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River ice breakup forecast and annual risk distribution in a climate change perspective

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River ice jams represent a serious flood damage and security threat along many cold region channels of varying sizes and morphologies. Damages can often be mitigated using structural and non-structural methods, the latter including the development and exploitation of river ice breakup forecast models. Breakup processes are affected by several meteorological, hydrological, morphological, and cryologic parameters, most of which are difficult to measure or to evaluate. Also, most existing breakup models depend on empirical equations that are very site-specific. So far, existing breakup onset and ice jam forecast equations and models have been developed for large, low-gradient rivers and very few models are adapted to forecast breakup processes along gravel-bed rivers. This paper identifies a number of indicators used to determine the timing and intensity of river ice breakup along a gravel bed channel and discusses the data, hypotheses, and assumptions that are required for a simple, yet reliable forecast model to be developed. Breakup timing and intensity indicators are used to evaluate the relative breakup risk distribution over the winter period. Based on the projection of specific breakup indicators using climate models, it would be possible to evaluate how the risk associated with ice jams could evolve in a changing climate.

1. Introduction

Several existing and conceptual ice jam mitigation measures can contribute in reducing the risk associated with winter floods and ice damage. They can be classified as structural and non-structural, depending on the nature of the intervention. They can also be classified on the basis of their risk reduction emphasis: reducing the frequency or the consequences of damaging breakup events. Structural measures are often intended to reduce the frequency of specific ice-induced events and they usually include building and installing equipment in the river channel or along the channel banks (ice run interception structures [e.g., Credit River; Burrell, 1995], dikes [e.g., Beltaos and Doyle, 1996], floating ice booms [e.g., Abdelnour et al., 1994], etc.). On the other hand, non-structural measures can reduce the frequency (e.g., using ice weakening approaches [e.g., Kusatov et al., 2012]) or the consequences (e.g., with evacuations) of specific events.

An early-warning breakup system usually consists of multiple non-structural measures that will reduce the consequences of ice-induced floods. The objective of such system is to provide the population and public security services with a maximum preparation time in order to apply different levels and types of emergency measures such as closing or opening dam gates, building sand bag dikes, breaking the ice cover downstream of a vulnerable site, moving basement furniture to higher levels, closing roads and bridges, and evacuating people and therefore saving lives. From a practical point of view, an early-warning breakup system may be composed of breakup forecasts tools, breakup detection instruments, flood maps, intervention protocols for public security services, and information pamphlets for the population.

Detecting breakup using different instruments such as real-time cameras and water level data may provide enough time to adequately apply a number of non-structural mitigation measures in vulnerable areas. The location of the equipment used to detect ice movements must be placed at optimal locations along the river to reduce the frequency of false warnings (placed too far upstream) or no-warning situations (placed too close to a vulnerable site). However, two physiographic realities may make breakup detection inappropriate from a warning time point of view: in small watersheds and along reaches that usually breakup first (especially considering that javes can travel at very high celerity; e.g., Jasek and Beltaos, 2008).

In these particular situations, forecasting the timing and the potential intensity of breakup events before they begin is suitable because it can provide many hours or days of warning, thus allowing the methodical application of adaptable non-structural mitigation measures. The current knowledge on breakup processes and the numerous interdependent parameters directly or indirectly driving breakup conditions do not allow to adequately forecast the process using deterministic approaches (e.g., White, 2008). Nonetheless, these parameters, some of which are either known (e.g., actual water level), measurable and evaluable (e.g., ice cover thickness), or fairly predictable (e.g., short term weather conditions), represent potential river ice breakup indicators.

This work presents a breakup timing and intensity forecast model developed for a relatively small gravel bed river flowing from a non-populated area towards Quebec City, Quebec, Canada. The model is meant to be user friendly and applicable in operational mode. Breakup indicators are used to depict the annual dimensionless breakup risk distribution. This risk curve can be used to evaluate the impact of climate change on the breakup regime of cold region rivers.

2. Background

This section presents a review of the parameters affecting breakup processes that are used in breakup forecast models or breakup equations. As proposed in Beltaos (2008), these parameters, or factors, can be divided into two classes: driving and resisting. Direct driving breakup parameters include hydrodynamic factors such as flow shear and channel gradient, while direct resisting breakup factors include ice cover strength, grounding, and lateral confinement. A global diagram of the parameters affecting breakup dynamics is presented in Figure 1. Boxes in gray identify parameters that are difficult to evaluate or to measure while white boxes represent parameters that can be measured or determined rather easily. Black boxes present weather conditions. Dash-contoured boxes identify parameters that are very site-specific whereas solid-contoured boxes identify parameters that can be transferred to other sites. Arrows in Figure 1 either mean "parameter used as an indicator of" or "parameter used to calculate".

