stress to lateral stress, 0.3 to 0.4)
- Ice-cohesion strength (assumed to be nil for breakup ice jam with no re-freezing)
- Length of ice contributing reach (for ice mass balance purposes[1])
- Channel geometry and presence of structures

Therefore, the model computes the water level along the ice jam based on a balance of resisting and driving forces (section 3.1), the latter often being calculated using simple input parameters such as the channel discharge and gradient. Dynamic ice-jam models (simulating the formation of the ice jam over time) will require additional parameters but may not need location of the ice jam to be specified. Lindenschmidt (2017) presents an example of this type of model.

Evaluating the structural weakening, or strength degradation of an ice jam over time, is as complex as for a monolithic ice cover (the presence of open water upstream may lead to a fast degradation of the ice-jam head while the toe, its downstream support, may be exposed to limited heat). Therefore, even under a stable discharge (constant mobilization driving parameters), it is very difficult to determine when the ice jam or the downstream ice cover will be weak enough to release (see also Jasek and Beltaos 2008). It may be demonstrated that the ice jam will entirely melt over a specific period of time (based on upstream heat budget and ice thermal property calculation), but it is more likely to become weak enough to release before it melts entirely.

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[1] Before performing an ice mass or volume analysis, it is important to consider the potential amount of ice left along the banks as breakup progresses downstream. In narrow rivers and for very dynamic breakup events, a large ratio of the broken ice cover may form high vertical shear walls and ice may be deposited on the floodplain. In wider channels, this ratio should be smaller, but can still be significant.

3.3 Direct Potential Impacts of Climate Change on Ice-Jam Frequency and Magnitude

River-ice, hydrological, and morphological processes and their interactions are complex. Therefore, a gradual climate warming accompanied by extreme events will generate a multifaceted modification of winter ice regimes. This subsection attempts to provide a global picture of the impact of climate change on the frequency and intensity of ice-jam floods.

An increase in mean air temperatures and in air temperature variability, and a modification of precipitation patterns represent the most obvious changes in climate observed in Canada (Figures 1 and 2). An increased air temperature has a direct impact on the thickness of an ice cover (a factor affecting its resistance, Figure 9) and therefore, at first thought, warmer winters would reduce the potential severity of ice jams. This is illustrated in the upper grey area of Figure 10. In turn, a modification in winter and spring precipitation patterns will affect runoff and therefore channel discharge, which is a dominant factor affecting dynamic ice-cover breakup and cover mobilization.

