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Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/40000413
Technical Report (National Research Council of Canada. Ocean, Coastal and River Engineering), 2018-03-22

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TECHNICAL REPORT
OCRE-TR-2018-007

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Ocean, Coastal and River Engineering

A Brief Review of the Numerical Modelling of Ice Jam Flooding and Studies Relevant to Coastal Communities of Ontario’s Far North

Technical Report – UNCLASSIFIED

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National Research Council Canada
Ottawa, Ontario

23 March 2018

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Report Documentation Form

NRC·CNRC Ocean, Coastal and River Engineering – Génie océanique côtier et fluvial

Document Details

Report Number OCRE-TR-2018-007	**Project Number** A1_0082_63	
Program Ocean, Coastal and River Engineering	**Security Classification** UNCLASSIFIED	**Distribution** Unlimited
Title (and/or other title) A Brief Review of the Numerical Modelling of Ice Jam Flooding and Studies Relevant to Coastal Communities of Ontario's Far North		
Author(s) – Please specify if necessary, corporate author(s) and non-NRC author(s) Hossein Babaei		
Client(s) Ontario's Ministry of Natural Resources and Forestry	**Publication Type** Technical Report	**Language** English
Keywords (5 maximum) Ice-jam Flooding, Modelling, Data Needs, Ontario's Far North, Historical Events, Past Studies	**Pages** v, 18	**Confidentiality Period**

Document Version Control

Date	REV#	Description	Prepared by	Checked by	Approved by
03/23/2018	1	Final draft report	H. Babaei	M. Johnston	

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Executive Summary

Coastal communities of Ontario’s Far North located near the shores of James and Hudson Bay are prone to ice jam flooding. The ability to forecast flooding is required for effective and optimized emergency planning and the reduction of threats and costs. The present report is a brief review of numerical modelling approaches, available tools, required data and supporting technologies and methods for the development of modelling and forecasting tools. The report also provides a summary of available studies about numerical modelling of ice jam flooding concerning Ontario’ Far North based on a review of open literature. The report also provides recommendations for the Surface Water Monitoring Centre of Ontario Ministry of Natural Resources and Forestry on next steps towards developing such model and forecast tool developments.

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Acknowledgments

Hossein Babaei thanks his colleague, Richard Burcher for checking RADARSAT-1 and -2 data availability and coverage for Ontario’s Far North.

1 Introduction

An ice jam is the stationary accumulation of fragmented river ice cover or frazil ice along a reach of a river [1]. This accumulation restricts the normal flow of rivers and can lead to the fast and substantial elevation of water levels upstream of the location of the jam. This increase in water level can lead to flooding damage to buildings and infrastructure, and threats to human lives. In extreme conditions when fragmented ice leaves river channels and moves into floodplains, damages and threats could be more significant. Besides flooding which is usually the most concerning threat, ice jams could have other adverse effects including river bed scour caused by an increase in the flow speeds under the jam and weakening of structures under the river bed including pipelines and bridge pier foundations.

Ice jams frequently happen in Canada because of the existence of numerous river systems, and the favorable combination of river discharges and morphology and extremely cold weather, which generate large river ice extent and thickness. Whether the frequency and severity of ice jam flooding is expected to rise in Canada is debatable and an active field of research. A study found that increased mid-winter break-up events and larger freshet flows in certain parts of Canada could increase the frequency and severity of ice jams [2].

Many First Nation majority communities of Ontario's Far North (OFN) have experienced extreme difficulties, damages and/or loss of life because of ice jam flooding in the recent past [3]. Historically, the most vulnerable communities are located in remote locations at the mouth of five major OFN rivers (Severn, Winisk, Attawapiskat, Albany and Moose Rivers) in Ontario's James and Hudson Bay coastal regions. These regions are the home of seven communities with total approximate population of over 10,000 people[1]. These communities are Fort Severn, Peawanuck, Attawapiskat, Kashechewan, Fort Albany, Moosonee and Moose Factory, as shown in Figure 1.

Ministry of Natural Resources and Forestry of Ontario (MNRF) with other federal and provincial governing entities have been taking measures for prediction and mitigation of, protection against, and timely response to ice jam flooding in OFN. Particularly, the Surface Water Monitoring Centre (SWMC) of MNRF has an ongoing project to create hydrologic data products and web-based communication tools to integrate satellite-derived data products, First Nations traditional knowledge and hydrometric and other data to support emergency management in the region. Among different types of riverine flooding, the most concerning type for the coastal communities mentioned above is spring break-up ice jam flooding[2]. A critical question that needs to be answered is whether and when a spring break-up ice jam will cause flooding and how significant the flooding will be. This is essential for emergency preparedness and planning for evacuation of the communities most of which are not accessible by ground transportation.

The main purpose of the present report is to provide a brief review of available ice jam forecasting and modelling approaches and tools, data needs, and other technologies that support forecasting

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[1] Mainly based on census 2016.

[2] Personal communication with Andy Beaton with the SWMC.