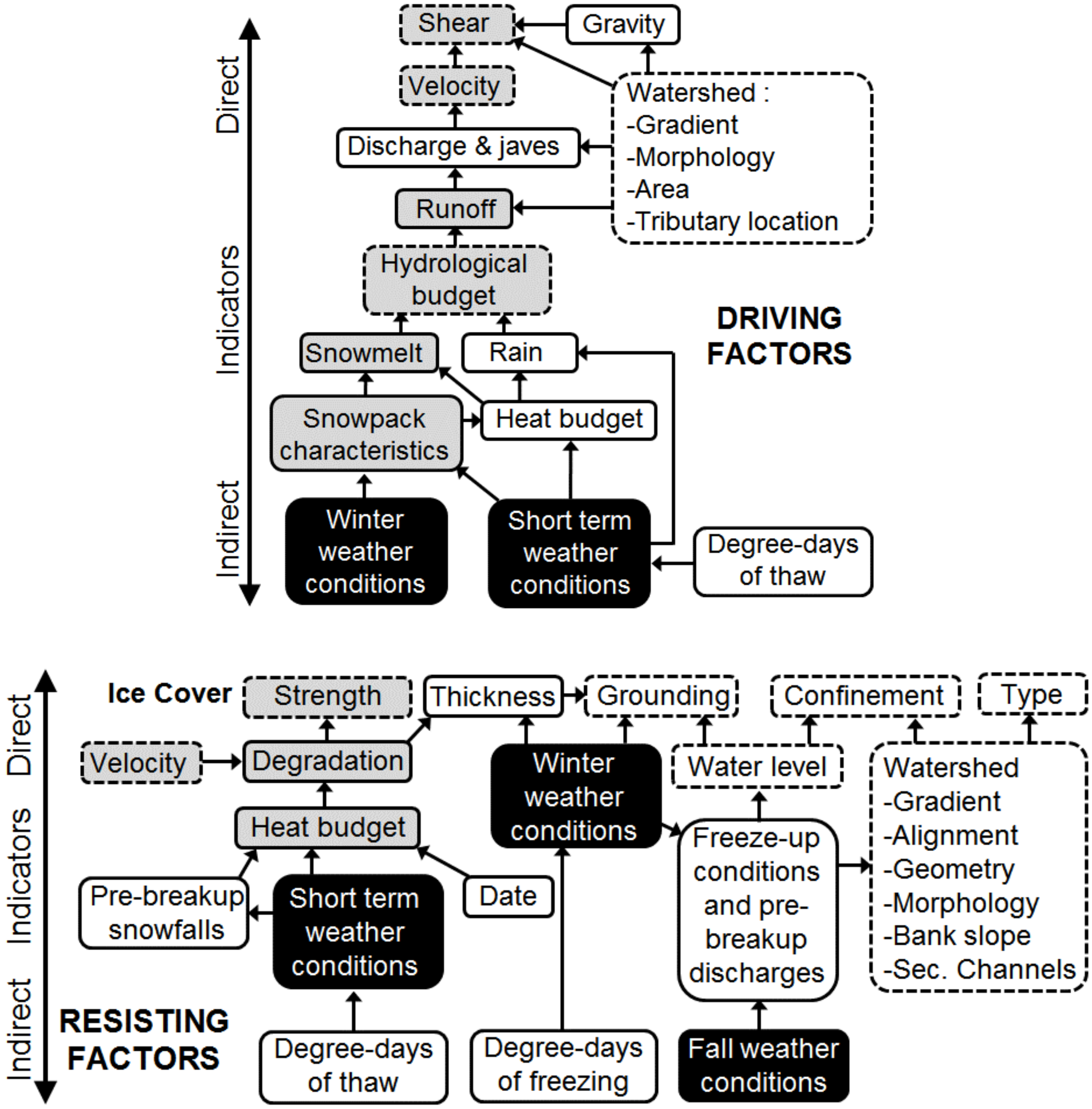

Figure. 1. Driving (above) and resisting (below) factors affecting river ice breakup and ice jamming processes.

The diagrams in Figure 1 illustrate that the task of developing an accurate and versatile breakup forecast model would be complex, especially if based on direct breakup indicators. Therefore, key breakup indicators (such as shear stress and ice cover degradation) are often expressed with site-specific empirical equations that are, in turn, based on indirect indicators (such as discharge and cumulated degree-days of thaw). The use of empirical and statistical approaches can still yield accurate models, but their versatility, or applicability to other sites becomes compromised. Indeed, the weight (factor and exponent) attributed to each parameter in an empirical equation is highly site-specific and the form of the equation itself (the parameters considered) may also be site- or morphology- specific. Tests presented in Beltaos (2008; section 6.4) reveal that breakup onset criteria cannot be transferred to other rivers without a proper site-specific data set.

A review of breakup forecast models is presented by White (2008). The table in Annex presents a non-exhaustive list of breakup onset and ice jam forecast models. Some models rely on very few breakup timing and/or intensity indicators (e.g., freezeup water level of the Lena River; Shulyakovskii, 1963), some of them rely partially on physical equations (e.g., Beltaos, 2013), and others depend on hidden equations and multiple parameters (e.g., artificial neural networks; Zhao, 2012). All models present important strengths (simplicity, reliability) and weaknesses (unacceptably frequent false-positive forecasts [false alerts], limited warning time, and dependency on parameters that are difficult to measure or estimate). The parameters that are most readily used in breakup forecast models include discharge and discharge variations, water levels and water level variations, degree-days of freezing, degree-days of thaw, and date. The potential intensity of breakup ice jams can occasionally be evaluated many months in advance while the timing of breakup mostly relies on hydraulic parameters that can only be estimated a few days in advance.

The table in Annex also reveals that a majority of breakup and ice jam forecast models have been developed for large rivers presenting a low-gradient (below 0.1%), leaving the breakup forecasting of small, gravel-bed channels largely unexplored. Moreover, a majority of models only account for spring breakup events, leaving mid-winter breakup events (largely dynamic events) unforecasted. This reality might become an issue at increasingly northern latitudes and high altitudes (e.g., Beltaos and Prowse, 2009). Finally, very few studies seem to have reported how breakup intensity forecast indicators can be used to explore the effect of climate change on the ice regime and on the flood frequency of cold region channels (e.g., Beltaos and Prowse, 2009). The present study explores these avenues.

3. Lower Montmorency River

The Montmorency River is a gravel-bed river flowing southward from the Laurentian Plateau in a forested 1100 km^2 watershed. The river is particularly notorious for its 80-m high Montmorency waterfall located immediately upstream of its confluence into the St. Lawrence River. At another level, it is also recognized for the intensity of its breakup events. Two recent research efforts have documented breakup events and ice jams of the Montmorency River. The first research effort ended with ice jam mitigation measure recommendations presented in a scientific report (e.g., Morse et al., 2002) and a scientific paper (e.g., Morse et al., 2006). The second research effort started in 2010 with intensive river ice condition observations and monitoring. This effort evolved from a freezeup emphasis (e.g., Turcotte et al., 2014) to a breakup emphasis (present study).

Figure 2 presents a map of the river with relevant information. From kms 5 to 25 (from downstream to upstream), the River can be divided into five reaches of relatively homogeneous morphology and gradient (Table 2). Ice jams of length varying from 500 m to more than 3000 m are recurrent at km 5 (head of reservoir), km 10 (anastomosed reach), km 14 (downstream of a residential island), and km 21.5 (the transition from a rapids to riffle-pools). These jams are most often grounded and generated backwater levels as high as 5 m (Morse et al., 2002). The ice jam that almost forms on an annual basis at km 10 is particularly problematic because it affects a vulnerable area (there are two municipal water intakes at kms 9.5 and 11, and a small residential area at km 10).

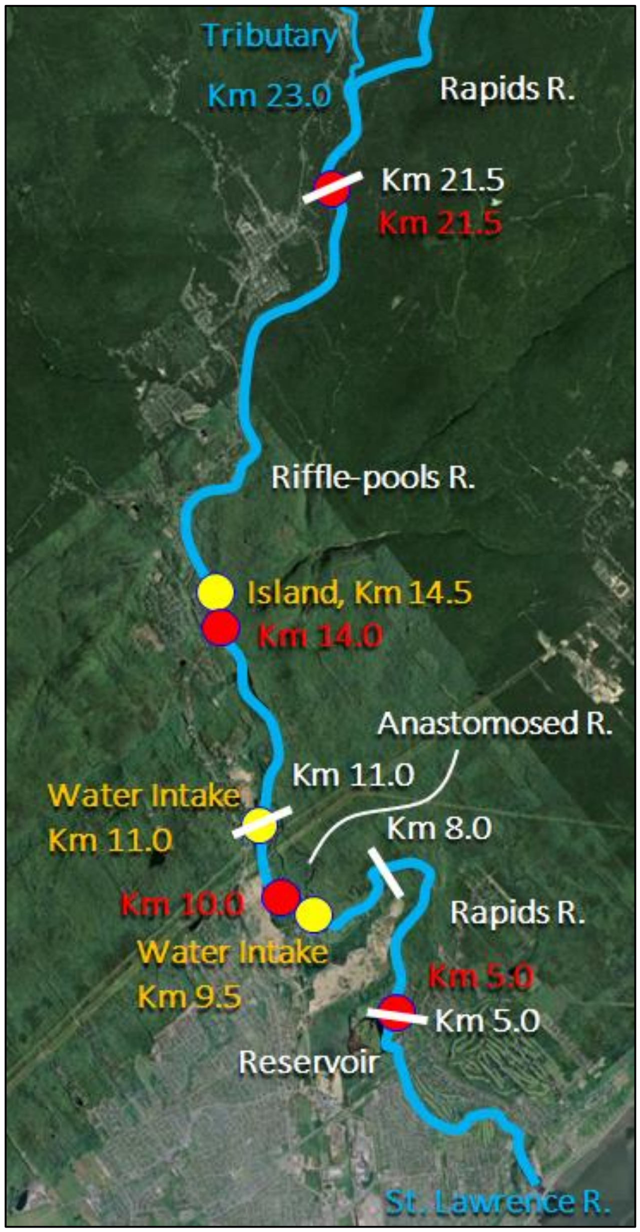

Figure 2. Map of the Lower Montmorency River. White lines represent the limits between reaches of homogeneous morphology, yellow circles represent vulnerable sites, and red circles represent recurrent ice jam sites.