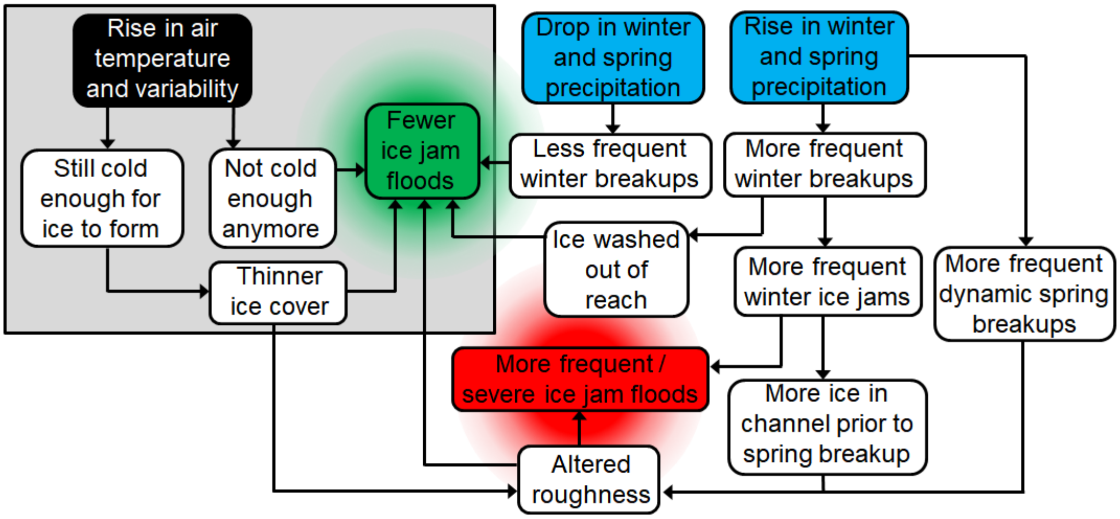

Figure 10. Diagram showing the most direct impacts of climate change in terms of air temperature (black box) and precipitation (blue boxes) and their consequences (white boxes) on the potential frequency and severity of ice-jam floods (green and red boxes).

Since the winter discharge will likely rise more often in the future and that the ice cover will offer, on average, less (to significantly less) resistance to breakup, freeze-up consolidation events and mid-winter breakup events will likely occur more frequently in the future in many drainage systems (as it had been proposed and reported by Beltaos and Prowse 2009), which will likely increase the potential for ice-jam floods. Following a partial mid-winter breakup, the presence of long reaches of open water upstream of ice jams would promote further ice formation and production (if air temperatures can still consistently drop below 0°C), and therefore, the total amount of ice produced by specific (often the steepest ones) river reaches throughout winter could be greater than if only a single river ice-formation - breakup cycle would have occurred. On the other hand, during specific years or in specific regions, the thinner ice cover could very well completely disappear thereby reducing the overall ice-jam flood potential (Figure 10). Beltaos and Prowse (2001) suggested that this would be the case in regions where the historical river-ice cover thickness was about 0.3 m or less.

The earlier spring snowmelt period means that the ice cover could be exposed to less short-wave radiation (the sun angle increases over time) as the discharge begins to rise, which means an increase potential for mechanical breakups, and higher ice-jam-induced water levels. This may or not be compensated by the reduced ice-cover thickness and altered ice-jam roughness (smaller ice pieces, but potentially higher flows). Moreover, the potential ice cover volume prior to spring breakup may be reduced (through thickness), but the presence of previously formed winter ice jams, probably presenting low porosity and strong freezing links, could increase end-of-winter wash thresholds in terms of discharge, therefore increasing the probability of ice-jam flooding. The combination of these potential outcomes are presented in Figure 10. It can be concluded that future ice-jam flood risk may increase, decrease, or remain unchanged, depending on a complex interaction of hydroclimatic factors, as well as on site-specific morphological conditions (ice jam locations could also be altered by climate change). Therefore, each flood-prone community would benefit from a reach-specific ice-jam flood assessment.

Figure 11 presents the worse-case scenario with a limited number of winter runoff events generating ice jams, no complete mid-winter wash, cold enough temperatures to reform a new, but thinner ice cover, a superior pre-spring breakup resistance (winter ice-jam locations), an earlier spring runoff and freshet hydrograph, a higher spring ice-jam mobilization threshold, and therefore a greater potential for winter and spring ice-jam floods compared to the scenario presented in Figure 7 (see dotted lines in Figure 11).