Figure 1: Northern Ontario and its main coastal communities. The vertical extent of the map is approximately equal to 550 km on the ground.

and modelling. Additionally, the report briefly reviews available studies on modelling of ice jams pertinent to the five major rivers in the vicinity of their coastal communities. The content of the report is as follows: Section 2 provides a review of modelling approaches for the estimation of the evolution of ice jams and their impact on water levels and materialization of flooding. The section also reviews available tools for modelling and their input data needs and cites a few previous studies conducted by some of available tools and approaches. Section 3 reviews past studies relevant to the numerical modelling of ice jam flooding of OFN coastal communities based on a review of open literature. It also provides a brief history of ice jam flooding events in the region. The report ends with section 4 which provides general recommendation for the SWMC for their future ice jam flood model/forecast developments. The general topics that this report covers were selected based on communications with the SWMC of MNRF. The author would like to emphasize that the present report is not a comprehensive review of any of the topics that it covers. The report is meant to be a starting point for future efforts for modelling and forecasting tool developments and data collection planning pertaining to ice jam flooding of Ontario's Far North coastal communities.

2 A Review of Approaches and Tools for the Numerical Modelling of Ice Jams

We start this section with a brief introduction of some river ice and ice jam processes and terminologies.

As defined earlier, an ice jam is a stationary accumulation of fragmented or frazil ice over a reach of a river that limits the flow of the river. Ice jams can materialize at different times of the year, when reaches of rivers are substantially ice covered: Early in cold seasons during freeze-up, or at the end of the cold season during break-up, and sometimes in the middle of the cold season usually after a warm period accompanied by rain[3]. The break-up ice jam flooding events are generally more common because there is more and thicker ice at the end of the season to restrict flows which are generally higher during the break-up season. Break-up ice jams are mainly caused by the restriction of the motion of ice floating downstream of rivers. This restriction could be caused by downstream intact river ice, islands or structures including bridge piers and encouraged by sudden reduction in river slope or flow speed or a sudden increase in the curvature of the river [4]. Although the potential location of ice jams over a river could be identified based on reviewing and studying history of ice jams over a certain reach of a river, river morphology and the distribution of structures along the reach, forecasting the location and extent of ice jams and its release time are still a knowledge gap [5]. Ice jams could be also categorized as wide or narrow jams. Narrow ice jams, also referred to as hydraulically thickened jams, are formed by simple rotation, turning, submergence and entrainment of fragmented ice arrested at the upstream edge of the jam. Wide ice jams however are generated by the consolidation and shoving of fragmented ice into a floating rubble ice [6]. Wide jams are more common, thicker and rougher than narrow jams and more strongly obstruct river flows compared with narrow jams. An ice jam can have both narrow and wide regions. Figure 2 shows an artistic rendering of a mainly wide break-up ice jam.

2.1 Physics-based Modelling

Physics-based modelling in the present context refers to the modelling that considers physics and mechanics of ice and river flows in the estimation of ice deformation, pile-up and water surface elevation changes caused by ice jams. Estimated water levels can be subsequently compared with the flooding threshold values to know whether flooding is expected. Such modelling could be analytical or numerical (computational). Analytical modelling is generally limited to simple conditions. For example the water depth, H, at the existence of a wide break-up ice jam is analytically estimated to be [7]:

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[3] A recent example of this mid-winter ice jam is the jam and associated flooding of the town of Brantford, On., on 21 Feb. 2018: http://www.cbc.ca/news/canada/hamilton/brantford-flooding-1.4544791, retrieved on 21 Feb. 2018.