Table 2. Reaches of the Lower Montmorency River

KMS	MORPHOLOGY	GRADIENT	ICE COVER TYPES
< 5	Reservoir	0.0%	Floating cover with hanging dam
5 to 8	Rapids	1.2%	Partial, suspended cover
8 to 11	Anastomosed riffle-pool	0.2%	Floating cover / grounded hanging dam
11 to 21.5	Riffle-pool	0.6%	Floating and suspended ice cover
> 21.5	Rapids	1.1%	Partial, suspended ice cover

Breakup usually begins in the rapids above km 23.0. The first javes normally either originate from a tributary (draining a watershed of 90 km^2) or from the main Montmorency channel. The ice cover along the riffle-pool reach is usually more resistant than the suspended ice cover along rapids. Nonetheless, impeded ice runs have been reported to travel at about 6 m/s through this reach (public security services pers. com.), forming an ice jam in the anastomosed reach where the gradient flattens and where multiple secondary channels can evacuate a significant ratio of the incoming discharge. The hanging dam at km 9 usually resists the increasing flow and ice forces for several hours (spring breakup) to months (mid-winter breakup) before releasing. The resulting jave usually reaches the head of the reservoir (km 5.0) a few minutes later and represents an additional threat to local residences.

4. Breakup and ice jam forecast model

Ice jams form at similar locations along the Lower Montmorency River almost every year. Therefore, the model does not emphasize the probability of an ice jam, but the apprehended intensity of breakup events that can potentially affect the infrastructure and population through ice jams and ice runs. Three emergency levels are normally considered by public security services (Normal Conditions [green], Pre-Warning [yellow], and Warning [red]) and are associated with three apprehended breakup intensities. The model is also used to evaluate the timing of river ice breakup and consequent ice jam formation. The selection of model variables was not based on an exhaustive statistical analysis, but on observations and interpretations of variables that are easily measurable and forecastable, universal, and representative of a long channel segment (km 8.0 to 23.0). The model has been designed to answer specific operational needs and has been used in 2013-2014 and 2014-2015. The Montmorency River is affected by both mid-winter and spring breakup events, which is an important aspect of the model.

4.1 Mid-winter breakup indicators and thresholds

Between late-November and mid-March, breakup events are assumed to occur while the ice cover (partial or complete) is not deteriorated. For the specific context of the Lower Montmorency River, the estimated discharge (Q) was identified as a key breakup driving parameter (Figure 1) because of its availability as a real-time and forecasted data (by the *Centre d'expertise hydrique du Québec*). Observed mid-winter breakup events in recent years (Jan. 2010, Jan. 2013, and Jan. 2014) propose that no ice movement occur in the rapids (the steepest and most runoff-sensitive reach located upstream of km 21.5) if Q does not increase above 35 m^3/s or so, a threshold that is comparable to what had been found by Morse et al. (2002). The ensuing ice run does not travel along the riffle-pool reach and limited overbank flooding occurs at the km 10.0 ice jam site if Q remains below 80 m^3/s. The breakup timing and intensity can therefore be based on a five-day Q forecast with the peak Q reaching or not the above-mentioned thresholds.

The hydrograph steepness (or rate of change in Q) is not considered as a mid-winter breakup driving parameter for three reasons. First, the model is easier to explain and to apply if it remains as simple as possible. Second, most meteorological systems produce rain for less than 24 hours, which restricts the duration of the mid-winter hydrograph rising limb. Third, as suggested in Turcotte et al. (2014), the ice cover (suspended with breached ice dams) in steep tributaries and in the rapids above km 21.5 can initially store an important ratio of the runoff. Based on Q data evaluated along four channels of different orders in the Montmorency watershed (e.g., Turcotte et al., 2014), this storage process either laminates the entire runoff event (no breakup) or delays the beginning of the event, but eventually generates a greater Q than a conventional hydrological model (that does not take ice processes into account) would suggest. Indeed, ice dams can be relatively fragile and their sudden breaching can release enough water and ice to trigger a reach scale breakup. The rate of rise in Q (jave) is therefore not only controlled by runoff rates or rain patterns, but also by reach-specific ice processes. A study is needed to confirm the relative independence of runoff intensity to winter hydrograph steepness. This, however, represents a very challenging task because (1) historical data are mostly available as daily-averaged values (while the response time of the Montmorency watershed varies between 6 and 12 hours) and (2) the actual runoff associated with rain-on-snow events is complex to evaluate.

An important breakup resisting parameter is the spatial distribution of the ice cover and the thickness of the (floating) ice cover over time (Figure 1). This parameter is indirectly expressed in the model with cumulated degree-days of freezing (CDDF, expressed in degrees C) because it can easily be forecasted on a five to seven-day basis using weather forecasts. Note that measured and forecasted air temperatures used as input parameters in the model are taken in Quebec City (international airport, Environment Canada). Data used to calibrate the model include the following:

- In Dec. 2011 and 2013, frazil congestion (hanging dams) started to generate ice bridges across the River at km 10.0 with 100 to 110 CDDF. In Jan. 2011, the same process occurred with 210 CDDF, but this ice formation process had been preceded by an ice clearing event at 80 CDDF.
- While the ice cover in the riffle-pool and anastomosed reaches was almost complete, ice dams began to form in the rapids above km 21.5 in Jan. 2011, Jan. 2012, and Dec. 2013 at about 260 CDDF. This dynamic ice formation process prevents frazil transport to downstream reaches.
- In Jan. 2011, 2012, and 2014, the suspended ice cover had reached its mid-winter state in the rapids above km 21.5 with 400 CDDF. Afterward, ice thickening did not occur in this reach because the ice cover was no longer in contact with the flowing water (Turcotte et al., 2013). This type of ice cover is supported by emerging rocks (partially grounded), it is relatively heterogeneous and fragile, and it presents open water leads throughout winter.

This information suggests that ice runs can be intercepted at km 10.0 with at 100 CDDF at the beginning of winter while the potential ice volume that can generate an ice jam attains a critical value at 260 and 400 CDDF. The alpha coefficient of the Stefan equation for the floating ice cover of the Montmorency River is estimated to 2.2, which yields a cover thickness of 45 cm at 400 CDDF and of 75 cm at 1150 CDDF in slow-flowing sections. The latter value represents a 1945-2015 maximum winter average.

4.2 Spring breakup indicators and thresholds

After mid-February, ice degradation may begin along rapids of the Montmorency River. Keeping spring breakup driving indicators that are comparable to those used for mid-winter processes, the first ice movements above km 21.5 in the spring are usually observed at a Q of 35 m^3/s and this remains the lower threshold for a spring breakup Pre-Warning. The ice clearing Q upstream of km 11 had been estimated to 200 m^3/s by Morse et al. (2002). Based on observed breakup events in 2010, 2011, 2012, and 2013, it was believed that this threshold also applied between km 8 to 11 (the anastomosed reach). However, in April 2014, after a cold winter (1500 CDDF), the ice jam at km 10 was mobilized and washed out at 500 m^3/s, making this, by far, the largest documented ice clearing Q in the Montmorency River. This event yields a Warning status overlap for ice jam-induced floods and open water flood (about 500 m^3/s).