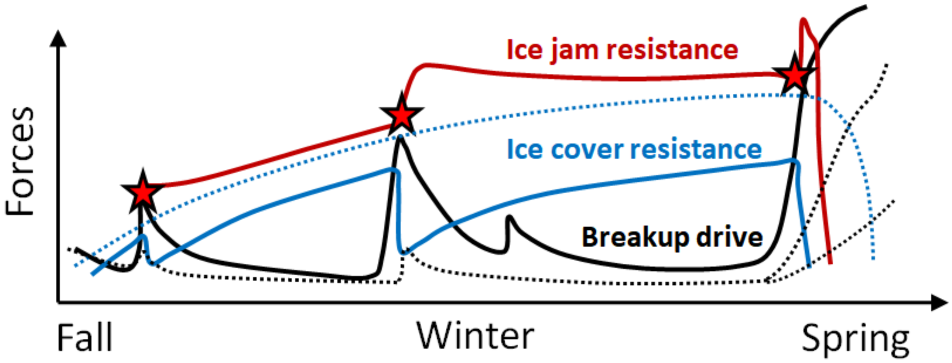

Figure 11. Conceptual graph showing how resisting (blue for intact ice cover, red for ice jams) and driving forces (black lines) may evolve under a shorter winter characterized by major mid-winter runoff events and cold enough temperatures, followed by a dynamic spring breakup event. Three ice-jam events are presented by a red star. This can be compared with a possible pre-climate change scenario (dotted lines from Figure 7).

In regions where the ice-cover thickness was already limited and where mid-winter runoff events will occur more frequently, breakup driving parameters may rise above ice cover resisting parameters so frequently that this will significantly reduce the probability of ice-jam floods (Figure 12).

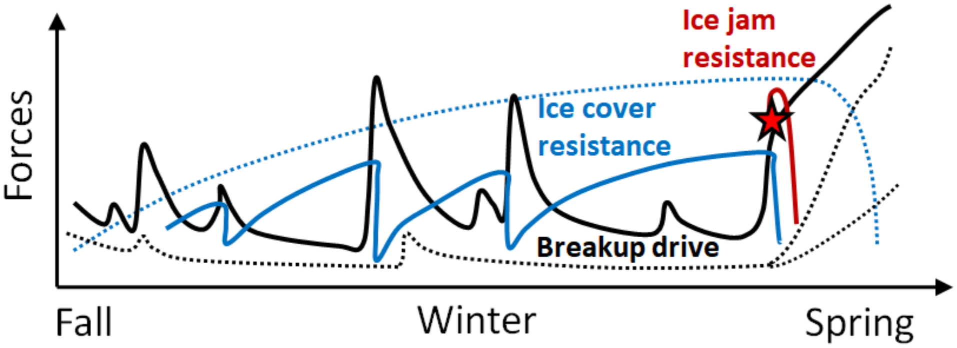

Figure 12. Conceptual graph showing how resisting (blue for intact ice cover, red for ice jams) and driving forces (black lines) may evolve under a very mild winter characterized by multiple mid-winter runoff events and air temperatures too mild to generate a resistant ice cover. Only one minor ice-jam event is presented by a red star. This can be compared with a possible pre-climate change scenario (dotted lines from Figure 7).

3.4 Indirect Potential Impacts of Climate Change on Ice-Jam Frequency and Magnitude

As presented in Subsection 3.3, no definite, broadly applicable conclusions about the impact of climate change on ice-jam floods are evident, especially in a context where climate variability is also increasing. For a specific river or river reach, quantifying this impact may require a research effort that involves significant data gathering and analysis as well as developing a thorough understanding of local ice processes under different winter and spring hydro-meteorological scenarios. Multiple research approaches are presented in Section 4 to determine the impact of climate change on the frequency and intensity of ice jams, by-passing, or confronting the complexity of reality. Before presenting this, the authors also seek to explore more indirect impacts of climate change on ice-jam floods:

- *Higher freeze-up levels and discharges*: If the amount of precipitation in the fall increases in the future, the river-ice cover could form at a higher discharge, or level. In low-gradient rivers, this has been associated with higher discharge breakup thresholds and in some cases, with a reduced probability of significant ice jams (Beltaos et al. 2006).

- *Sediment transport and morphology*: If the sediment transport capacity of river systems increases due to higher and more frequent open-water runoff events or because of more frequent dynamic ice processes, this could generate an alteration of the morphological equilibrium along specific reaches. Hicks (1993) proposed that ice processes could promote the formation and enlargement of secondary channels, a process that has also been confirmed along the lower Montmorency River near Quebec City (Pigeon et al. 2015). A review on the impact of ice processes on sediment transport has been presented by Turcotte et al. (2011). A modification of any channel geometry parameter (i.e., channel avulsion, channel widening, bank incision), alignment (i.e., meander migration acceleration) or profile (i.e., increased spacing between pools) could either reinforce or reverse the intensity and frequency of the generating ice process through an alteration of ice-cover or ice-jam mobilization resisting and driving forces. The location of ice jams could also be impacted.

