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Modelling probabilities of ice jam flooding from artificial breakup of the Athabasca River ice cover at Fort McMurray

Karl-Erich Lindenschmidt[1]
[1]*Global Institute for Water Security, University of Saskatchewan*
11 Innovation Blvd. Saskatoon, Saskatchewan, S7N 3H5
karl-erich.lindenschmidt@usask.ca

This study investigates the feasibility of artificial breakup of the ice cover along the Athabasca River at Fort McMurray to reduce the severity of breakup ice jamming and backwater staging. An ice breaking machine called the amphibex is an intervention that is used along some other rivers in Canada and could be considered as an option in this situation. A numerical river ice model called RIVICE was embedded in a stochastic (Monte-Carlo) framework to provide stage frequency distributions of backwater levels from ice jamming that could be caused from rubble ice broken apart from the ice cover by an amphibex. For the particular geomorphology of the studied reach, the results show that the severity of ice jamming and staging could increase beyond that occurring through natural breakup conditions. Reaches of different slope may be more conducive to artificial breakage as a mitigation strategy. This would require a separate analysis of its feasibility, similar to the method presented here. A subsequent study is also required to determine the effects of the additional backwater staging on the Clearwater River alongside Fort McMurray. Hence, at this point of the analysis, it is recommended to let the breakup process take its course naturally instead of implementing artificial means of ice cover breakage such as the amphibex, until such additional research has been carried out.

1. Introduction

The amphibex is an ice-breaking machine used on rivers and lakes to artificially break up ice covers or ice jams (for a video, see https://www.youtube.com/watch?v=h57A5Vyud8c). Ice-cover breaking just prior to or during the natural ice-cover breakup period is often utilised to alleviate the risk of ice jam flooding, as is often done on rivers in Manitoba (Topping et al., 2008) and other rivers in Canada (e.g. see Beltaos et al., 2007 and Simard-Robitaille et al., 2015). The Regional Municipality of Wood Buffalo (RMWB) is investigating the possibility of utilising the amphibex on the Athabasca River at Fort McMurray. The machine would be used along a 7 km stretch of the Athabasca River at Fort McMurray, from the bridges crossing the river to about ½ km downstream of the wastewater treatment plant (WWTP) outfall. The bridge piers can act as barriers to ice runs, form a lodgement and establish an ice jam, as was the case for the ice jam flood event of 1977 (Andres and Doyle, 1984). It is hoped that by breaking up the ice cover between the bridges and the WWTP, a passage of open water or rubble ice on open water can be cleared, allowing any ice runs from upstream to easily pass by the piers and continue flowing downstream along the reach of the artificial ice breakup. This may divert the risk of ice jamming and subsequent flooding away from the bridge location to areas further downstream that are less prone to flood damages and risk. It is also hoped that this would alleviate some of the backwater staging into Clearwater River and mitigate flood hazard in the downtown area of Fort McMurray. The ice between the bridges and the WWTP may need to be pre-cut so that the amphibex can break through the ice cover. The warmer water from the WWTP outfall is expected to keep the ice thinner for at least ½ km downstream of the outfall so that pre-cutting may not be necessary for this stretch.

A numerical modelling approach is presented here to determine the degree of ice jamming that may be caused by the artificial breakage along the 25 km stretch downstream of the bridges. The one-dimensional (variations in the longitudinal, flow direction), fully dynamic wave, river ice model RIVICE was implemented to simulate ice jams along the stretch. RIVICE has already been successfully implemented on other rivers to determine backwater staging from ice jams. Examples include the Dauphin River (Lindenschmidt et al., 2012a), lower Red River (Lindenschmidt et al., 2012b), upper Qu'Appelle River (Lindenschmidt and Sereda, 2014), Peace River (Lindenschmidt et al., 2015, 2016) and Athabasca River (Lindenschmidt 2017a, 2017b). Hence, the model is also well suited for this study. Since ice jam processes are stochastic in nature, particularly elements such as the location of the ice jam lodgements, volume of inflowing ice forming the jam and the flow and water levels along the river at the time of jamming, RIVICE is embedded in a Monte-Carlo framework to automatically repeat simulations many times, each simulation having a different parameter and boundary condition setting, to reflect the stochasticity of the ice jamming. For each simulation, parameter and boundary condition values are selected randomly from probability distributions established from the hydraulic and ice regime characteristics of the Athabasca River at Fort McMurray. The resulting ensembles of backwater level profiles are then collated to determine stage frequency distributions, which are then compared to stage frequency distributions established from gauge recordings. The comparison helps to calibrate the stochastic modelling system and determine the severity of possible ice jamming from different artificial ice cover breakup scenarios. This aids in determining the utility of the amphibex, if its implementation can mitigate or aggravate the natural occurrence of ice jamming during the Athabasca River's ice cover breakup period.

2. Study site description

Fort McMurray lies in the floodplain of the lower Clearwater River at the river's confluence to the Athabasca River (see Figure 1). Bridges cross the Athabasca River at one location, connecting Fort McMurray's downtown area with the town's west side. A 7 km stretch extending from just upstream of the bridges, where a water treatment plant is located, in the downstream, northerly direction, has the highest risk of ice jam flooding along this stretch of the Athabasca River due to the close vicinity to urban areas. Another area of concern of flooding is a lumberyard situated approximately 16 km downstream of the bridges. From Pictometry® contours, the lumberyard may be partially flooded at a water level elevation greater than 240 m a.s.l. (pers. comm. with RMWB). The wastewater treatment plant (WWTP) and its outfall are located approximately 4.5 km downstream (north) of the bridges. Ice jams regularly occur along this stretch in early spring.