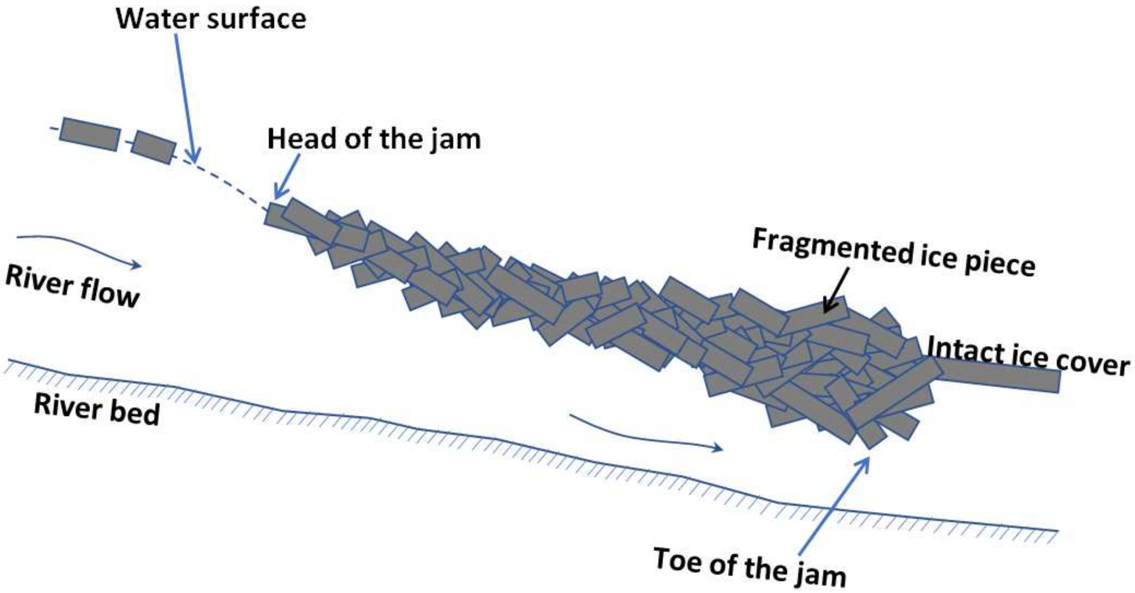

Figure 2: An artistic rendering of side view of a mainly wide break-up ice jam.

$$\frac{H}{S_0B} \approx 0.96\Big(\frac{(\frac{q^2}{gS_0})^{\frac{1}{3}}}{S_0B}\Big)^{0.82} + 4.79\Big(1+\sqrt{1+0.22\Big(\frac{(\frac{q^2}{gS_0})^{\frac{1}{3}}}{S_0B}\Big)^{0.82}}\Big)$$

in which S_0, B, q, and g are respectively river slope, channel width under the jam, river flow per unit width of the river, and gravitational acceleration. The above equation provides a reasonable estimate of the water depth when the condition is steady state (not changing with time) and channel section, slope, ice jam thickness and flow are uniform (the flow is not a function of location), and the ice jam is cohesionless (the forces between ice fragments is solely friction) [8]. As one can expect, such combination of conditions are not commonly found in reality. The real condition could be unsteady and the ice jam thickness can be variable leading to non-uniform flows and violating the assumptions for the validity of the above equation. The above equation has probably limited or no application for ice jams of OFN rivers in the vicinity of their coastal communities because of flow and geometrical complexities. Note that the water depth calculated based on the above equation is the maximum possible water depth that could be caused by an ice jam, i.e., observed values will be equal or smaller than this value depending on the amount of available ice for jamming. For cases when the river morphology, flow and the jam condition are not simple, more sophisticated models are needed to include relevant physics. Forces that act on ice jams include forces exerted by the flow including drag (acting on the underside of the jam) and thrust (acting on the head of the jam by incoming flow), by wind which drags the top surface of the flow, by gravity, and by river banks. These external forces create stresses in the ice jam. For an evolving jam, either thickening or failing, the internal and external forces are not balanced. This unbalance continues until and if the ice jam rearranges to another stable configuration. Several models are available to estimate the ice jam profile and water surface elevation changes by approximating external and internal forces and the deformation of the ice jam. Explaining the underlying equations and solution procedure of such models are out of scope of the present report and we only focus on introducing some of the well known models, their input and calibration data needs and applicability:

2.1.1 A Brief Review of Available Models

Three of the well-known public domain ice jam models are RIVJAM [9, 10], ICEJAM [11], and HEC-RAS [12] which are mainly based on the same ice jam stability criterion in which the ice jam thickness evolves to reach a profile to withstand gravity and flow-induced shear forces. These three models are one-dimensional steady state, wide-channel ice jam models and have been successfully applied to calculate ice surface and bottom profiles as well as water levels subject to ice jams in several previous studies including ice jam studies of Peace–Athabasca delta [13] by RIVJAM, Yukon River [14] by ICEJAM, and St. John River [5] by HEC-RAS, to name a few. Available ice jams models are not limited to the three aforementioned models. Other well known public domain models are steady state one-dimensional RIVER1D [15], and RIVICE [16] (the latter being open-source), which have been successfully employed for studying ice jams including RIVICE study of Lower Red River [17]. There are also commercial ice jam models including one-dimensional steady state ICESIM/ICEPRO [18] and MIKE 11 (MIKE-ICE) [19] models. To the knowledge of the author of the present report, most of the above models are fundamentally the same or have close similarities although some models consider more detailed aspects of ice jam formation and processes than others. For example, RIVJAM includes flow seepage through ice jams which enables the model to allow ice jam grounding. Readers are suggested to read the corresponding citations for an in-depth understanding of the model details and differences.

Applicability of steady state models named in the above paragraph are restricted to ice jams that reach the steady state conditions and to estimate the maximum possible water surface elevations that a certain jam can create since the water levels associated with unsteady ice jams are generally lower. One-dimensional models are on the other hand applicable to simpler flow conditions produced by river morphologies which are not complex. For many real ice jam conditions, steady state and one dimensional assumptions can still produce useful and reasonable results, as given by a few citations in the above paragraph.

In the case of two-dimensional flow conditions, caused by morphological complexity, and/or the need for unsteady analysis, the propitiatory CRISSP2D model can be employed [20]. One example of a previous application of the model includes river ice jam modelling of Hay River [21].

A comprehensive study has been conducted [22] to compare the performance of several different models for the estimation of ice jam thickness and water levels. Different test cases in terms of level of complexity and calibration data availability were designed for the evaluation of models.