- *Increased groundwater temperature*: A warmer water influx would have an impact along small streams (Dubé et al. 2015, Turcotte et al. 2014) with groundwater temperature having lesser impact further down the drainage system. At small stream confluences into large rivers, the presence of areas of open water or weak ice cover could promote an early mobilization of the ice cover, which could have an impact on downstream ice-jam processes.

- *Reduced (or increased) snowpack prior to breakup*: This reduces (increases) the potential for large freshet flows. In regions where the snowpack is already a limiting factor to breakup intensity, a reduced snowpack may lessen the potential for large ice jams. In turn, in regions where only a small ratio of the snowpack contributes to producing river-ice breakup flows, large spring breakup ice jams may remain as frequent or increase in frequency and intensity. Also, even a reduced snowpack would sooner reach a ripe state (readiness to melt or to let rain percolate), promoting an earlier rise in channel discharge in the spring.

- *Alteration of hydrological regime due to watershed and land-use changes*: It is known that forest fires or insect infestations (i.e., pine beetle in western Canada), documented consequences of climate change, reduce precipitation interception and retention, therefore increasing runoff and promoting a faster rise in channel discharge as well as higher discharges. The loss of vegetation due to logging has been reported to have an impact of the intensity of ice jams that form in the Restigouche River, New-Brunswick (Dube 2009). Changes in vegetation coverage in boreal and subarctic environments could also have an impact on snow interception, wind-blown snow redistribution and snowmelt (e.g., Musselman et al. 2015, Pomeroy et al. 2006), therefore spatially modifying snowpack characteristics and consequently, runoff patterns. In urban environments, higher runoff coefficients increase the steepness of the hydrograph, and therefore, the probability of dynamic breakup in urban rivers.

- *Permafrost melting*: The melting of permafrost in subarctic environments has a direct impact on surface water infiltration as well as on channel stability. This directly affects breakup and ice-jam mobilization parameters.

- *Sea level rise*: In tidal estuaries, the locations and magnitude of ice jams may shift due to a rise in sea level, therefore affecting communities and floodplain infrastructure.

- *Ice-jam flood mitigation and infrastructure interference*: For several decades, ice-jam floods have been mitigated using permanent (structural) approaches or by annual (non-structural) interventions (e.g., Burrell 1995). Their success, evaluated in terms of reduction of damage over time or in terms of lower maximum ice-induced water levels, affect hydrological records and this may introduce a bias to large-scale studies on the impact of climate change on ice jams. Finally, inappropriate structure designs (bridges impeding ice movement, roads affecting floodplain water evacuation, etc.) may alter the frequency and severity of ice-jam floods.

4. Approaches to Determine the Impact of Climate Change on Ice-Induced Water Levels

Different approaches exist to evaluate the impact of climate change on ice-jam frequency and severity. These can be divided into five different categories that depend on specific objectives, available data, research capacity (expertise and budget) and ambition, as well as research philosophy.

4.1 Statistical Analysis of Historical Water-Level Trends during the Presence of Ice

This is the most common approach because it only requires simple and often easily accessible data and does not rely on complex models to obtain valuable results. Water levels are usually measured at a specific location, the most reliable source of data being a hydrometric station operated by a government agency or by a private company that can attest some level of data quality. Since water levels and flows are usually unstable prior to and after freeze-up and breakup, the challenge of this approach often resides in identifying the last moment where stationary ice was present in the channel or at the hydraulic control section (located downstream of the station). This may be further complicated in regions where mid-winter breakup events are frequent. In some cases, a daily time step can lead to significant uncertainty because the discharge may rise significantly in less than 24 hours and because ice jams could form and release within a few hours. Therefore, the use of instantaneous (usually measured every 15 minutes) water level measurements is often required.