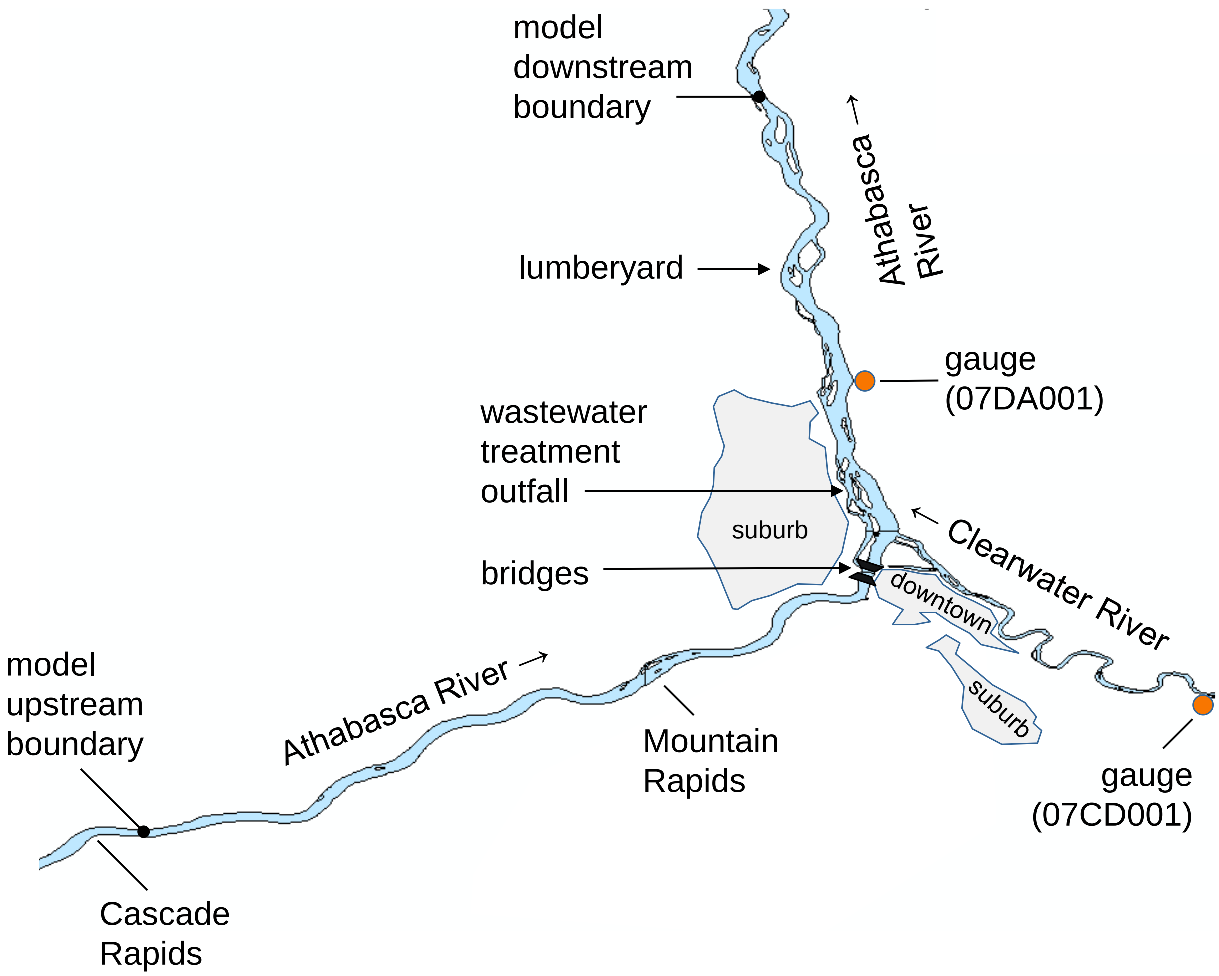

Figure 1. Fort McMurray at the confluence of Clearwater River and the Athabasca River

Two flow gauges operated by Environment Canada's Water Survey Office are located in the area: Gauge 07DA001 named Athabasca River below Fort McMurray (hereafter call the Athabasca River gauge) and Gauge 07CD001 named Clearwater River at Draper (hereafter called the Clearwater River gauge). Figure 2 provides the stage frequency distributions of (i) the instantaneous maximum staging caused by ice jams, (ii) daily mean values of staging at the end of the breakup period (last B-value), (iii) daily mean values of staging at freeze-up (first B-value[1] recorded each winter) and (iv) the annual maximum open water flood levels. This study focuses on the breakup period, at and approximately one month before the end of the ice covered season, hence the 'breakup end' distribution (see Figure 2) was used for model setup and calibration. The reader is referred to Lindenschmidt (2017a) for a model analysis using the 'instantaneous ice jam maximum' distribution. The 'freeze-up start' distribution is shifted for the input of the downstream water level elevation boundary condition, which is situated approximately 21 km downstream of the Athabasca River gauge.

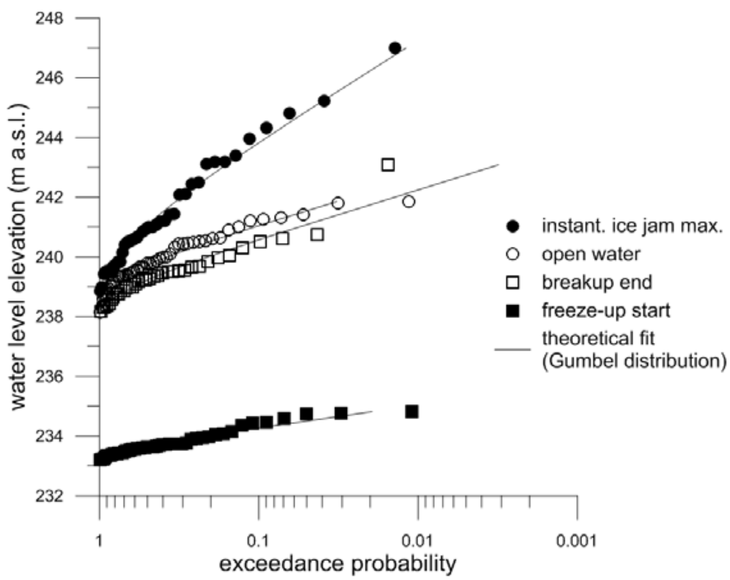

Figure 2. Stage frequency distributions from the values recorded at Gauge 07DA001 – Athabasca River below Fort McMurray (source: http://wateroffice.ec.gc.ca)

The flood frequency distributions of the flows at the end of the breakup period were also required for the model setup. The flow distribution from the Athabasca River gauge was used for the upstream boundary condition of the model, which is assumed to be the summation of the flows upstream of the bridges and the Clearwater River flows.

