A STOCHASTIC MODELLING APPROACH TO IMPROVE ICE-JAM FLOOD RISK MANAGEMENT

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By

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ABSTRACT

In the northern hemisphere, ice jamming can result in devastating flood events along many rivers. Understanding the physical and hydraulic processes of ice jam formation and predicting ice jam floodwater levels is a key requirement for ice jam flood management and planning. Over the years, river ice numerical modelling techniques have advanced and achieved unprecedented successes in simulating ice jam occurrences and associated impacts. However, there are still some limitations in understanding the impacts of model components on flood hazard delineation and finding a reliable modelling approach for implementing an effective ice jam flood mitigation strategy. Besides, there is a lack of a reliable modelling approach to quantify the severity of ice jam flooding along many rivers in northern communities under future climatic conditions. The main objectives of this dissertation are to address these research gaps using a stochastic modelling framework. A framework was developed to incorporate the model parameters, boundary conditions and digital elevation models (DEMs) in a global sensitivity analysis of flood hazard delineation. The global sensitivity analysis of these components shows that ice jam flood delineation is highly sensitive to DEMs and boundary conditions. The severity of ice-jam flood hazard under future climatic conditions has been quantified applying a novel modelling framework. The modelling results show that mean stage frequency distribution (SFD) is projected to be lower under the projected changes in climate in the period of 2041-2070 compared to the baseline period of 1971-2000 along the Athabasca River at Fort McMurray, Canada. Since the risk of ice jam flooding is exist both at present and in the future, a methodological framework was developed to explore appropriate mitigation measures to reduce ice jam flood risk along the Athabasca River at Fort McMurray. A total of three ice-jam flood mitigation measures (artificial breakup, sediment dredging and dike installation) were examined using a stochastic modelling framework for the potential to reduce ice-jam flood risk. The results show that, while sediment dredging may be able to reduce a certain level of expected annual damages in the town of Fort McMurray, Alberta, Canada, artificial breakup and dike system may be the most effective measure to reduce the amount of expected annual damages.

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DEDICATION

To my mother, Bijoy Loxmi Das and father, Sunil Chandra Das, whose continuous sacrifices, affection, encouragement and prays helped me to achieve this success, along with all my respected teachers in life.

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LIST OF ABBREVIATIONS

ASTER	Thermal Emission and Reflection Radiometer
BCR	Benefit-cost Ratio
CDF	Cumulative Distribution Functions
CMIP	Coupled Model Intercomparison Project
CCSM	Community Climate System Model
CDDM	Cumulative Degree-days of Melting
CGCM3	Third Generation Coupled Climate Model
CRCM	Canadian Regional Climate Model
CRI	Comprehensive River Ice
CDEM	Canadian Digital Elevation Model
DEM	Digital elevation Model
EAD	Expected Annual Damages
ECCC	Environment and Climate Change Canada
FEMA	Federal Emergency Management Agency
HBV	Hydrologiska Byråns Vattenbalansavdelning
GIS	Geographic Information System
GSA	Global Sensitivity Analysis
IJF	Ice-jam Flood
K-S	Kolmogorov-Smirnov
LiDAR	Light Detection and Ranging
MESH	Modélisation Environnementale communautaire-Surface Hydrology
MOCA	Monte-Carlo Analysis
NARCCAP	North American Regional Climate Change Assessment Program
PAD	Peace-Athabasca Delta
PEST	Parameter Estimation Program
RCM	Regional Climate Model
RMSE	Root Mean Square Error
RSA	Regional Sensitivity Analysis
SA	Senstivity Analysis
SFD	Stage Frequency Distribution
SRTM	Shuttle Radar Topography Mission
TFM	Town of Fort McMurray
VARS	Variogram Analysis of Response Surfaces
VIC	Variable Infiltration Capacity
WSA	Water Survey of Canada

CHAPTER 1

INTRODUCTION

1.1 Background

In the northern hemisphere, the hydrological regimes of the majority of rivers are affected by ice for several months during the year (Prowse et al., 2007a). River ice processes are characterized by a sequence of ice events, including freeze-up, ice-cover formation and growth, and breakup (Beltaos, 2008b). During these events, severe ice conditions such as ice jams and associated flooding may occur in many locations along a river.