Participating models include all of the above models excluding the RIVEICE model, although not all models participated in all the test cases. Model results were compared with each other and with observations. The general conclusion was that for the simple test case, model results were very similar. So were the results for a test associated with a real ice jam event when enough input and calibration data were available. However, when the required input and calibration data were not available/enough and hence the modelling procedure had to be based on the judgment of the modeller, computed water levels were slightly different. This difference in water level could be up to 0.5 m [23].

Ice jam models mentioned above are the most well-known/used/validated models. However, several other ice jam models exist. An example of a recently developed model is the fully coupled (flow and ice dynamics) ice jam model built on the public-domain and open-source Delft3D hydrodynamics toolbox. This two-dimensional unsteady model has been tested for Thames River in Ontario [24, 25]. All of the models mentioned so far are based on the continuum assumption for ice with different levels of complexity for the representation of granular behavior of ice. We end this subsection with mentioning the existence of ice jam models which treat ice as discrete elements (and not as continuum) and resolve contact and body forces acting on thousands of discrete ice elements (floes) to calculate motion and pile-up of floes [26]. As a general rule, as the complexity of an ice jam model increases, the number and duration of calculations increase and leads to longer computational time. This needs to be considered in the model selection, particularly when an operational ice jam flood forecasting tool is to be developed, which needs short computational times for producing timely forecasts.

2.1.2 General Data Needs

Essential data needs for simulating ice jams are as follows:

- **Hydrometric data:** Discharge and water level data are required at boundaries of the numerical domain over which the ice jam and its impact on the water level is computed. This data is usually discharge at the upstream boundary and water level at the downstream boundary. The existence of such data can be a criterion for the selection of domain extent. In the absence of upstream discharge data in the close upstream vicinity of the ice jam, hydrology can assist. This could be as basic as using the first far upstream gauge station data and add an estimated flow value contributed by the watershed/basin between the gauge and the upstream location of the computational domain. Alternatively, the discharge data can be provided by hydrological models developed and calibrated for the watershed/basin of interest. Data collected by, and/or based on hydrometric gauges at locations where highly concentrated and/or deformed ice exist are probably inaccurate and need to be considered as rough estimates. This is because of the fact that the rating curves, relating stage to discharge values, are prepared for open-water conditions. For locations where the river is covered with intact ice cover however, some approximations exist to reasonably correlate stage to realistic discharge. Concerning the usually required downstream water level when data are not available, modeller's judgment and assumptions are required.

- **River geometry and morphology data:** River bathymetry and slope are essential for the calculation of flow velocity and its variations, both of which impact water levels and ice jam configuration. If the bathymetry is only measured along river cross-sections (not two-dimensional mapping of the river) there should be enough cross-sectional measurements to realistically represent the bathymetry of the river. If the river bathymetry is highly variable, more cross-sectional measurements are required. If it is operationally and financially possible, it is advised to collect as much bathymetric data as possible. When there is not enough bathymetric data, interpolations along and across the river could be done. This would reduce the reliability of model/forecast results.

  Hydraulic roughness of the river (Manning's n-value) is also needed. This value depends on the river bed material and condition. This value is usually adjusted during model calibration to reasonably estimate ice jam thickness and water levels.

  To know whether an ice jam results in flooding, computed water levels upstream of the jam are to be compared with the elevation of the river bank. River bank elevation data can be retrieved from Digital Elevation Models or by field measurements, if it is practical.

- **Ice-related data:** Since models cannot reliably estimate the location of a jam, they require input information about the jam location. This information is either the location of the head and the toe of the jam, or the location of the toe and the expected total volume of ice available for jamming. A basic calculation method for the estimation of the volume is estimating the aerial extent of the ice upstream of the jam toe and multiplying it by the thickness of (intact) ice sheet. Sheet ice thickness can be calculated by sophisticated models or if not practical or possible, by basic calculations based on the value of cumulative freezing degree-days [27].

  Hydraulic roughness of the underside of the ice is usually needed. This value is usually calibrated to reasonably estimate ice jam thickness and water levels. It is statistically confirmed that the roughness of the underside of the jam is a linear function of the jam thickness [28], and some models including ICEPRO calculate the ice roughness based on this linear relationship. Another usually required ice-related data is ice strength parameters including angle of repose of ice rubble. Additionally, some models require a threshold flow velocity value above which ice cannot be deposited under the jam and is transported under the jam and is removed from computations. The threshold velocity and strength values usually require calibration.

The above data are required to run an ice jam simulation. An essential additional step to numerical modelling of phenomena where the physics is not fully known and/or the contributing (input) factors cannot be fully measured is calibration. Calibration needed for ice jam models is usually done by varying roughness values of the river bed and/or ice, and also ice strength and other parameters until model outputs are satisfactorily consistent with observations. Main outputs of ice jam models are the location of the free surface and underside of the jam and water surface elevation upstream of the jam. Observed counterparts (some or all) of these quantities are needed for the model calibration. It is common to first calibrate the model when ice is absent and/or when the river is only covered with intact ice sheet (if relevant observations exist) to find some of the model parameter including river bed and intact ice sheet roughness before calibrating the model with an observed ice jam. If the calibration data is not enough/available, it is recommended to introduce some level of conservatism in the model input data and results have to be treated with care and considerable judgment.