The amphibex would typically be utilised before the onset of ice cover breakup. Flow frequency distributions 10, 20 and 30 days prior to the completion of the breakup period were derived from flows recorded 10, 20 and 30 days before the last B-value of each year (see Figure 3). It must be noted that there is a degree of uncertainty in such flow values due to the poor relationship between water levels and flows under ice. Field surveys are regularly carried out by Environment Canada personnel to measure the actual flow under the ice cover near the Athabasca River gauge. Such field measurements are used to shift the rating curve to provide better estimates of winter flows. The distributions for flow at the end of breakup and 10, 20 and 30 days before are provided for the upstream boundary condition (discharges) in Figure 3. Values from these distributions were extracted randomly to serve as boundary conditions in the Monte-Carlo analysis. The same

[1] B-values that accompany the daily flow readings. A "B" (for backwater) is marked beside a flow recording if the discharge was influenced by backwater effects from ice covering the river at or immediately downstream of the gauge. The flow with the first B-value of a winter season marks the beginning of the river's freeze-up, the flow with the last B-value at the end of winter indicates the end of the breakup period

probability distribution of the downstream water level boundary condition was used for all Monte-Carlo runs. The resulting ensemble of backwater level elevation profiles providing stages from which stage frequency distributions could be derived for any chainage along the river.

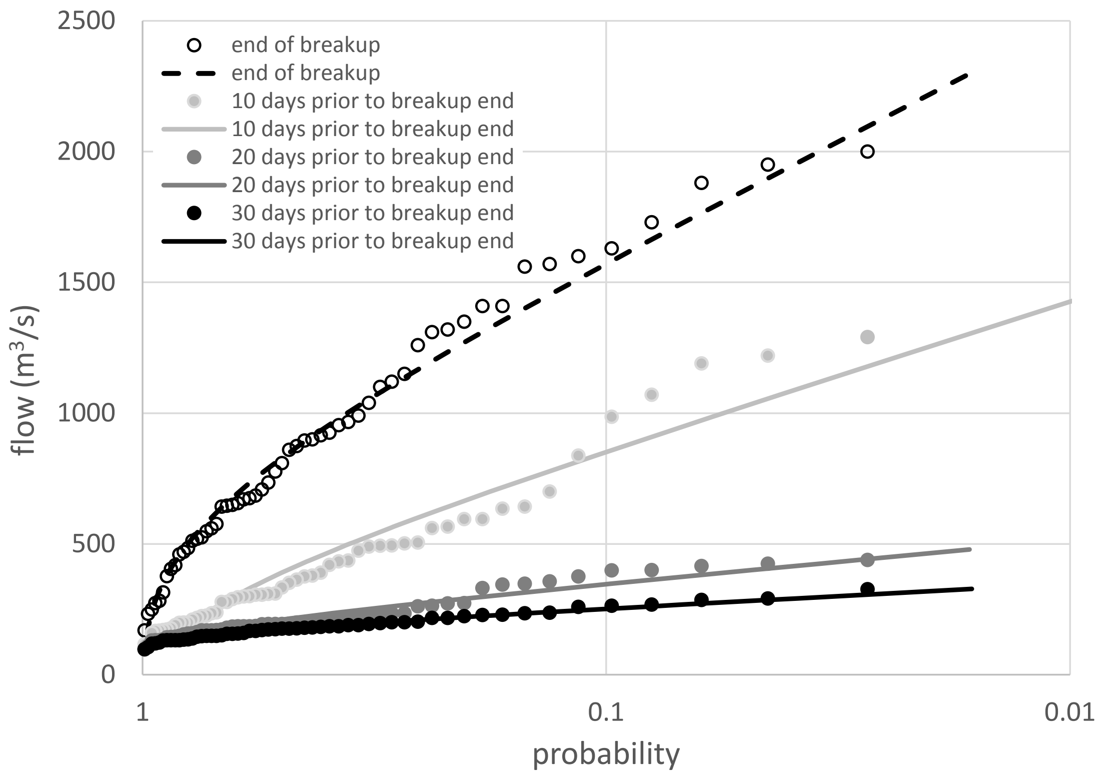

Figure 3. Flow frequency distributions of the upstream model boundary.

3. Model description

The key river ice processes implemented in RIVICE that are relevant to this study are shown in Figure 4 and described below. More detailed information on the model can be drawn from the RIVICE manual at http://giws.usask.ca/rivice/Manual/RIVICE_Manual_2013-01-11.pdf.

In this study, only the potential formation of an ice jam by rubble ice broken apart from an ice cover will be considered, not frazil ice generated jams. The volume of inflowing ice per time step represents the ice blocks and rubble broken apart from upstream ice sheets. This ice floats along the water surface at mean flow velocity of the river until it reaches the ice cover's leading edge. Once the ice reaches the leading edge, two processes are at hand for the progression of the ice cover:

Shoving of the ice cover in the downstream direction by the telescoping of the ice to thicken the already existing ice cover further downstream. Shoving occurs when the balance of external forces on the cover:

+ F_T (thrust of the flowing water against the leading edge),
+ F_W (component of ice weight in the sloping direction),
+ F_D (drag on the ice cover's underside by the flowing water),

– F_F (friction force between the ice and the river bank)
exceeds the ice cover's internal resistance F_I to the external forces ($F_I < F_T + F_W + F_D – F_F$). The thickness of the generated ice cover contributes much to the internal resistance. Shoving continues until $F_I > F_T + F_W + F_D – F_F$. Cohesion of the ice to the river banks was not incorporated in the model since little re-freezing of the ice cover to the banks is expected at the end of the winter season.

Juxtapositioning of the ice cover occurs when the internal resistance within the cover F_I remains larger than the balance of the external forces ($F_I > F_T + F_W + F_D – F_F$) and the ice blocks accumulate at the leading edge to stack up against each other and extend the ice cover upstream. As more and more ice accumulates, external forcing anywhere along the juxtapositioned ice cover may be large enough to again collapse and shove the ice at the ice cover front.