According to the International Association for Hydraulic Research (IAHR) working group, an ice jam can be defined as "a stationary accumulation of fragmented ice or frazil that restricts flow". Ice jams often form during spring ice-cover breakup; however, they can also form during freeze-up and in mid-winter. The freeze-up jams on a river form when cold weather cools the water to produce frazil slush and pans, while the breakup jams form when warm weather leads to breakup of the winter ice cover. In both cases, when ice floes are transported and their flow is then arrested, an ice jam may form. Mid-winter ice jams usually occur when air temperatures rise above freezing and/or by rain-on-snow events. Ice jams may last from a few minutes to many days and then release when hydraulic conditions of the river change. There are many randomly varying factors linked to ice-jam formation, such as channel geomorphology (e.g., channel width, sinuosity, depth and slope), hydro-meteorological variables (e.g., temperature, flow and freeze-up stage) and ice characteristics (e.g., ice thickness and ice types). Previous studies and observations suggest that sharp bends, channel constrictions, braided channels and abrupt reduction in river slope are potential ice jamming locations on a river (Beltaos, 1995).

Ice jams can cause extremely high-water stages since an ice jam creates large hydraulic resistance along its underside. Ice-jam flooding can result in significantly higher water levels than open-water flooding at the same or lower river discharge. Ice jam floods are often sudden and unpredictable; therefore, they allow very little time for implementing emergency measures, such as warnings and evacuation. Additionally, the swift-moving water and the tremendous forces applied by ice blocks can create life-threatening conditions during an ice-jam flood event. In the case of freeze-up or mid-winter ice jam flooding, the freezing floodwater can cause additional damages to property and infrastructure as well as to ecological habitat (Burrell et al., 2015).

Since many river-ice numerical models have been developed to simulate ice jams, they are widely used in ice jam flood management program. These models range from 1D steady-state to 2D dynamic and data-driven models (Carson et al., 2011). The basic theory of these models has mostly been formulated based on studies by Pariset et al. (1966) and Uzuner and Kennedy (1976). However, some of the important features and parameters of ice-jam processes, such as hydraulic roughness and ice jam grounding, are defined separately. The 1D steady-state models assume that the flow is steady and gradually varied along the model domains and they solve the force and energy balance equations using a standard step function method. The 1D steady-state river ice models include ICETHK (Tuthill et al., 1998), HEC-2 (US-Army, 1990), RIVJAM (Beltaos, 1996) and ICEJAM (Healy and Hicks, 1999). The main limitation of these models is that they cannot consider the dynamic conditions of river ice processes.

To overcome this limitation of the steady-state model, 1D unsteady dynamic models have been developed and these include RICE (Lal and Shen, 1991), RICEN (Shen et al., 1995), CRISSP1D

(Chen et al., 2006) and RIVICE (EC, 2013). These hydrodynamic models usually solve mass and momentum conservation equations (1D Saint Venant Equations) with floating ice using the implicit finite element method. They are able to simulate many key processes of river ice, such as ice generation, ice transport, ice cover progression (shoving, submergence and juxtaposition) and ice jam formation. 2D models have also been developed to overcome some of the limitations that exist in 1D unsteady state models, such as details concerning the characteristics of flow regimes and complex river geometry. The available 2D models are DynaRICE (Liu and Shen, 2000) and CRISSP 2D (Liu and Shen, 2005). They use explicit finite element methods to solve the 2-D depth-integrated hydrodynamic equations to model ice formation, growth and evaluation.