The beginning and end of the ice season, and maximum ice-induced water levels, can be identified or assumed by:

- Estimated freeze-up (ice-in) and breakup (ice-out) dates by the agency or company that provides water level data. Ice-affected data is identified with the symbol B by the Water Survey of Canada (e.g., de Rham et al. 2019). These are often based on a number of assumptions and historical evaluations may not be highly reliable. This is especially true for thermal breakup years.

- Instantaneous water-level signal analysis, to discern local ice-induced water level fluctuations from runoff variations. Often, comparing the signal of two nearby stations is necessary and this technique should only be performed by cold regions hydrology experts or by experienced technologists.

- Observations and real-time camera images (the possible presence of stationary ice located further downstream and still affecting water levels at the station should be taken into account).

- Breakup detection instruments that monitor lateral or longitudinal movement of the ice cover such as upward looking ADCP or, more simply, a tripod connected to a timer located on the ice cover of the Yukon River in Dawson (this may not provide information about the maximum ice-induced water level and timing of the wash).

Degree-days should only be used as an approximate indicator of river-ice freeze-up and breakup as these processes include a dynamic component that also depends on hydrodynamic conditions (Figures 8 and 9). The elevation and age of ice scars on trees may reveal enough information about high-water levels to establish a relatively long historical trend (e.g., Lagadec et al. 2015, Dahl et al. 2017), which is useful along reaches that have not been monitored with a water level instrument in the past. However, limitations prevent this technique from being representative, including the probability of ice run-up far above prevailing water levels and the loss of historical data caused by any type of vegetation destruction. Maximum water levels can also be confirmed on the ground using elevation survey instruments during or after a flood event (e.g., using satellite or aerial images), but only in rare occasions are these records long enough to establish any significant trend, especially because there is no motivation to perform a survey during non-flood years.

By compiling and plotting historical annual maximum water levels in the presence of ice over time, an interpolation can reveal any long-term tendency of the latest impact of climate change (Figures 4 and 5). Also, a statistical analysis of recent years' data may reveal the overall frequency, or return period, associated with ice-jams floods (Figure 13). This technique can be very reliable, but may only apply to very short river reaches (i.e., close to a hydrometric station), especially if the channel morphology varies significantly and if no hydrodynamic ice-jam modelling has been performed on an annual basis in the past.

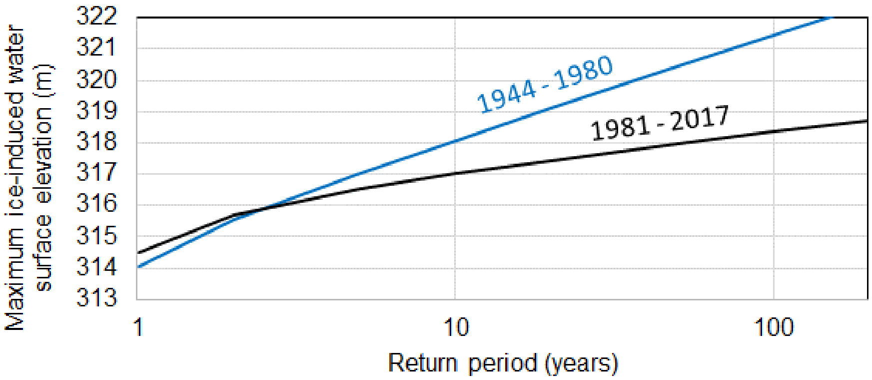

Figure 13. Return period for maximum ice-induced water elevation at Dawson, Yukon, for two periods (1944-1980 and 1981-2017), based on the data presented in Figure 5.