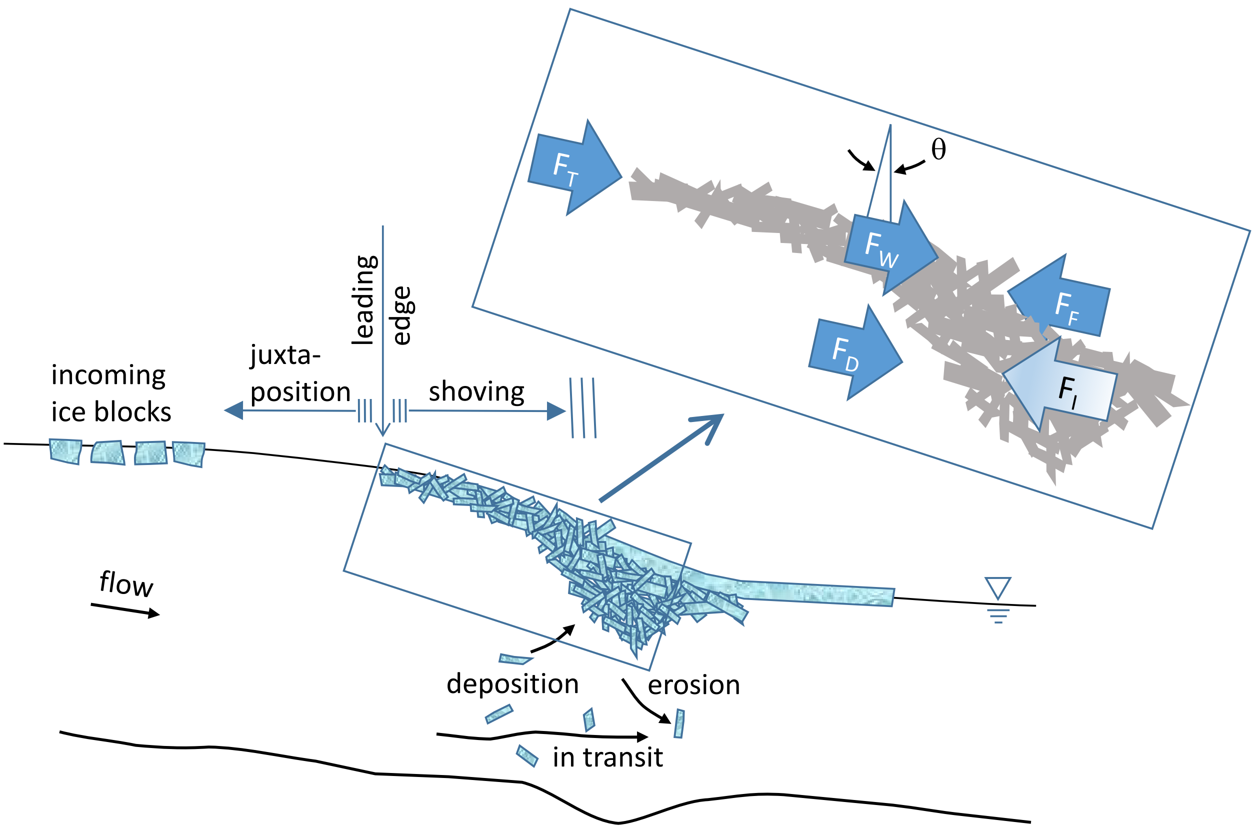

Figure 4. River ice processes mimicked in RIVICE

Ice under the ice cover may be eroded and transported downstream as ice in-transit, if the mean flow velocities underneath the ice cover exceed a threshold value v_{erode}. Should the mean flow velocity drop to below another velocity threshold $v_{deposit}$, the ice will deposit on the ice cover underside. Roughness of the river bed and the underside of the ice cover are important parameters controlling the hydraulics of the flow and ice regimes. Bed roughness is a constant value represented by Manning's coefficient, while the ice cover roughness is a function of ice cover thickness. Important boundary conditions are the upstream discharge of the water entering the modelled stretch of the river and the downstream water level elevation where the water exits the stretch.

4. Stochastic modelling framework

The following methodology of calibrating, validating and simulating scenarios using flood and stage distributions within a Monte-Carlo framework is a novel method developed and published by the author, e.g. Lindenschmidt et al. (2015, 2016), Lindenschmidt (2017a) and Das, Rokaya and Lindenschmidt (in prep). Figure 5 depicts this Monte-Carlo analysis methodology. At the top of the figure are histograms representing probability frequency distributions of the boundary conditions: upstream inflow $Q_{u/s}$, downstream water level elevation $W_{d/s}$, location of the ice cover front x and the inflowing volume of rubble ice reaching the ice cover front V_{ice}. The first two stem from Gumbel extreme value distributions and the latter two from uniform distributions. Parameter values (not shown) are also extracted from uniform distributions. Many model runs are executed with parameter and boundary condition values extracted randomly from the probability frequency distributions. Many simulations produce an ensemble of backwater level profiles, shown in the middle area of Figure 5. The water level elevations at the chainage of the flow gauge are extracted from each profile to form a cumulative Gumbel distribution of the stage frequencies, shown at the bottom of Figure 5. This distribution can be compared to the stage frequency distribution derived from observed values, for example, the stages at the end of the natural ice cover breakup period (last B-value at the end of each winter season). If the simulated and observed stage frequency distributions do not coincide, the histograms of the input parameters and boundary conditions are adjusted and multiple simulations are again carried out within the Monte-Carlo framework. This process is repeated until there is reasonable agreement between the resulting simulated and observed stage frequency distributions. Once this point has been reached, the model is considered calibrated and scenarios can be run to mimic artificial breakup.

For the calibration, at the end of the breakup period, the incoming volume of ice V_{ice} is assumed to be negligible (= 0). This is a reasonable assumption since the last B-value is the last day on which staging is still influenced by ice cover effects. After this point, any ice that flows past the gauge is free-floating and free-flowing, with no ice accumulation immediately downstream to cause backwater effects noticeable at the gauge. During artificial breakup, within the month prior to the end of the breakup period, when the amphibex is in operation, the inflowing volume of ice corresponds to the volume of ice that can theoretically be broken up between the bridges and the location of the downstream ice cover front. The frequency of this volume of ice is assumed to follow a uniform distribution and is a function of the ice front locations where an ice jam could form ($x \rightarrow$ uniform distribution), the ice thickness ($h \rightarrow$ uniform distribution) and the river width (known value at each location along the river).

5. Stochastic modelling setup

The calibrated and validated model for the Athabasca River by Lindenschmidt (2017b) was used as the basis for the stochastic modelling in this study. Figure 6 shows a longitudinal profile of the 1979 ice jam with good agreement between simulated and observed (high water marks) backwater elevation profiles.