After the model is calibrated, it is recommended to run the model for another independent well-documented ice jam (if it exists) and evaluate the model performance (model validation).

2.1.3 Supporting Technologies and Methods

This part of the report provides a summary of a technology to provide (parts of) required input data and a method to include and quantify uncertainty in ice jam model results. Two items are highlighted here:

- **Probabilistic/stochastic modelling with a physics-based core:** It is highly probable that values input to ice jam models will be uncertain. These values include, but are not limited to: (1) Discharge, because of uncertainties in results of hydrological models providing runoff values which could be partially caused by uncertainties in precipitation, accumulated snow depth and temperature estimations, (2) Intact ice thickness, because of uncertainties in field measurements or modelling of thermal growth of ice, (3) Incoming ice volume, because of ice thickness uncertainties and/or uncertainties in estimation of upstream ice extents that can mobilize (break off the river banks), and (4) Downstream water level because of uncertain judgment of the modeller. To include uncertainties in ice jam model outputs, modellers can simply run the model with different combination of input values (Monte-Carlo simulation) and evaluate the output and even quantify probability (if the probability of input values are known) of a certain upstream water level to materialize. Monte-Carlo simulation of ice jams is gaining increasing attention in recent past. Two recent examples of such modelling are studies of ice jam flooding of city of Tornio in Finland [29] and Town of Peace River in Alberta [30]. Whether this approach can be used for operational forecasting depends on the number of required runs, the computational time for a single run, and the available computational hardware capacity. The stochastic approach can be taken to establish upper and lower bounds of water levels for a given combination of input variable. Forecast input variables can then be compared with the inputs to the model (when it was run in stochastic mode) and learn whether flooding is expected.
- **Remote sensing:** Information derived from data collected by sensors onboard of satellites are increasingly used for environmental monitoring. In the field of ice jam modelling, satellite-derived data have been used to estimate discharge and extents of ice jam and incoming areal ice extent.

Examples include the estimation of break-up discharge of Mackenzie River by tracking the motion of floating derbies and ice fragments [31], and the estimation of incoming areal ice extent for numerical ice jam studies of Slave River Delta in Northwest Territories [32] and Exploits River in Newfoundland [33]. The limitation of remote sensing technologies for the support of numerical modelling of ice jam depends upon several factors including: (1) The applicability of the technology at the existence of clouds and darkness (radars are not subject to these limitations), (2) Spatial resolution of data (if data is very course it might not resolve the region of interest), (3) Re-visit time which is how frequently a sensor "sees" a certain location (if this is infrequent, an ice jam could form and release without being captured), and (4) The availability of the data for the region of interest, its cost and the time required to receive such data for numerical modelling. The latter is of great importance if the data is to be used for forecasting.

2.2 Non-physics-based Modelling

In the context of river ice flood R&D, the purpose of non-physics-based approach is to relate parameters that influence the materialization of ice jams and/or ice jam flooding to the actual formation of such events. The relationship is not based on physics. It is based on historical data and observations and/or heuristic knowledge of experts or local residents of the flood prone region of interest. As an example, based on some observations it might be believed that extremely cold winters or winters with significant snowfall in the headwater areas have a higher chance of producing a significant downstream ice jam and flooding. Whether a slightly cold winter with a slightly greater than average snowfall will lead to ice jam flooding in the spring is a question that the non-physics based approach could aim to answer. The idea is that the influential parameters are readily available (here in this example, the winter snowfall and mean daily temperatures). A few non-physics based approaches that have been previously used to predict ice jam flooding and break-up are statistical, e.g., multiple linear regression, neural network and fuzzy logic. An example is the application of fuzzy logic approach to predict the maximum break-up water levels of Athabasca River and ice jam induced flooding at Fort McMurray in Alberta using average snow water equivalent, soil moisture content and ice thickness in [34] and accumulated summer precipitation, accumulated freezing degree-days, ice thickness in late January and snow-water equivalent in [35]. Note that the influential parameters could differ from one location to another depending on region-specific hydrological regimes. The models for the Athabasca River can be used to generate long-lead (a couple months prior to break-up) qualitative information about maximum break-up water levels. This information can be used by emergency and water resource managers.

3 Review of Past Ice Jam Flooding Events and Available Numerical Studies

This section briefly reviews major ice-induced flooding events that inundated Ontario's Far North coastal communities and provides a summary of relevant numerical modelling studies found in open literature.