As opposed to mid-winter breakup events, the intensity of spring breakup events can be attenuated by ice degradation. A detailed heat budget would be a suitable approach to evaluate ice degradation (e.g., Hicks et al., 2008). Dominant factors of the spring heat budget include air temperature (T_{air}), incident short waves, and ice cover surface albedo. Short wave radiation intensity is certainly a dominant parameter of the spring heat budget and cumulated degree-days of thaw above -5°C (CDDT-5) are meant to partially consider their effect. Even though the -5°C time-constant air temperature correction should probably be a time-varying correction (e.g., CDDT-0 in early-February and less than CDDT-8 in mid-April), CDDT-5 are considered in the present model for simplicity reasons. The surface albedo is only considered indirectly in the model (Section 4.4). Key information linking ice processes and CDDT-5 include:

- Ice deterioration (collapse and melting) in the rapids of the Montmorency River usually begin with the first mid-day air temperatures above 0°C. A daily-averaged air temperature of -5°C is therefore an indicator of the onset of thermal melting in the steepest reaches and tributaries of the watershed.
- On the other hand, the ice cover downstream of km 21.5 can remain visually intact (and snow-covered) during many additional days (and CDDT-5).
- In April 2014, the worst ice jam of the last 5 years was only mobilized at 100 CDDT-5. This means that important ice jam floods and damage can occur below this threshold.
- In turn, in April 2015, after an equally very cold winter (1500 CDDF), the river ice cover had completely melted in place after only 160 CDDT-5.
- Historical records show that no ice jams have been reported above 200 CDDT-5.

The literature (and Figure 1) presents multiple breakup timing and intensity indicators that are not considered in this model. For example, Shaw et al. (2013), among others, considered the date as a breakup intensity indicator. Indeed, Julian days are used to calculate short waves radiation intensity and are also correlated with historical averaged T_{air}. However, in a small watershed such as the Montmorency River, intense breakup events have been reported at about 100 CDDT-5 in mid-March (2012) and mid-April (2014). Therefore, CDDT-5 was were preferred to Julian days as a breakup indicator.

The freezeup water level was also discarded as a breakup intensity parameter (e.g., Beltaos, 2008; Shulyakovskii, 1963) for various reasons. First, this water level varies significantly along the different reaches of the river. Second, river ice formation lasts several weeks along the Lower Montmorency River while Q can resume to pre-runoff event values in a few days. Third, the physical meaning of the freezeup water level is mostly associated with floating ice covers in large, trapezoidal channels and this type of cover is not dominant in a coarse gravel-bed river. Fourth, frazil slush accumulation under discontinuous floating ice cover segments (in riffle-pools) can generate post-freezeup water level rises that complicate the estimation of the freezeup water level. Water levels are correlated with Q but historical data (1964 to 2015) show that important ice jams have been reported for all ranges of average Q between 50 and 100 CDDF (Figure 3).

4.3 The graphical model (basic operational mode)

Based on the above-mentioned breakup indicators and their respective thresholds, a graphical version of the model was developed (Figure 4) to forecast potential breakup ice jams timing and intensity. Figure 4 also presents reported or observed ice jams (white diamonds) from 1973 to 2015 associated with their respective runoff event (max Q) and CDDF or CDDT-5. Apart from one event (ice jam reported in 1974), all reported or observed ice jams are either positioned in the yellow (Pre-Warning) or red (Warning) zones. Finally, Figure 4 shows runoff events ($Q > 10$ m^3/s and $\Delta Q > 5$ m^3/s [Q variation over 24 hours]) from 1964 to 2015 that are not associated with reported or observed ice jams, and that occurred at least 50 CDDF after a former potential breakup event ($Q > 80$ m^3/s) and below 200 CDDT-5 (black diamonds). Runoff events falling in the Pre-Warning and Warning zones are assumed to have generated minor to major ice jams that were either not observed (most snowmelt runoff events peak during night time) or that did not affect the population (forming in less vulnerable or in low population density areas). A similar assumption had been adopted by Tuthill et al. (1996).

Figure 5 presents examples of winter data sets (2001, 2008, and 2014) applied to the model with reported or observed ice jams (white diamonds). A number of particularities about the model (Figures 4 and 5) need to be explained:

- The Pre-Warning and Warning zones are defined between breakup onset Q and ice clearing Q for specific ice conditions (CDDF and CFFT-5) and apply from km 23 (downstream of a major tributary junction) to km 8 (downstream of the anastomosed reach).
- The breakup onset Q and ice clearing Q increase in the downstream direction, not because Q increases with the cumulated drained area, but because the gradient and morphology change in the downstream direction.

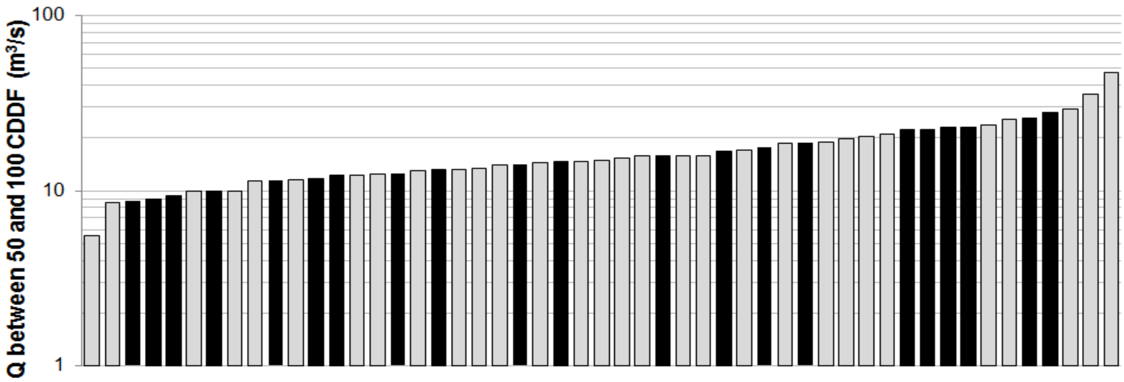

Figure 3. Discharge (Q) during (between 50 and 100 CDDF) the ice cover formation period for reported ice jam (black) and no-reported ice jam (gray) between 1964 and 2015.