Over the years, these models have been successfully applied in a variety of applications to solve ice-related problems. These include ice-jam flood hydrology and frequency analyses (Beltaos, 2010), flood risk analyses (Lindenschmidt et al., 2016, Alaghmand et al., 2012), regulation impact studies (Beltaos, 2014, Beltaos, 2003), operational flood forecasting (Warren et al., 2017, Lindenschmidt et al., 2019b, Lindenschmidt et al., 2019a) and climate change impact analyses (Beltaos et al., 2006, Rokaya et al., 2019). Although our ice-jam hydraulic modelling capabilities have advanced significantly over the years, there are still some limitations, such as capturing the stochastic phenomena of ice-jam processes, understanding the interaction between different river ice and hydraulic parameters and boundary conditions (e.g., relationship between streamflow and inflowing ice volume), and climate change impacts on the severity of ice jam flooding. Some effort has been made on accounting for stochastic characteristics of different ice parameters in flood delineation (Lindenschmidt, 2017b, Lindenschmidt et al., 2016, Rokaya et al., 2019), but more research is needed. The hydrotechnical approaches need to be more advanced to model ice-jam flood rates-of-rise and to estimate the duration of the flood on the floodplain. The feasibility of mitigation strategies needs to be assessed by estimating the probable risks posed by implementing these strategies. The extension of the hydraulic modelling approaches for assessing these probable flood risks and identifying suitable mitigation measures is necessary. Very few studies have been carried out on climate change impacts on ice-jam flooding; therefore, advancement in numerical modelling of this aspect is needed.

The stochastic processes of a system may refer to a sequence of random variables whose value change through time according to probabilistic laws (Loucks et al., 2005). Stochastic approaches are often used to model flows, rainfall, temperature and other environmental phenomena, which change through time. There are several methods available for stochastic models, such as Monte-Carlo (MOCA) simulation, the first-order reliability method, numerical integration, and stochastic differential equations. Although the applicability of these methods depends on the characteristics and a degree of complexity of the scenario that needs to be modelled, the MOCA simulation is relatively robust to repeatedly simulate a hydrodynamic model with a different set of random variables for each simulation.

Since ice-jam processes are stochastic in nature, many hydro-meteorological and river-ice variables vary randomly during the processes. Hence, the stochastic approach can be adapted to simulate hundreds/thousands of ice-jam scenarios and present the results in a probability context (Lindenschmidt et al., 2015). A calibrated hydraulic model is embedded in a MOCA framework to simulate hundreds or thousands of ice-jam scenarios. For each simulation, a set of model parameters and boundary conditions is extracted from their feasible ranges and distributions (e.g. uniform and Gumbel). The ensemble of ice-jam water-level profiles from the MOCA simulation is then used to derive the exceedance probabilities and stage-frequency distributions for ice-jam flooding. In recent years, this approach has been applied in a variety of studies and proven to be an effective approach in ice-jam flood frequency analyses (Das et al., 2017, Lindenschmidt et al., 2016a, Rokaya et al., 2019, Warren et al., 2017). Although the stochastic approach has been recognized as an effective method for delineation of ice-related floods, the applicability of this method still needs to be assessed by additional research, to identify, for example, its usefulness in the implementation of new flood mitigation strategies and determination of climate change impacts on the severity of ice-jam flooding in the future.

Flood mapping is an exercise to define a flood-prone area using various information related to flood hazard (depth and extent) and vulnerability information (land uses). According to the EU flood directive, there are two types of flood maps: flood-hazard and flood-risk maps. While a flood-hazard map provides information on flood extent and the degree of flood hazard, the flood-risk map presents the potential adverse consequences associated with different flood events (Tsakiris et al., 2009). The degree of flood hazard may include flood frequency, flood depth and flow velocity, or a combination of this information. In the case of ice-jam flooding, flood maps should provide some additional information, such as the rates-of-rise of ice-jam flood or probable duration of floodwater on the floodplain (Burrell et al. 2015, Lindenschmidt and Das, 2020). In order to produce a flood-hazard map, basic topographic data such as ground elevation data or digital elevation models (DEM) is required. The DEM is a gridded representation of ground elevation values. A DEM is often produced from field measurement or remote sensing techniques. For example, an airborne laser altimetry DEM, LiDAR (Light Detection and Ranging), provides data with high accuracy and fine resolution and is used for producing maps. However, the LiDAR data is expensive and data for many locations are still unavailable. To overcome these limitations, many practitioners rely on open-access and relatively low resolution (30 m) global DEMs, such as the Shuttle Radar Topography Mission (SRTM) and Thermal Emission and Reflection Radiometer (ASTER).