3.1 Past Ice Jam Flooding Events

This subsection is mainly based on the Canadian Disaster Database[4] and a study conducted by MNRF [36] and it does not include all events. The events are listed below according to the relevant community:

- **Fort Severn:** This community is located on the north shore of Severn River approximately 8 km inland from Hudson Bay. Since the community is located 10 m to 15 m above normal river level, flooding of this community has been uncommon. The flooding of the community and its airport located nearby is however, not entirely impossible mainly because of the existence of a large island at the river mouth which is a common ice jam site.
- **Peawanuck:** This community is approximately 30 km inland from Hudson Bay, 10 m to 12 m above normal river level, and located on the north shore of Winisk River. Initial members of this community were inhabitants of the village of Winisk located at the mouth of the River. The village of Winisk was almost entirely swept into Hudson Bay by ice floes carried by ice jam floodwater on 16 May 1986 which killed two people[5]. The flooding of Peawanuck has been infrequent although in May 2015 some parts of the region were inundated because of an ice jam including airport access road. This flooding subsided relatively fast, after which the airport was accessible.
- **Attawapiskat:** Ice jam flooding has been an issue for this community mainly because of its low elevations and narrow river constrictions. Examples of past flooding events include floods of years 1992, 2002, and 2004 when residents were evacuated by air to other communities as a safety measure. Total cost of such evacuations and additional expenses are very high. As an example, the flooding of 2004 cost approximately $5.7 M.
- **Fort Albany and Kashechewan:** These two communities are also highly ice jam flood prone with several occasions of severe inundation of the north (Kashechewan) and south (Fort Albany) shores of Albany River mainly because of low elevations of the communities with respect to normal river level and the existence of several islands which hinder the motion of ice towards James Bay. Years of major ice jam flooding include 2008, 2012, and 2015.

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[4] Canadian Disaster Database, https://www.publicsafety.gc.ca/cnt/rsrcs/cndn-dsstr-dtbs/index-en.aspx, retrieved on 20 March 2018

[5] Flooding events in Canada: Ontario, https://www.canada.ca/en/environment-climate-change/services/water-overview/quantity/floods/events-ontario.htmlcoroner, retrieved on 14 March 2018.

- **Moosonee and Moose Factory Island:** These two communities are located on the floodplains of Moose River at the vicinity of James Bay at elevations varying approximately between 7.5 m to 9 m from normal river level where there are several narrow river constrictions which increase the possibility of ice jam formation. The region was inundated in years 1976, 1985 and May 2013 because of ice-induced flooding. The May 2013 event particularly damaged several properties and infrastructure close to the shores of the river.

3.2 Past Numerical Modelling Studies

An extensive search of the world wide web using Google and Google Scholar search engines was conducted to find studies relevant to the numerical modelling of ice jams and ice jam flooding of Ontario's Far North coastal communities. The result of this search was two studies concerning First Nation communities of Kashechewan and Fort Albany, both of which are on the floodplains of Albany River. A summary of each study follows:

3.2.1 A Physics-based Model for the Flooding of Fort Albany First Nation Community

Grover et al. [37] developed a model to estimate water levels upstream of ice jams in the coastal region of Albany River. Results of the study were to inform the design/extension of dikes for the protection of the community of Fort Albany First Nation against ice-induced floods of different magnitudes (probability of occurrence). Historical observations about past ice jam regimes, flooding events and processes were the basis of the model development and calibration. These information were required for the modelling and calibration of ice jam flooding of complex multi-channel Albany River in the vicinity of the community, shown in Figure 3. The modelling work revealed that the flooding of the community, located on the south of the South Channel, is improbable unless an ice jam exists in the North Channel, which is the path of least resistance when there is an ice jam in the South Channel. The model was hence developed for the condition when there are concurrent ice jams on both North and South Channels. The model work consisted of three main steps. The first step was the calculation of flow splits (proportion of the river flow passing though each channel) in open water and ice covered conditions. This step was performed by the application of Mike 11 computer tool. To model the existence of ice cover, Manning's n-value of the river bed was set to a large value[6]. Results of the ice-covered component of the model were verified by a simplified spreadsheet calculation assuming uniform ice thickness. The second step was modelling of ice jam in the South Channel, with its toe in the close vicinity of Willow Island. This is the usual location of the ice jam toes as the river slope decreases before the river connects to James Bay. RIVJAM model was used for the ice jam modelling and the calculation of upstream water levels. Since multi-channel rivers cannot be directly modelled with RIVJAM, the South Channel was split to a few reaches of constant flow and the ice jam was modelled from the most downstream section towards upstream.

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[6] The ice module of Mike 11 did not exist at the time of the study.

Different sub-models of this study (open water and ice covered conditions) were calibrated with limited high water/ice level data. The final ice jam model was calibrated by the 1985 ice jam high water/ice level data inferred from a field survey of vegetation in the floodplain. Historical discharges of the river were statistically analyzed to calculate different rates-of-returns corresponding to 2, 5, ten, fifty and hundred years. The model was run for each of these upstream discharges and the discharge of year 1985 to calculate the water elevations at the location of dykes. The downstream boundary condition was the James Bay sea level. A sensitivity study revealed insignificance of tides on the high water levels. The third (final) step of the modelling work was the calculation of joint probability of occurrence of discharge and an ice jam based on historical observations and the calculation of stage-frequency curves at the location of dykes.