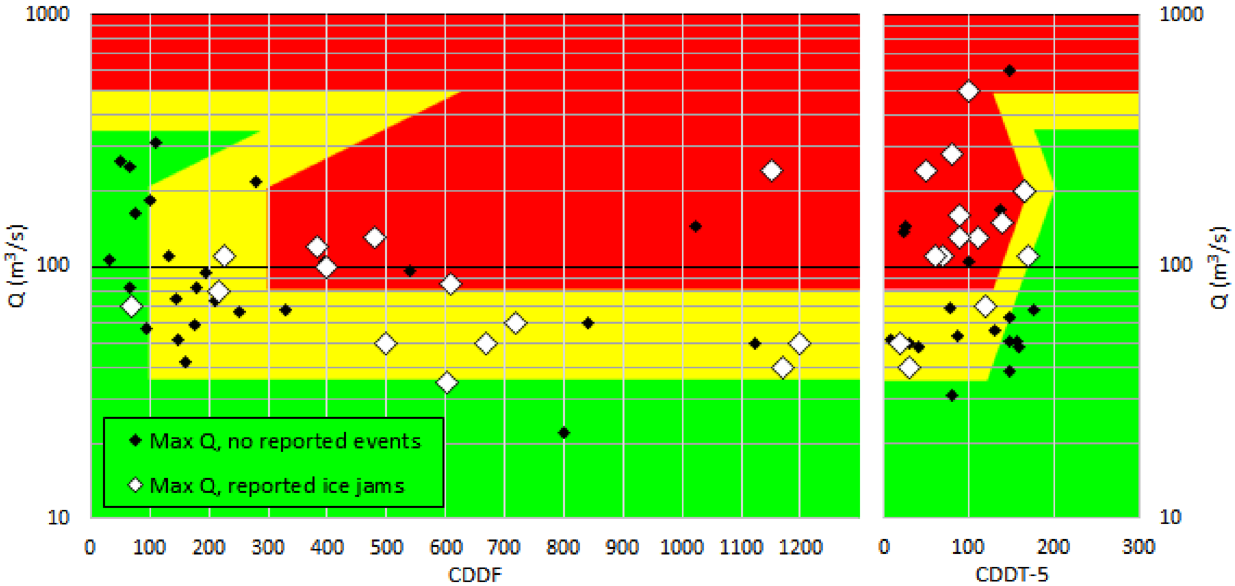

Figure 4. Breakup timing and intensity forecast model for the Montmorency River between km 23 and km 8. Mid-winter breakup events are forecasted on the left graph (CDDF) whereas spring breakup events are forecasted on the right graph (CDDT-5). White diamonds represent reported or observed ice jams whereas black diamonds represent runoff events that have not been associated with a reported or observed ice jam.

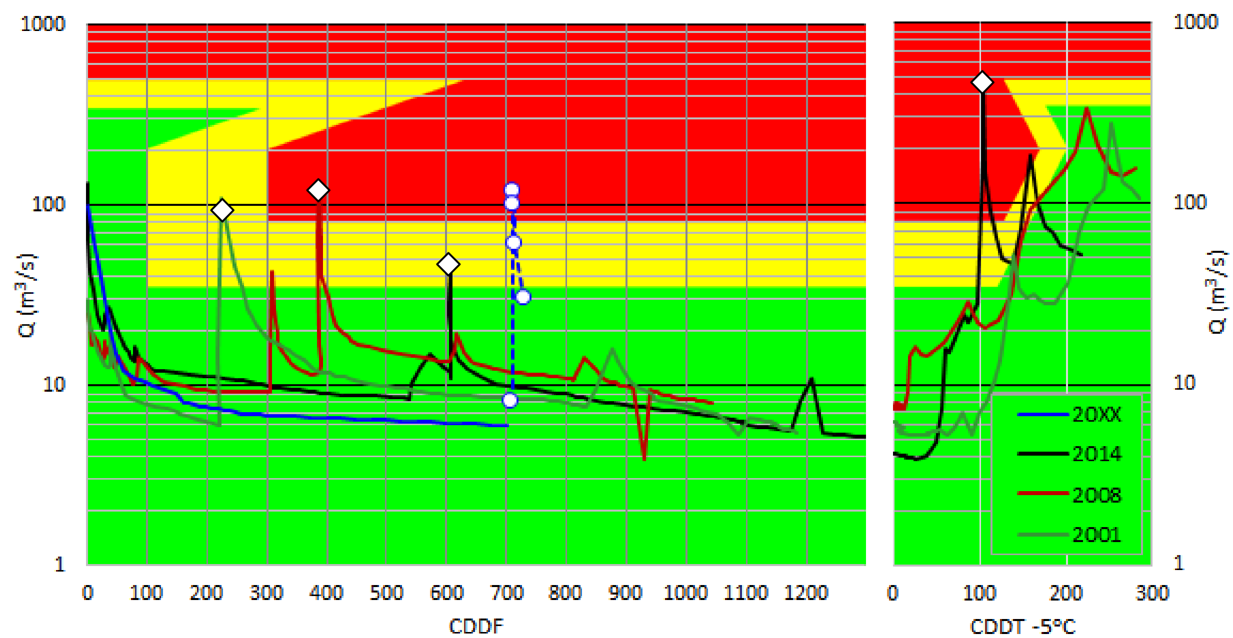

Figure 5. Breakup timing and intensity forecast model for the Montmorency River with winter data sets illustrated and reported or observed ice jams (white diamonds). The 20XX data set represents an imaginary series ending with a five-day (white circles) forecast.

- The breakup onset Q is set to be independent of CDDF (horizontal trend) because border ice remains fragile between 100 and 300 CDDF, and because the suspended ice cover in rapids remains fairly fragile above 300 CDDF, independently of the winter coldness.
- The ice clearing Q is set to depend on floating ice cover thickness at the beginning of winter (increasing CDDF) and on ice cover deterioration in the spring (increasing CDDT-5).
- Although there is no time scale in Figures 4 and 5, time is implicitly presented on any forecasted trend, depending on the forecast span (see fictional five-day forecast in figure 5 for year 20XX).
- The boundaries of the different zones in Figures 4 and 5 indirectly take into account breakup parameters such as (1) ice presence, (2) ice resistance evolution (thickness, degradation, melting), (3) potential ice volumes that can generate an ice jam, and (4) snowmelt runoff.
- During spring breakup events, if Q increases too gradually, thermal degradation will dominate snowmelt runoff and the trend will remain below the Pre-Warning zone (2001 and 2008 trends in figure 5). In turn, if Q increases suddenly (intense snowmelt runoff in 2012 or intense rain in 2014 [figure 5]) and prematurely, the forecasted trend will cross the Pre-Warning and Warning zones. Note that there is always enough snow water equivalent in the Montmorency watershed to generate breakup many days to many weeks before the freshet peak, even in the absence of any rainfall.

The graphical model is meant to be used in operational mode:

- If a forecasted Q-CDD trend goes through the Pre-Warning zone, ice movement could be observed or detected and low-impact ice jams could form.
- Low-impact ice jams could also be mobilized and generate javes with a Q > 80 m^3/s (Warning zone).
- If a forecasted Q-CDD trend goes through the Warning zone, ice movement will be observed or detected and high-impact ice jams could generate flooding and damages.
- If the forecasted Q-CDD trend goes back to the Normal Conditions (green) zone, water levels should recede below flooding levels.
- A Warning or Pre-Warning status could end before the trend goes back to the Normal Conditions zone if no more ice is observed in the river. When the ice jam at km 10 cedes, there are normally no more ice jams or intact ice cover segments over 20 km of upstream channel. It is therefore assumed that the residual probability of ice-induced flooding is very low upstream of km 10. If subsequent runoff events occur after the ice clearing discharge has been reached (see 2014 trend in Figure 5 after the 500 m^3/s peak), they cannot be associated with potential ice-induced floods and a Normal Condition status prevails.

The blind use of this model (with no experience in river ice sciences) in specific hydrometeorological contexts (e.g., consecutive runoff events) can lead to false Pre-Warning and Warning statuses (false-positive situations). The table version of the model can help reducing these situations with a complementary, fine-tuning interpretation of specific conditions.

4.4 The table model (fine-tuning operational mode)

The Table version of the model (Figure 6) presents a number of ice, hydrologic and meteorological conditions that complement the graphical version of the model. For example, the snow cover characteristics are considered in the Table:

- A high surface albedo is taken into account as an aggravating factor (late spring snowfalls delay ice cover degradation)
- Under-mature snow (with a heat deficit) is taken into account as a alleviating factor (the snow cover prevents or delays rain and snowmelt runoff)

This table is particularly useful if Q forecasts (or real-time estimations) are unavailable or to sanction a decision of sending security services in the field for an ice condition survey. Weather forecast indicators for breakup timing (24-h Rain [mm] and 24-h $T_{air\ max}$ [ºC]) are also taken at the Quebec City Airport (Environment Canada weather station). Their values represent estimates of the weather conditions that can generate a corresponding Q in the Montmorency River less than 24 hours after their occurrence, based on observations from recent (2010 to 2015) years. Values published by Morse et al. (2002), used for model validation, were comparable.