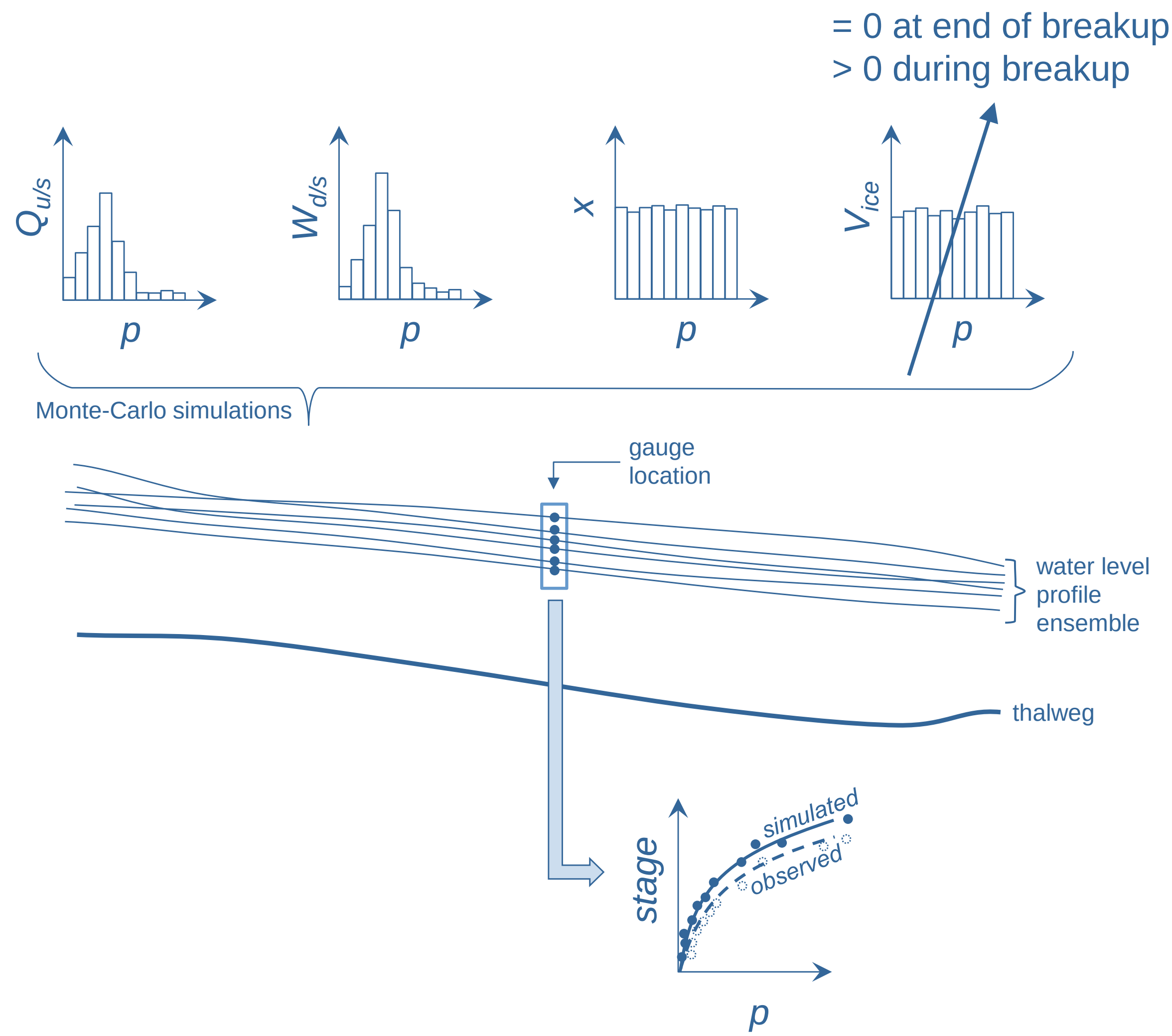

Figure 5. Conceptualisation of Monte-Carlo analysis methodology

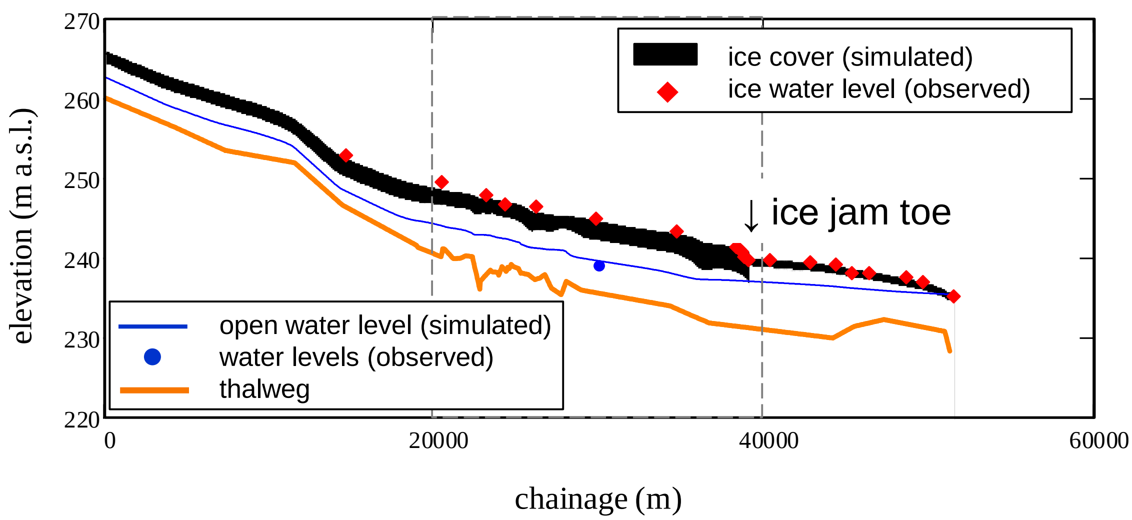

Figure 6. Longitudinal profile of simulated and observed maximum ice water levels elevations for the 1979 jam (source: Lindenschmidt, 2017b)

The calibrated/validated RIVICE was embedded within the Monte-Carlo framework to carry out repetitive simulations automatically, with each simulation having a different set of parameter and boundary condition values randomly chosen from probability distributions. Most parameter values were chosen from uniform distributions between ranges typically observed from other studies. End-of-winter ice thicknesses h were also drawn from a uniform distribution within a range of a 95% confidence band established from a correlation between ice thicknesses and the square root of the cumulative degree days of freezing (CDDF) corresponding to those days that the ice thicknesses were measured, as shown in Figure 7, and calculated using the Stefan's equation:

$$h = \alpha\sqrt{CDDF} + b$$

The slope α was determined to be 0.01 and the y-intercept $b \approx 0.3$ m (average of 30 cm ice thickness at initial freeze-up). The range of ice thicknesses was taken to be between 0.72 and 0.82 m, which corresponds to a CDDF of 2500 °C. Most CDDF values at the end of March were below 2500 °C between 1996 and 2016, as indicated by the histogram in Figure 8.