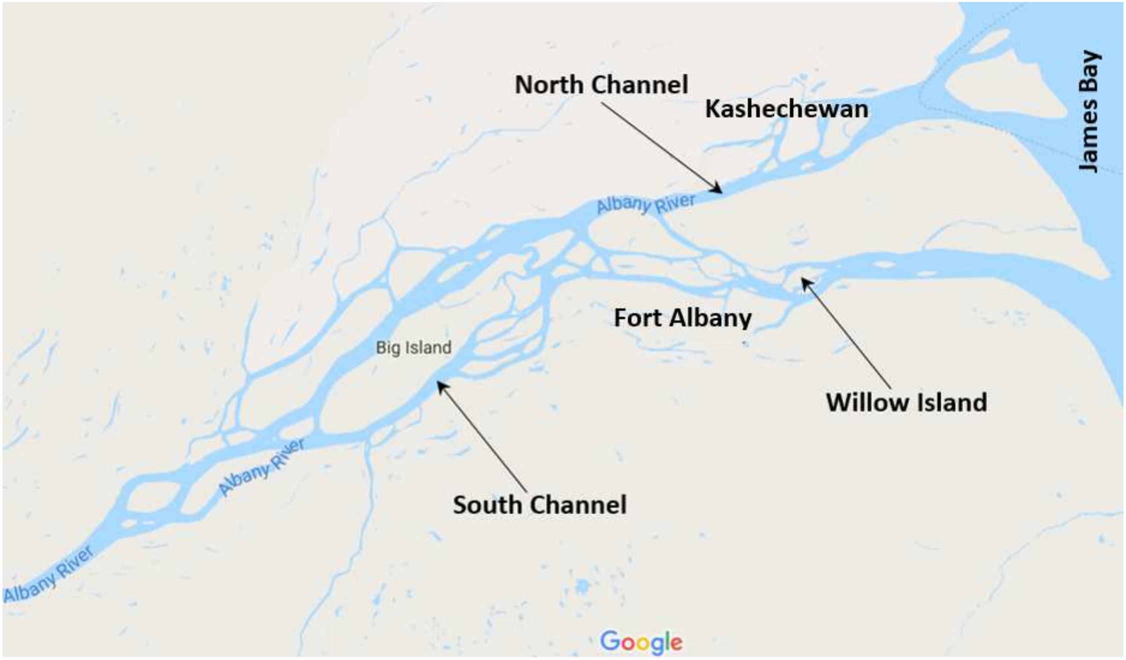

Figure 3: Albany River in the vicinity of First Nation communities of Fort Albany and Kashechewan located close to James Bay. The horizontal extent of the map is approximately 50 km on the ground.

The study does not provide any information about the source and existence of bathymetric data for the modelled reaches of the river. It is possible that no/limited bathymetric data has been available for this study and the river depth has been a calibration parameter. Communications with authors of the publication are required to obtain information concerning bathymetric data for this study. Additionally, as mentioned earlier, the information for the calibration of the final ice jam model was based on a field survey of vegetation and condition for the identification of vegetation type and age and signs of scars caused by ice. Although the ice jam flooding of 1985 has been very severe, other severe ice jam flooding events occurred prior to the flooding of 1985. The study however, does not provide justification on why the vegetation landscape of the floodplains are believed to be formed by the 1985 flood and not by earlier floods. This justification is also needed to be sought by communicating with authors of the publication.

3.2.2 A Non-physics-based Model for the Flooding of Kashechewan First Nation Community

Shaw et al. [38] developed a simple model to provide ice jam flood warnings for the First Nation community of Kashechewan. Historical conditions which led to the ice jam flooding of the community were analyzed and established the basis for the development of the model which provides two warning types: An early warning which is based on the summation of the accumulated rainfall and snowmelt (the latter calculated based on temperature data provided by the weather station at Moosonee located approximately 130 km flying distance from the community) calculated from March 1^{st} of each break-up season. If this value exceeds 150 mm, the probability of ice jam formation and flooding is high. This summation can be calculated using forecast rainfall and snowmelt for several days in advance. The second warning type was named a late warning which is based on the Albany River discharge and its rate of increase, both calculated based on the Water Survey of Canada gauge data collected near Hat Island located approximately 200 km river distance upstream of the community. A discharge of 4750 m^3/s and its increase rate of 700 $m^3/s/day$ are two threshold values over which the probability of flooding is deemed high. Flows more than the threshold value are required to flood the community when an ice jam is in place and flow increase rates more than the threshold value are required to break the bonds between the ice and land and mobilize ice to potentially form ice jams and flooding. Since historically no ice jam flooding has happened after April 28[8], the model does not output flood warning even if any of the above values exceed threshold values. The model has been implemented in Microsoft®Excel which visualized time-series related to each of the warning types mentioned above.

The performance of the model was evaluated for seven break-up seasons. The model is generally reliable considering its simplicity. A couple of false positives (model forecast flooding but it did not occur) were encountered. This was partially attributed to the overestimation of discharge because of the existence of ice jams in the vicinity of the water level gauge at Hat Island.