Montmorency River breakup forecast between km 23 and km 8

Breakup timing	*The worst indicator dominates*				*Aggravating Factors* →	*Alleviating Factors* ←
	Q (m^3/s)	< 20	< 50	≥ 50	- Tributary breakup	
	24-h Rain (mm)	< 15	< 30	≥ 30	- Preceded by ice-rain - $T_{air\ max}$ > 10ºC - Prevailing Q > 20 m^3/s	- Under-mature snow
	24-h $T_{air\ max}$ (ºC)	>5	> 15	≥ 15	- 24-h Rain > 15 mm - Prevailing Q > 20 m^3/s	- Under-mature snow
Breakup intensity	*The weaker indicator dominates*				*Aggravating Factors* →	*Alleviating Factors* ←
	Q (m^3/s)	< 35	< 80	≥ 80	- Tributary breakup - Existing ice jam	
	CDDF	< 100	< 300	≥ 300	- Observed freezeup jam above km 8	
	CDDT-5	≥ 200	< 200	< 120	- Late spring snowfalls	- Water on ice cover - Open water leads

Figure 6. Table version of the breakup timing and intensity model for the Montmorency River in Quebec City. Aggravating and alleviating factors are also presented.

4.5 Mitigating false-positive errors

The different thresholds of the model are calibrated to minimize the probability of false-negative situations. As stated by White (2008) this calibration approach normally generates relatively frequent false-positive situations. This is probably only a minor inconvenience in the case of the Montmorency River. The breakup forecast model is indeed only used as a part of an early-warning breakup system. Public security services can follow an intervention protocol that could include the following steps:

1) At the beginning of winter:
   - Information sent to the population (existence of the system, preparation procedure, etc.)
2) Two to three days before a forecasted (Pre-Warning or Warning) breakup event:
   - Automated-calls and website update to inform the population
   - Preliminary survey to confirm the state of the ice cover
   - Recommendations to move furniture to higher levels
3) One day before the forecasted breakup event:
   - Maintenance of evacuation roads (snowplow and water drainage)
   - Ice conditions survey
4) Twelve hours before a forecasted (Pre-Warning or Warning) breakup event:
   - Immediate evacuation of vulnerable areas for a Warning forecast
   - Public security roadblock
   - Constant ice conditions survey team positioned at km 21.5 (bridge downstream of rapids)
   - Use of real-time instruments to detect ice movements
5) Once ice movements are observed or detected:
   - Possible evacuation of (additional) vulnerable areas (people already prepared)
   - Helicopter survey if ice runs have stalled at an inaccessible location
6) Once an ice jam is formed:
   - Continual discharge and ice conditions survey
   - Possible evacuation of downstream vulnerable areas (people already prepared)

False-positive breakup forecast situations would therefore not necessarily lead to unnecessary evacuations. In turn, the model means to act as a sentinel to prevent sudden, unexpected ice jam floods.

5. Annual breakup risk distribution

A statistical analysis was performed to evaluate the *Dimensionless Breakup Risk distribution* over an average winter (Nov 1st to May 1st) using historical data from 1964 to 2015. The Dimensionless Breakup Risk represents the relative *frequency* of expected breakup events multiplied by a relative *level of consequence*. The relative breakup frequency was directly linked to the frequency of runoff events (Q) that drive breakup. The relative breakup consequences were associated with the resistance of the ice cover, which is expressed in the model by CDDF (from Nov. 1st to Feb. 13th) and of CDDT-5 (from Feb. 14th to May 1st). Categories were defined for each parameter, based on the breakup forecast model thresholds (Table 2). Probabilities (P) were calculated on a weekly basis for each parameter category. An intensity factor (I) was attributed to each category, in accordance with the model.

Table 2. Parameter categories and intensity factors based on the forecast model thresholds

RUNOFF	ICE FORMATION	ICE DEGRADATION	INTENSITY FACTOR
Q < 35	CDDF < 100	CDDT-5 > 200	0
35 < Q < 50	100 < CDDF < 200	200 > CDDT-5 > 160	1
50 < Q < 80	200 < CDDF < 300	160 > CDDT-5 > 120	2
Q > 80	CDDF > 300	CDDT-5 <120	3

The probability of runoff events $P(Q_i)$ was smoothened using best-fit third and fourth order polynomial equations to attenuate the slight scatter caused by the relative infrequency of winter runoff events over a period of 50 years. This was not necessary for the CDD statistics. The following equation (1) was used to calculate the relative winter risk for each week between Nov. 1st and Feb. 13th:

$$R_{week} = \sum_{i=1}^{4} P(Q_i) I(Q_i) P(CDDF_i)\, I(CDDF_i) \qquad [1]$$

The relative spring risk (Feb. 14th to May 1st) was evaluated similarly:

$$R_{week} = \sum_{i=1}^{4} P(Q_i) I(Q_i) P(CDDT-5_i)\, I(CDDT-5_i) \qquad [2]$$

The weekly risk was then divided by the sum of the winter risk to obtain the Dimensionless Breakup Risk distribution (Figure 7). The trend describes a moderate and long breakup risk period during early-winter followed by a low risk mid-winter period prior to a short and high risk spring period. Figure 7 also shows the frequency of reported and assumed (see Section 4.3) ice jam events from 1973 to 2015. The difference between the *breakup* risk curve and the *ice jam* frequency trend can be explained by a number of reasons: (1) the risk is only based on breakup indicators that are assumed to be independent, (2) the ice jam frequency data does not take into account the intensity of ice jams while the breakup intensity is only theoretically expressed in Table 2, (3) the periods considered are different (starting in 1964 and 1973), and (4) there was only 51 reported and assumed ice jams from 1973 to 2015.