Another limitation of this approach is that extrapolating an observed (even if statistically significant) trend into the future (e.g., extending the trends presented in Figure 4 and 5) may not be realistic because the interaction of multiple, evolving meteorological and hydrological parameters that dictate the intensity and frequency of ice jams (Figures 8 and 9) does not necessarily lead to linear or monotonic impacts under any climate change scenario. Therefore, this approach should be used with caution when for land use planning or for hydraulic structure design.

4.2 Climate-Simulation Outputs, Hydrological Models, and River-Ice-Jam Models

This second technique involves more work, but it may produce valuable information about the impact of climate change for both past and future water levels. The first step consists in developing or using one or multiple existing ice-jam models:

- Coupled ice-hydrodynamic models (e.g., River 1D, HEC RAS) can be calibrated for and used on a specific site or reach, based on one or multiple monitored historical high-water level events. When used by experienced river-ice researchers, this type of model can perform relatively well at simulating ice-jam conditions. However, using this approach remains experimental to evaluate the frequency of ice jam floods, largely because of the interdependence between multiple input parameters (section 3.3).

- Empirical ice-jam or breakup timing and intensity models such as those reported in Turcotte and Morse (2015) can also be used to estimate the elevation of water levels in a specific reach. This type of model usually requires more calibration data over many years as it relies on fewer physical equations and input parameters. This approach can provide an evaluation of the frequency of dynamic breakup events, especially if a link has been made between the locations of ice jamming and hydrometeorological parameters.

- Researchers can prefer to combine both types of tools in order to benefit from their strength and versatility. For instance, empirical breakup models can determine when an ice jam will form while ice-hydrodynamic models can simulate water levels along the ice-jam reach until a certain mobilization threshold is reached.

To simulate the impact of climate change, future weather data series need to be produced as they represent major inputs for ice-jam models. Different scenarios of low and high greenhouse gas emissions intensity can be simulated to produce future climate data (air temperatures, precipitation, humidity, wind, and even a complete estimated heat budget).

For most ice-jam or breakup-intensity models, channel discharge data series represent a key input parameter (Subsection 3.2). Many existing hydrological models can simulate snowmelt over time, given that future snowpack conditions can be simulated as well. This is important as snowmelt runoff dominates the river-ice breakup hydrograph in most regions of Canada. In turn, few hydrological models can adequately simulate the release of water stored in the channel (hydraulic storage and bank or groundwater storage), which represents a limitation to produce representative future discharge data series during breakup. Indeed, in some instances, the release of water storage represents a dominant breakup mechanism along extensive river reaches (i.e., a self-sustained, upstream to downstream, breakup as presented by Jasek et al. 2005, and Beltaos 2017). Finally, ice-induced discharge instabilities such as ice-jam release waves cannot be simulated with current hydrological models, and as a consequence, hydrological data series can probably be used to estimate breakup timing and intensity, but not necessarily ice jam formation and release. Experienced hydrologists and river-ice scientists and engineers can draw useful conclusions by comparing historical and future freshet hydrographs; the slopes of the respective rising limbs can indicate future breakup scenarios.

River-ice breakup and ice-jam models also require the input of ice-resistance parameters, as presented in Subsection 3.3. In turn, empirical river-ice breakup models can use past weather and hydrological indicators to simulate the overall residual resistance of an ice cover or ice jam (Figure 9).

Once all input parameters have been calculated or estimated, future ice conditions can be simulated using selected river-ice breakup and ice-jam models, and associated annual maximum water levels in the presence of ice can be compiled and analyzed. Then, measured historical (Figures 4 and 5) and simulated future water-level trends can be juxtaposed and compared. Given the uncertainty associated with the input and outputs of the different models, a lack of agreement in terms of maximum water elevation and tendency is to be expected. This is why maximum water levels associated with the simulation of past climate conditions should also be evaluated using the same models (in order to introduce a corresponding model bias to historical data). Even when the agreement is reasonable, results should still be discussed and moderated. It is important to acknowledge the complexity of nature and the influence of many directed and indirect parameters (Section 3) on dynamic ice processes and associated floods.