There are two main components of flood hazard delineation: hydraulic modelling and flood mapping. While a river hydraulic model is applied to simulate water-level profiles, a DEM extends the flood water levels from the river to the floodplain to estimate the flood hazard (Lindenschmidt et al., 2015, 2016). Ice-jam flood hazard mapping is difficult because of the stochastic nature of river ice characteristics, such as type of ice-jam formation (e.g. grounded or floating), the inflowing ice volume and the location of the ice jam. To incorporate these processes, the models require the user to specify several parameters (e.g., porosity, ice-thicknesses), which introduces a degree of subjectivity and uncertainty. Moreover, DEMs may also have inherent uncertainty. To quantify these uncertainties, characterization of the role and impact of different parameters and DEMs on flood hazard delineation is necessary. Although several studies have already been carried out to assess the role of model parameters and boundary conditions on ice-jam hazard flood delineation through sensitivity analysis (Sheikholeslami et al., 2017, Lindenschmidt and Chun, 2013), impacts (accuracy in flood depths and extent) of DEMs on ice-jam flood hazard delineation still need to be explored.

Sensitivity analysis (SA) is an effective way to understand the role of key factors (e.g. parameters and boundary conditions) in a hydraulic model. SA can be classified into two categories: local and global SA methods. While local methods evaluate model output based on the local impact of input factors' variation around a single point in the factor space, global methods evaluate the impact of uncertain input factors over the entire factor space (Zhou and Lin, 2017b, Zhou and Lin, 2017a). Although various methods are available to perform SA, regional sensitivity analysis (RSA) has been widely used to measure the influence of model parameters and boundary conditions on a river ice model (Lindenschmidt and Chun, 2013, Lindenschmidt, 2017b). The advantages of RSA methods are that they are conceptually simple and model independent. The details description related the RSA method has been described in Chapter 4.

Climate change has already been changing river ice regimes and affecting the severity and frequency of ice-jam floods along many northern rivers (Prowse and Beltaos, 2002). A significant reduction in the duration of the ice season has been observed along many rivers and lakes in the Northern Hemisphere (e.g. Lacroix et al., 2005, Prowse et al., 2007b, Ionita et al., 2018, Magnuson et al., 2000, Duguay et al., 2006). However, an opposite trend, extension of the ice season, has also been observed in some regions, such as Atlantic Canada (Zhang et al., 2001). An earlier ice-cover breakup may lead to more dynamic (mechanical) breakup events and can cause extreme ice-jam floods, while the delay in ice-cover breakup may allow enough time for the ice cover to disintegrate thermally and reduce the possibility of extreme ice-jam events.

With the current implications and projected future changes, there is a need for robust modelling combination of reliable climatic, hydrological and river ice hydraulic models that can describe climate change impacts in order to identify efficient and effective adaptation strategies. Historically, river ice hydraulic models have been largely applied to simulate local river ice processes or understand site-specific ice jam phenomena. Hence, despite the significance of climate change impacts on ice-jam floods, appropriate modelling approaches to assess climate change impacts are not well defined. A scoping review of ice-jam flood research by Rokaya et al. (2018a) found that less than 10% of the river ice research articles addressesd the application of hydraulic models on climate change impacts analyses. Therefore, given the broad economic and environmental significance of ice-jam floods and their sensitivity to a changing climate, a clear understanding and evaluation of current capability of modelling for simulating climate change impacts is necessary.

1.2 Research Objectives

Over the years, extensive research has been carried out to further understanding of ice-jam processes and minimize the impacts of ice-jam flooding on riverside communities and ecology. These efforts include the development of robust numerical techniques (e.g. 1D and 2D dynamic numerical models), expanding of experimental studies and applying advanced data acquisition tools (e.g. remote sensing and drone) in ice-jam research (Hicks, 2009). However, there are still some knowledge gaps, such as fully understanding the role of different parameters in ice-jam flood hazard delineation, developing an effective methodology for designing and adapting suitable ice-jam flood mitigation measures, and assessing the impacts of climate change on the severity of ice jamming in rivers. The main purpose of this study is to provide a stochastic modelling framework to advance river ice modelling techniques for ice-jam flood delineation, develop flood mitigation strategies and assess the impacts of climate change on the severity of ice-jam flooding. The specific objectives of the research are:

- to evaluate the influence of model parameters, boundary conditions and Digital Elevation Models (DEMs) on ice-jam flood hazard delineation;
- to develop a framework for quantifying flood hazard under future climatic conditions; and
- to provide an effective approach for selecting appropriate mitigation measures to reduce ice-jam flood risk.