4 Conclusions and Recommendations

Main communities of Ontario's Far North are located on the floodplains of Severn, Winisk, Attawapiskat, Albany and Moose Rivers in the vicinity of James and Hudson Bay. These communities are prone to ice jam flooding. A majority of them have experienced severe flooding events in the recorded history and recent past. The annual possibility of such flooding and its materialization reduces the quality of life of community members and imposes substantial financial spending to evacuate and accommodate the community members, among others. Reliable tools to predict ice jam flooding and its magnitude are needed both for the design of protective structures and for emergency planning. The present report summarizes numerical approaches, tools and data needs and supporting technologies and methods for such predictions and reviews numerical studies relevant to ice jams flooding of the communities. The report is to inform the SWMC of MNRF about future efforts for data collection and model developments. Concerning the relevant studies, despite the high frequency and adverse consequences of flooding of the communities, only two studies were found in the public domain both of which relate to the coastal communities of Albany River, namely Kashechewan and Fort Albany. The reason for the low number of relevant studies could be partially attributed to the inadequacy of data for running and calibration of models.

The following is a list of general recommendation for the future efforts of SWMC of MNRF:

- **Field Campaigns:** Based on a brief review of open literature, bathymetry of the rivers close to the communities are not well known (if known at all). Field campaigns for the bathymetric mapping of the rivers are needed for physics-based modelling of ice jam flooding. Field campaigns could also focus on survey of vegetation type and age to approximate the extent and identify regimes of past ice jam flooding events for calibration of both physics-based and non-physics-based models. Such a vegetation survey was done in 1999 for Albany River close to Fort Albany [37] and might need to be repeated to survey new flooding impacts since 1999. The author is not aware of any similar survey for other four rivers. Note that vegetation survey is not needed if past ice jam events recordings include water levels impacted by the existence of ice jams. Such data could be collected by water level gauges located in the backwater zone of ice jams, and potentially by air-borne or satellite altimetry, or if not possible by inferring water levels upstream of the jam by comparing the location of water surface with other features with known elevations. Interviewing people who have observed ice jam events is an additional approach in collecting (qualitative) data about water levels and other flooding conditions. Another field campaign could focus on the installation of hydrometric gauge stations. The closest stations to Fort Severn, Peawanuck, Attawapiskat, Fort Albany/Kashechewan, Moosonee/Moose Factory are respectively more than 400, 150, 60, 100, and 80 km river distance away.
- **Hydrological Modelling:** The ability to correctly estimate river flows is crucial for the estimation of ice jam backwater levels and the determination of whether flooding is going to happen. Such

models do not exist for any of the rivers of Ontario's Far North[7]. Natural Resources Canada is developing/extending a model based on satellite-derived snow depth data coupled with temperature forecasts [39] to forecast peak river discharges for Ontario's Far North rivers. Any effort in such flow estimations is highly needed and requires calibration using historical river flows. For a higher accuracy, it is recommended to calibrate such models for locations close to the communities and with long-term data, if they are available.

- **Break-up Forecasting:** Considering the inability of existing models/technologies to confidently forecast the time of an ice jam flooding and since ice jam flooding can only happen after break-up and it could be historically rare if the break-up happens after a certain date (as it is the case for ice jam flooding of Kashechewan [38]), it is useful to be able to forecast the time of break-up. To this end and until all required data and science for fully physics-based modelling of ice processes of Ontario's Far North rivers are available, the development of non-physics-based models for break-up forecasting is recommended. Such models will rely on flow, precipitation, temperature and historical break-up data. Historical break-up data could be obtained by checking satellite-derived river ice coverages and/or recordings of ground cameras (if available). A source of satellite-derived ice coverage data for Ontario's Far North rivers is RADARSAT-1 and -2 with data available since 1997.

- **Application, Refinement and Expansion of Available Models:** It is worthwhile to evaluate whether the available models mentioned in section 3 can be used operationally and refined, and to develop similar tools and models for other communities.

- **Communications with other Jurisdictions with Ice Jam Issues:** Since many Canadian and international communities face ice jam flooding, communications between the SWMC of MNRF and other jurisdictions are recommended to learn the state-of-the-art technologies and practical approaches in modelling and forecasting ice jam flooding. As an example, Town of Hay River in the Canadian Northwest Territories has long faced break-up ice jam flooding and several studies have been conducted to help forecast flooding events (see [40] as an example). Perth-Andover in New Brunswick and St. Raymond de Portneuf in Quebec are two additional towns with frequent ice jam flooding issues [41].

At the end, it is recommended to stay up-to-date in advances in the field of river ice. Particularly, the application of satellite-derived data and their analysis in fields of hydrometry and river ice is on the rise, thanks to advances in remote sensing technologies and growing number of environmental satellites missions. Examples include the application of satellite-derived data to measure river surface elevation [42] and discharge [43] with application in ungauged river basins. Whether such technologies are applicable and useful for the development of ice jam flood models for Ontario's Far North is to be investigated and beyond the scope of the present report.

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[7] Personal communication with Andy Beaton with the SWMC of MNRF.

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