As for the historical approach presented in 4.1, this approach can hardly be transferred to other locations and results should only be assumed representative of the reach under investigation unless a meticulous analysis of river parameters and regional weather and topographic homogeneity is completed.

4.3 Climate-Simulation Outputs and Hydromorphologic-Climatic Transfer

Anctil and Parent (2012) mentioned that the future (~2050) climate of southern Quebec will compare with the actual climate of Pennsylvania and New Jersey. If watersheds of similar sizes and orientation as well as of comparable profile, morphology and hydrological regime (vegetation and land use) can be identified in Canada and in northern United States, this could provide an idea of the impact of climate change on dynamic ice processes that cause floods. The same could apply within Canada, by comparing actual hydroclimatic conditions of southern watersheds with future conditions in northern watersheds. This approach could be resource-consuming as any relevant result should be based on the comparison of multiple watersheds. While the frequency and intensity of site-specific ice-jam processes could probably not be addressed with this approach, it could still provide a qualitative assessment of future breakup intensity at a regional or watershed scale.

4.4 Climate-Simulation Outputs and River Ice-Jam Parameters

Instead of relying on complex breakup and ice-jam models to evaluate the impact of climate change on future ice-induced high-water levels, researchers may prefer to rely on a simpler and straightforward approach based on a thoughtful comprehension of river-ice breakup driving and resisting parameters. Section 3.3 represents an example of this approach. In this instance, as it should be expected for site-specific case studies, the impact of climate change on weather and hydrological conditions may generate opposing potential consequences, and the net impact of climate change on the frequency and severity of ice jams may still remain unclear. Historical trends revealed by the approach described in Subsection 4.1 can be used to identify which parameter or processes seems to dominate others and then, future trends can be established with more confidence.

4.5 Climate-Simulation Outputs and Conceptual River Ice-Jam Models

The approaches described in 4.2 and 4.3 rely on a high level of knowledge about the physics of dynamic ice processes. Despite their scientific basis, the representativeness of their results may be limited because ice processes are spatially and temporally so complex and chaotic. From the river-ice formation period to mid-winter weather conditions, a unique hydrological scenario affects the drainage system every winter while shaping the boundaries of the next breakup season. This reveals that the simulation of a “real future ice jam” (in terms of location, length, overall resistance, and backwater effect) should rely on the simulation of ice and hydrological processes over an entire winter in the entire upstream drainage system. Otherwise, this simulated ice jam may be based on a combination of input parameters that are highly improbable. Experienced researchers may want to confront this reality by further improving the capacity and representativeness of their models. At the opposite, they might prefer to take another step back and to investigate the winter behavior of cold region watersheds from a more conceptual perspective.

This becomes possible when one realizes that an ice jam is caused by a minimal amount of solid (ice) destabilized and shaped by a fluid (water). Tracking the origin, in time and space, of an ice jam that would have caused a major flood (in an unregulated context) will always lead to a change in meteorological conditions combined with a first, very local ice movement (e.g., the tilting or collapse of a single ice slab). The resulting pulse will have travelled from upstream to downstream in a river system of evolving gradient, geometry, and morphology. Most pulses usually vanish, but some of them are large and powerful enough to travel great distances, dislodging a significant quantity of ice and generating major ice jams. The proof of the presence of pulses in cold-regions river systems in winter is revealed by the simple observation of the water-level signal over time at any given location. These pulses are not present during the open- water season (therefore the idea of a water-level signal analysis to determine the beginning and ending of the ice season, as presented in 4.1).

Climate change generates more climate instabilities (it is associated with a higher level of energy after all). This could logically result in a reduced homogeneity of winter ice cover characteristics in space and time (see how the channel discharge at freeze-up tends to vary in a warming climate). If the drainage system presents a reduced ice cover uniformity and that weather conditions prior to breakup are also more variable, this sets the table for an increase potential in the development of pulses that could generate large ice jams.