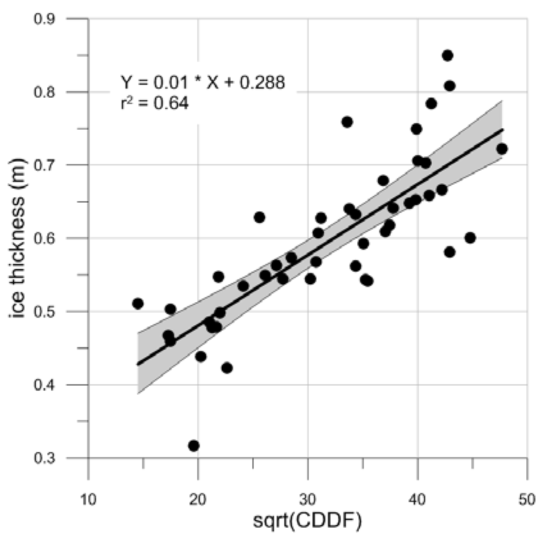

Figure 7. Relationship between average ice thickness and the square root of cumulative degree days of freezing at the Athabasca River gauge below Fort McMurray (source: Water Survey of Canada).

A Gumbel distribution was fitted to the Athabasca River gauge flows and used as the upstream flow boundary condition at breakup (characterised by the last B-value in the daily flow data of each winter). The distribution of all downstream water level elevation boundary condition values (extrapolated along the river slope from the Athabasca River gauge) at freeze-up (characterised by the first B-value in the daily flow data of each winter) could also be characterised by a Gumbel distribution. The location of the ice jam toe was chosen randomly from a uniform distribution at locations between the bridges and the downstream model boundary, an approximately 25 km stretch. The Monte-Carlo Analysis was first run for end-of-winter conditions without any inflowing ice volume, to test if the distributions chosen for the model parameters and boundary conditions yielded agreement between the simulated and observed stage frequency distributions at the Athabasca River gauge. The stochastic modelling was considered calibrated when the observed stage frequency distribution from the gauge values coincided with the distribution established from the stages extracted from the ensemble of simulated backwater profiles at the same gauge chainage.

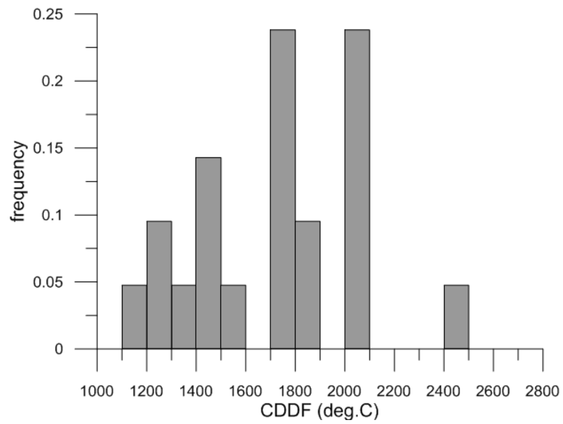

Figure 8. Histogram of cumulative degree days of freezing (CDDF) on 31 March for the years 1996 to 2016 (source of air temperature data: Environment Canada).

Additional assumptions for the model setup include:

(i) All of the ice extending across the river width is broken up by the amphibex.
(ii) All of the rubble ice broken up by the amphibex does not melt during the breakup period. An energy balance model would need to be applied to determine the rate of melting, which is outside the scope of this work.
(iii) The area artificially broken up does not refreeze to form a frozen solid ice-rubble cover. This may happen naturally, though, should an extreme cold weather period occur after the amphibex has completed its breakup operations. Some areas of the refrozen cover may also be thicker and rougher than the original winter ice cover prior to breakage, which may pose additional resistance to ice flow during natural breakup and promote jamming more extreme than during a natural breakup event.

6. Results and Discussion

An ensemble of 36 backwater level profiles for the end-of-breakup case is shown in Figure 9. The values from the Athabasca River gauge location were extracted to construct the simulated stage frequency distribution in Figure 10. This distribution was compared with the observed stages recorded at the end of the ice season, also shown as the ‘breakup end’ distribution in Figure 2. There is good agreement between the two distributions, as shown in Figure 10, indicating a successful calibration of the stochastic modelling system.

Figure 11 shows the simulated distributions (solid lines) of the stages extracted from the backwater level profiles obtained from the Monte-Carlo runs using upstream flows 10, 20 and 30 days before the last B-value of each winter season as the upstream boundary condition distribution. The ‘breakup end’ distribution is also included for each scenario to compare the severity to the natural breakup event. In these scenarios, not only all of the ice between the bridges and the Athabasca River gauge (7 km stretch) is assumed to have been broken up; the scenarios also incorporate the possibility of the broken up ice running further downstream to break up the intact ice cover downstream of the gauge location, as observed in the past under natural conditions. All this ice has the potential to jam and cause backwater staging. Hence, for each simulation, the location of the jam is randomly selected between the gauge location and the downstream boundary condition.