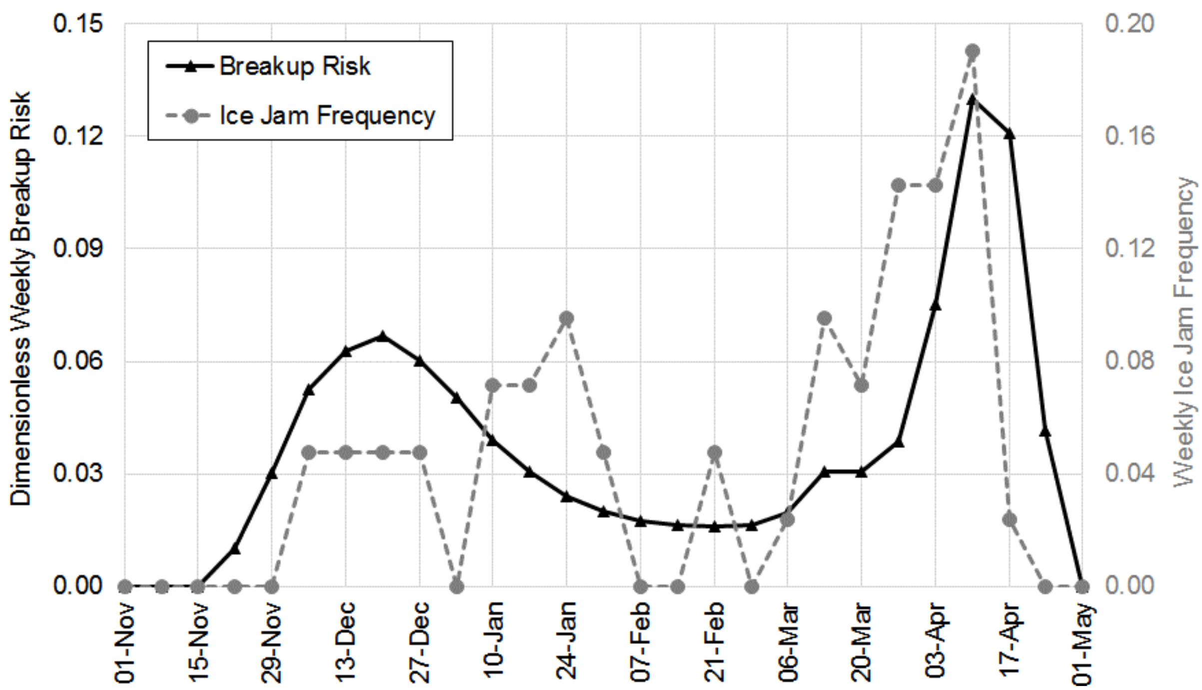

Figure 7. Dimensionless Weekly Ice Breakup Risk distribution calculated on the basis of historical hydrometeorological data from 1964 to 2015 and Weekly Ice Jam Frequency of observed and assumed events from 1973 to 2015.

The breakup risk distribution presented in Figure 7 can be used to inform public security services about the theoretical probability of emergency situations associated with ice-jam induced floods (note the relatively high probability during Christmas holydays). It can also be used to evaluate the impact of climate change on the breakup regime of a river, as described next.

6. Climate change perspectives

The effect of climate change on the ice regime of cold region rivers is a topic of increasing interest. Some publications have already identified climate change effect trends such as delayed ice cover formation dates, earlier river ice breakup dates (e.g., Milburn, 2008), and average ice cover thickness reductions (Huntington et al., 2003). Beltaos and Burrell (2003) mentioned that ice jams in Atlantic Canada may become more severe in a near future, but studies about ice jamming intensities in a climate change perspective are still relatively scarce. This might be due to limited data associated with the frequency and the severity (maximum water level or economical cost) of ice jam floods. Beltaos and Prowse (2009) stated that "climate has a key influence on the frequency and severity of major ice jams". Some research avenues on this topic are introduced here and will be further explored in future publications.

One can easily imagine producing a risk distribution curve (similar to figure 7) to express the effect of climate change on the frequency and intensity of ice jams at a specific site. Long-term historical hydrometeorological data are available at many locations to develop the actual or historical risk curve while climate change projections can simulate the trend that some breakup indicators might follow in decades to come. It is therefore possible to anticipate the future frequency and intensity of breakup or ice jamming events by foreseeing the evolution of breakup indicators. While the frequency and intensity of some indicators will probably vary measurably (e.g., rain-on-snow events frequency, snow water equivalent), others will remain unchanged (e.g., short waves). This combination might significantly affect the shape and amplitude of the projected relative risk distribution curve.

Figure 8 presents 25 year-averaged data (1965-1990 and 1991-2015) showing how two specific parameters indirectly affecting breakup dynamics (ice resistance) in the Montmorency River have evolved. The breakup forecast model (Figure 4) suggests that the ice jam risk increases over 300 CDDF and decreases above 120 CDDT-5. A preliminary analysis of Figure 8 therefore indicates that the high risk period would have decreased by 11 days on average over 25 years.

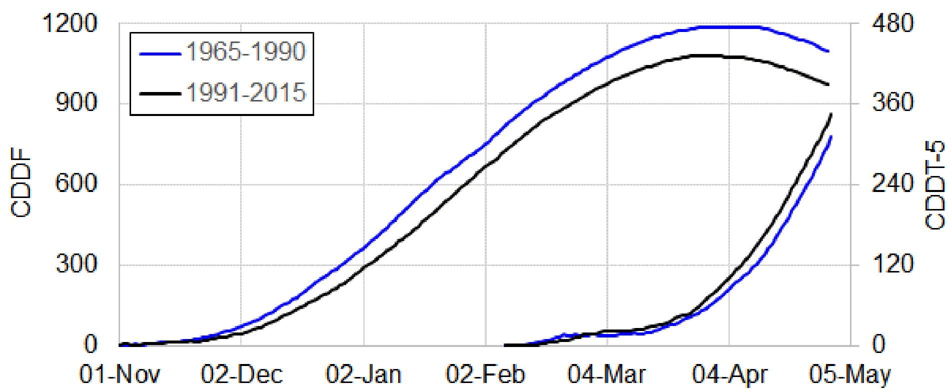

Figure 8. 25 year-averaged CDDF (left axis) and CDDT-5 (right axis) between 1965 and 1990 and between 1991 and 2015 at Quebec City.

However, when considering the combination of runoff events (breakup driving parameter) and CDD (breakup resisting parameters), Figure 9 presents a different result: the risk period is slightly shorter, but the early winter breakup risk remains the same, and the spring breakup risk has actually been postponed. Note that the area under the dimensionless breakup risk curve from 1965 to 1990 is equal to 1 whereas the area under the 1991-2015 curve is equal to 0.8 to account for the evaluated total risk reduction (based on eq. [1] and [2]).

This unexpected result can be explained by the fact that (1) 25 years of data is insufficient to obtain a representative climate change trend, (2) the physically representative limit of breakup indicators has been reached, (3) the breakup indicators climate change impact cancel each other, or (4) a handful of events have influenced one or both trends. Using different breakup indicators could yield different results. However, some of these indicators are difficult to measure or to simulate. For example, evaluating runoff rates associated with rain-on-snow events would not only depend on rainfall frequency and intensity, but also on snow pack characteristics. The actual state of knowledge on the topic represents a serious limitation to the translation of projected meteorological (climatic) indicators into a breakup risk distribution.

7. Discussion

The breakup timing and intensity forecast model presented in this work is based on several hypotheses and technical limitations that have not been described so far:

- Before 2010, historical winter Q data were only available in the form of daily-averaged values. Instantaneous Q_{max} associated with runoff and breakup events were based on daily-averaged peak discharge values multiplied by 1.3. This peak factor is relatively high for the Montmorency River and usually varies between 1.1 (mid-day peaks) to 1.5 (mid-night peaks).
- Ice clearing Q thresholds in the model are mostly based on the maximum discharge of a runoff event associated with reported or observed ice jams. Although ice jams may have been washed out at a lower discharge, the 2014 event (ice jam mobilization at 500 m^3/s) discourages any modification of the model.