From a morphological context, the presence of lakes or reservoirs will logically attenuate pulses and therefore absorb the potential impact of climate change. In rivers of relatively homogeneous gradient and areal patterns, additional climate-change pulses will simply be transmitted downstream with possibly limited impacts. On the other hand, along rivers composed of reaches of distinct morphologies without lakes, pulses could combine and superpose to amplify the impact of climate change on the frequency and magnitude of ice jams.

This approach remains largely exploratory. Comparing historical trends of ice-jam-induced water levels in rivers systems presenting (1) large lakes, (2) a homogeneous morphology without lakes, and (3) heterogeneous morphologies without lakes may yield results that would prove that this pulse-based approach is valuable.

5. Summary and Research Needs

As stated in the introduction, the development of flood-resilient communities and infrastructure in Canada depends on the consideration of ice-jam floods. Section 2 has shown that further studies are needed to establish representative future ice-jam frequency and severity trends across the country. Section 3 has presented basic science to explain ice-jam floods and the potential impact of climate change on ice-jam parameters. Section 4 has presented different approaches to perform ice-jam flood studies.

In order to answer societal needs regarding current and future ice jam floods, river-ice scientists and engineers are facing some challenges:

- There is lack of available water level records in the presence of ice, including during years of low water levels. This can be reversed with minimal time and resource investments and should be highly encouraged.

- Limited data on observed or reported historical ice jams exists. This is currently addressed through a new national ice-jam data-base, a project undertaken by Natural Resources Canada and *Institut National de la Recherche Scientifique* (INRS, Quebec City).

- There is an overall scarcity of documented ice-jam flood events. There is a need for spatial and temporal surveys, either from the ground (people, remote cameras), from the air (drones, airplanes, and helicopters) or from space (satellites), to understand the origin and extent of ice jams as well as river-ice breakup patterns upstream and downstream of communities.

- Education and knowledge transmission within jurisdiction is often insufficient. There is a need to produce adapted information dissemination tools, a task currently undertaken at the academic and government level. Developing the interest and curiosity of scientists, engineers, and decision makers concerning dynamic ice processes is logical step forward.

- Assessing the frequency of ice-induced floods is more complex than performing an open-water flood-frequency analysis. It all begins with a recognition that the hazard already represents, or will represent a tangible risk, and it subsequently depends on proportional and adequate funding.

- Once monitoring and breakup or ice-jam models will reach a suitable development stage, our ability to estimate and forecast the channel discharge will become the most significant limiting factor to quantify ice-jam floods. Therefore, it seems urgent to promote research in winter hydrology to explore new discharge quantification approaches, especially at freeze-up, during mid-winter runoff events, and at breakup, when ice conditions are unstable and when estimating the discharge is challenging.

- Traditional knowledge from First Nation communities needs to be included in historical ice-jam records. Despite the fact that this provides mostly qualitative material, it certainly represents valuable information, especially in low population density areas of the North.

CRIPE has certainly a role to play and a leadership position to embrace in order to promote and support ice-jam flood studies in Canada. The authors provide the items below for river-ice researchers to consider:

- The best approach to evaluate the impact of climate change on ice-jam frequency and severity is to carry out a site-specific study where needed.

- An increase in computational power does not replace judgement and experience.
- The best textbook cannot replace the value of site-specific observation and monitoring.
- Statistics cannot eliminate the uncertainty associated with chaotic natural processes such as ice jams nor statistical significance and thresholds serve as the only means of evaluating hazard.
- Qualitative information should not be overlooked especially where quantitative data is scarce.

Acknowledgements

This work represents the first publication of the Working Group on the Impact of Climate Change on River Ice formed by members of the Committee on River Ice Processes and the Environment (CRIPE). The authors would like to acknowledge the contribution of Jennifer Nafziger from Alberta Environment and Yuntong She from the University of Alberta. The authors also recognize the constructive comments provided by Karen Dow, Brittany Peters and Brian Morse.

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