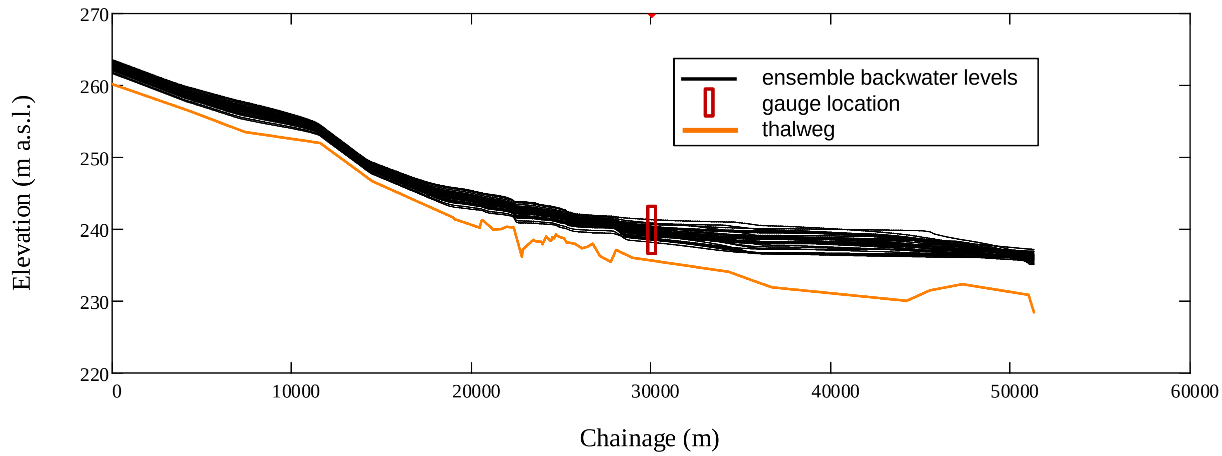

Figure 9. Ensemble of backwater level profiles for the end-of-breakup simulations. Stages from the gauge location were extracted to construct the simulated stage frequency distribution in Figure 10.

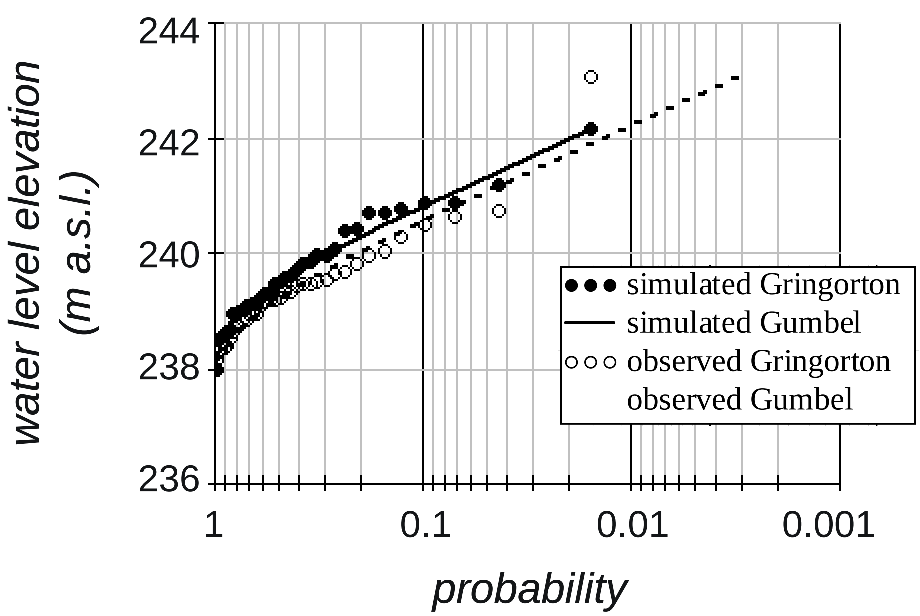

Figure 10. Calibrated stochastic model showing good agreement between simulated and observed stage frequency distributions at the end of breakup (last B-values at the end of the winter season). Values for the simulated stage frequency distribution were extracted from the ensemble of backwater level profiles in Figure 9. The observed stage frequency distribution is the same as the 'breakup end' distribution in Figure 2.

The graphs in Figure 11 show that, for more than 20 days before the end of the breakup period (dates of last B-value minus 20 and 30 days), the staging has the same or less severity as the natural end-of-breakup conditions. This is due to the low discharges occurring during this time despite the rubble ice volume available for jamming. For higher discharges, such as those 10 days before the breakup end dates, the rubble ice can cause more severe jamming than during the natural conditions at the end of the breakup period. Although artificial breakup well in advance of the end-of-breakup date (> 20 days) does not increase the severity of the natural jam staging, the increasing discharge throughout the breakup period could result in higher jamming severity, as if the amphibex was implemented 10 days before the breakup period is finished (this is assuming that none of the rubble ice that was artificially broken has melted to reduce the volume of ice available for jamming).

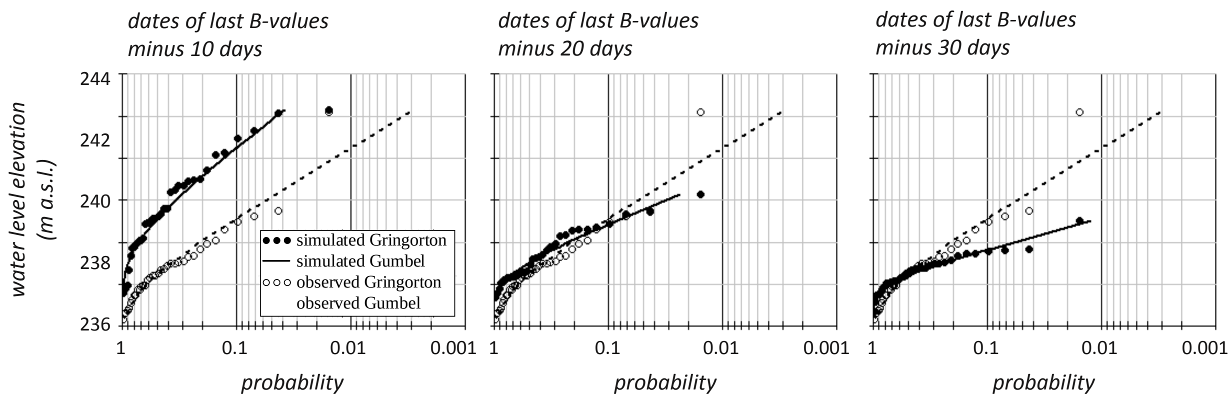

Figure 11. Comparison of simulated stage frequency distributions for artificial breakup using flows 10 (left panel), 20 (middle panel) and 30 (right panel) days before the end of the breakup period as upstream boundary condition distributions. The observed 'breakup end' stage frequency distributions from Figure 2 are provided for comparison.