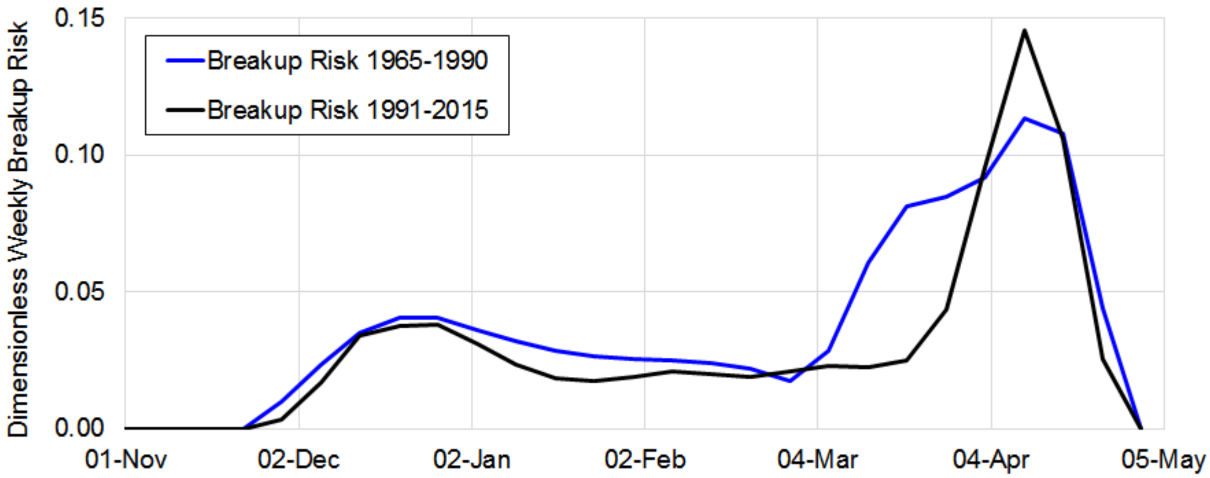

Figure 9. Dimensionless weekly breakup risk between 1965 and 1990 and between 1991 and 2015 for the Montmorency River based on equations [1] and [2].

- The hydrometric station in the Montmorency River is located at km 2.2, downstream of vulnerable areas (Figure 2) and of reaches where the model is valid (km 23 to km 8). In Jan. 2013, the Q associated with an impeded ice run was probably as high as 100 m^3/s while the hydrometric station located downstream was only measuring 25 m^3/s. In addition, javes can be significantly attenuated upstream of km 2.2 (in a reservoir; Table 1). Water level stations should be installed further upstream for the benefit of agencies that would use the breakup forecast model presented in this work.
- Actual winter discharge forecasts do not take ice processes into account (most importantly hydraulic and ice storage release events). In turn, the breakup model presented here means to be conservative in this aspect.
- No statistic or climatic study has been used to confirm that the occurrence of winter and spring runoff events, the winter coldness (CDDT), and the spring suddenness (CDDT-5) represent independent variables. In turn, equations [1] and [2] assume that these variables are independent. The independence hypothesis needs to be confirmed.

Future research on the breakup model and on the ice jam or breakup risk distribution should include:

- Continuing breakup and ice jam data acquisition in order to further develop the model, to take into account changes in the morphology (especially along the anastomosed reach), and to consider the effect of climate change.
- Investigating the physical meaning of diagonal trends presented in Figure 4 that mimic physical ice processes (ice formation and degradation). These trends should be compared with theoretical and empirical breakup equations developed for low-gradient channels (presented in Beltaos, 2008). Empirical ice resistance values specifically associated with gravel-bed channels could be obtained.
- The model in its actual form does not forecast frazil jams (km 5 and km 9 to 11) or sudden breakup events associated with the failure of ice dams (above km 21.5) during their formation. These processes are known to occur and to cause flooding events along the Montmorency River during early winter (CDDF < 400) cold spells. They could be implemented to a future version of the model.
- Investigating runoff associated with rain-on-snow events using historical rainfall and snow depth data as well as heat budget equations should be performed. So far, this approach seems to severely underestimate runoff rates or to overestimate the heat deficit of the snow column. Field data is needed to improve winter runoff models.

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David Dugré, undergraduate student in the Department of Civil and Water Engineering at Laval University, produced a significant amount of statistical results that were essential to this research. The *Centre d'expertise hydrique du Québec* and Environment Canada respectively provided hydrological and meteorological historical data. *La Ville de Québec* has provided funds for field data acquisition and analysis.

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Annex: Non-exhaustive list of breakup onset and ice jam forecast models

River name	**River type**	**Data set length**	**Reference**	**Breakup onset or ice jam indicators**
Tornealven River		~33 y	Zachrisson (1990)	- Discharge - Degree-days of thaw - Precipitation
Lena River	Low-gradient single channel (0.01%) and low-gradient braided (0.02%)	70 y	Kil'myaninov (2012)	- Air temperatures (monthly anomalies and monthly averages) - Date
Lena River	Low-gradient	21 y	Shulyakovskii (1963)	- Water level
Amur River	Low-gradient braided (~0.005%)	~27 y	Shulyakovskii (1963)	- Water level - Heat budget
Yenisei River	Low-gradient single to anastomosed channel (~0.03%)		Shulyakovskii (1963)	- Freezeup water level
Yellow River	Low-gradient meandering (0.02%)	5 y	Wang et al. (2013)	- Discharge (ice mechanics approach)
Yukon River	Variable (0.013% on average)	19 y	White (1999)	- Ice jam location archives
Mackenzie River Delta	Low-gradient –Delta (0.003%)	11 y	Beltaos (2013)	- Water level - Shear stress - Channel geometry - Channel alignment - Ice cover resistance - Ice cover thickness (Degree-days of thaw) - Date - Discharge
Mackenzie River at Fort Providence	Lake transition into an anastomosed reach with few rapids (~0.02%)	4 y	Hicks et al. (1995)	- Heat Budget - Ice cover strength (hinge, buckling, shear, compression)
Hay River	Low- gradient single channel transition to delta	~ 40y	Zhao (2012)	- Multiple (Artificial Neural Network)
Athabasca River	Low-gradient single channel (0.06%)	~22 y	Robichaud (2003)	- Freezeup conditions - Snow characteristics - Ice thickness - Degree days of thaw - Solar radiation - Runoff (water level)
North Albany River	Low-gradient transition to delta		Shaw et al. (2013)	- Rain and snowmelt - Discharge (level) - Discharge increase - Date
Thames River	Low-gradient meandering	~ 8y	Beltaos (1987)	- Water level - Ice cover thickness

Thames River	Low-gradient meandering	~9 y	Beltaos (2008) or Beltaos (1997)	- Water level - Ice cover thickness - Degree-days of thaw - Ice cover resistance - Channel geometry - Channel gradient
Moose River	Low-gradient single channel transition to braided (~0.04%)	~14 y	Beltaos (2008) or Beltaos (1997)	- Water level - Ice cover thickness - Degree-days of thaw - Ice cover resistance - Channel geometry - Channel gradient
Grand River	Wandering riffle-pool channel (0.2%)	4 y	Beltaos (2008) or Beltaos (1997)	- Ice cover thickness - Degree-days of thaw - Channel geometry - Channel gradient
Restigouche River	Low-gradient single channel (~0.04%)	~11 y	Beltaos (2008) or Beltaos (1997)	- Water level - Ice cover thickness - Degree-days of thaw - Ice cover resistance - Channel geometry - Channel gradient
Saint-John River		36 y	Galbraith (1981)	- Degree-days of thaw - Heat budget - Snowmelt - Rain
Platte River	Braided (0.1%)		White (2008); White (1996)	- Degree-days of freezing - Date - Water level
Missouri River	Low-gradient meandering with confluence		Wuebben et al. (1995)	- Degree-days of freezing - Discharge - Date - Water level - Snowpack
Allegheny River	Meandering with few riffles (0.05%)		White (2008)	- Discharge - Degree-days of freezing
Allegheny River	Meandering with few riffles (0.05%)		White and Daly (2002)	- Discharge - Tributary discharge - Degree-days of freezing
Winooski River	Rapids transition to low-gradient with two weirs (~0.3%)	38 y	Tuthill et al. (1996)	- Discharge - Degree-days of freezing - Date