A scenario was also run to see the effects of just the ice cover broken up between the bridges and immediately downstream of the WWTP on the staging at the bridges. The rubble ice would only jam at the ice cover front situated just downstream of the WWTP. The stage frequency distributions for the river section immediately downstream of the bridges, which has a slightly greater mean slope than further downstream by the WWTP, are shown in Figure 12. The curves indicate that staging could exceed those of the natural breakup event for artificial breakup of the ice cover, 10 days prior to the end of the breakup period, albeit only for the regime with return periods less than 15 years ($p > 0.07$). Hence, if the right conditions prevail, artificial breakup could be efficient to reduce the severity of ice jams and associated floods. Backwater staging from artificial ice cover breakage may be different in reaches that have a different mean slope. However, more study is need to see how backwater staging would react to artificial breakage on river reaches of different mean slope. Also, strategic breakage along certain corridors with widths less than the total river width would reduce the amount of rubble ice supplying the downstream jam.

Figure 13 provides stage frequency distributions at and 10 days prior to the end of the breakup period (dates of the last B-values in the flow record) at the lumberyard situated 16 flow km downstream of the bridges (see Figure 1 for location). The theoretical distribution for the 'breakup end minus 10 days' curve is slightly below the 'breakup end' curve, although some of the plotting positions of the former are higher in elevation than those of the latter for return periods more than 10 years ($p < 0.1$). This may be due to the increased jamming and backwater staging upstream of this area when artificial breakup of the ice cover is pursued. The theoretical distributions show that the flood threshold of 240 m a.s.l. is exceeded for return periods of T = 15 years ($p < 0.067$) for the natural breakup process and T = 22 years ($p < 0.045$) when the ice cover downstream of the bridges is broken up.

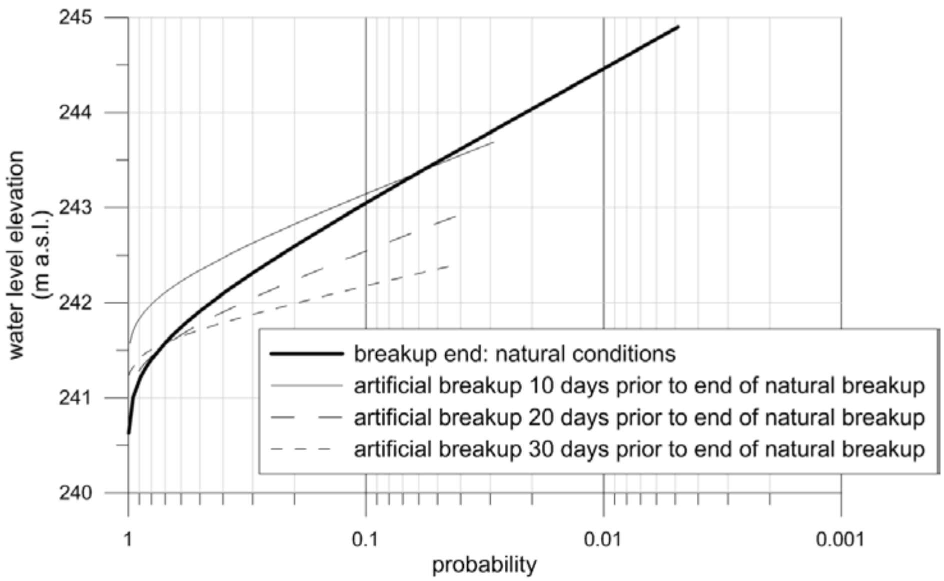

Figure 12. Simulated stage frequency distributions just downstream of the bridges due to ice jamming from rubble ice artificially broken up from the ice cover between the bridges and just downstream of the WWTP.

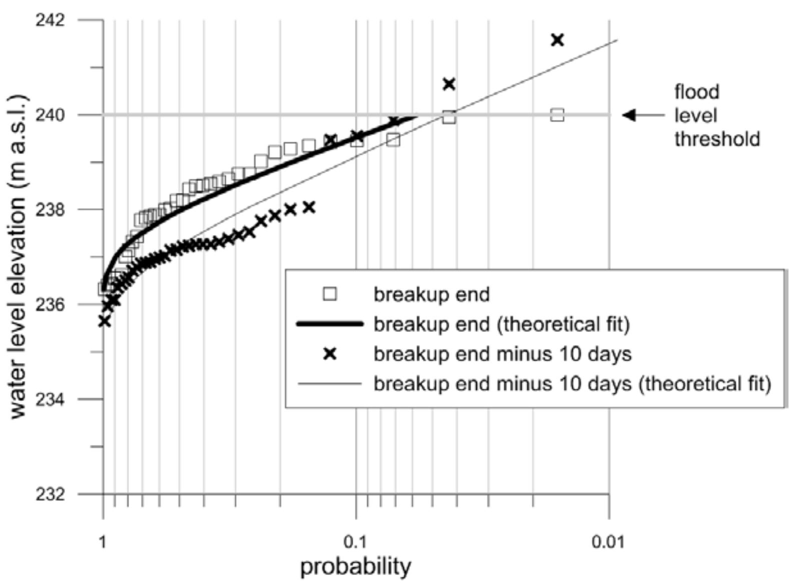

Figure 13. Simulated stage distributions at the lumberyard at and 10 days before the end of breakup as indicated by the date of the last B-value in the flow record.

7. Conclusions and Recommendations

There is a high possibility that artificial breakage of the ice cover along the Athabasca River downstream of the bridges at Fort McMurray could increase the severity of ice jamming and subsequent backwater staging beyond levels experienced through natural breakup events. At this stage of the analysis the results indicated that artificial breakup along the studied reach could aggravate ice jamming and increase subsequent staging. This may be an artefact of the particular geomorphological conditions of the reach. Other reaches of different slope may be more conducive to the implementation of the amphibex as an ice jam flood mitigation approach, which would require their own separate analyses like the one carried out here. A subsequent study is also required to determine the impact of the backwater staging on the flood hazard of Fort McMurray alongside Clearwater River. Hence, at this point of the study, it is not recommended to implement the amphibex for artificial breakup of the ice cover along this particular reach of the Athabasca River. Additional modelling, including in-situ melting, should be accomplished in order to confirm or infirm this recommendation.

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