1.3 Thesis Outline

The next two chapters carryout literature reviews to address current state of knowledge about ice jam processes, climate change impacts on ice jam floods and ice jam flood hazard and risk assessments. Chapter 2 reviews the current model, modelling capabilities and challenges to quantify the severity of ice jam flooding under future climatic conditions. Chapter 3 addressed the current status and advancement suggestions for ice jam flood hazard and risk assessments.

The following three chapters address the objectives of the thesis: Chapter 4 evaluates the sensitivity of hydraulic model parameters, boundary conditions and digital elevation models to ice-jam flood delineation variables, Chapter 5 provides a framework for climate change impact assessment of the severity of ice-jam flooding in the future, and Chapter 6 evaluates the implementation of various mitigation strategies to reduce overall flood risk in ice-jam flooding. Following this, Chapter 7 describes the overarching goal of the entire dissertation and how the preceding three chapters fit together and contribute to the progression of ice-jam modelling and ice-jam flood risk management fields. Finally, Chapter 8 concludes the study by describing the main findings of this dissertation and suggesting future research directions in the field of ice-jam modelling.

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Preface to Chapter 2

CHAPTER 2: MODELLING CLIMATIC IMPACTS ON ICE JAM FLOODS: A REVIEW OF CURRENT MODELS, MODELLING CAPABILITIES, CHALLENGES AND FUTURE PROSPECTS

This chapter discusses the current status of research related to climate change impacts on river ice regimes and associated extreme events, assess current modelling capabilities for simulating future climate impacts on river ice processes; and provide recommendations for future research.

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CHAPTER 2

MODELLING CLIMATIC IMPACTS ON ICE JAM FLOODS: A REVIEW OF CURRENT MODELS, MODELLING CAPABILITIES, CHALLENGES AND FUTURE PROSPECTS

Abstract

River ice is an important hydraulic and hydrological component of many rivers in the high northern latitudes of the world. It controls the hydraulic characteristics of streamflow, affects the geomorphology of channels, and can cause flooding due to ice jam formation during ice-cover freeze-up and breakup periods. In recent decades, climate change is considerably altering the ice regimes and affecting the severity of ice-jam flooding. Although many approaches have been developed to model river ice regimes and severity of ice jam flooding, appropriate methods that account for impacts of future climate on ice-jam flooding are not well established. Therefore, the main goals of this study are to review current knowledge on climate change impacts on river ice processes and assess the current capabilities for modelling the severity of ice jams under future climatic conditions. Finally, a conceptual river ice jam modelling approach is presented for incorporating climate change impacts on ice jams.

2.1 Introduction

River ice is one of the major components of the hydrologic regime in the high northern latitudes of the world, where more than 60% of the rivers are seasonally affected by river ice (Yang et al. 2020, Prowse et al., 2007). Whether the ice is stationary to the river bank or anchored to the river bottom or whether it is suspended in the water column and moving with the river flow, river ice affects the hydrologic and hydraulic conditions of rivers, resulting in range of positive and negative impacts on riverside communities, economies and ecosystems. (Beltaos, 1996a, Prowse 1994, 2001).

River ice has a significant influence on the hydraulic conditions of a river. Figure 2.1 shows stage-discharge relationships for different hydrological and ice processes along the Athabasca River at Fort McMurray. Figure 2.1 illustrates that, under open-water conditions, there is a deterministic relationship between water level elevation and stream discharge, in contrast to the relatively scattered distributions depicting the relationship between water level elevation and stream discharge during freeze-up and spring ice cover breakup. However, the water level elevations are relatively consistent and characterized by low flow conditions during intact ice-cover. The ice-affected instantaneous-maximum water level elevations are highly inconsistent with their corresponding discharges, as instantaneous-maximum water level elevations could be occurring due to downstream ice jam formation and upstream ice jam release.

The presence of river ice disrupts the unique open-water stage-discharge relationship because ice changes conveying capacity and the hydraulic characteristics of rivers. The presence of an ice cover increases a river's wetted perimeter and overall channel resistance, which alters the velocity profile and forces water levels to rise (Beltaos 2013). If geomorphology of the channel remains unchanged, the open-water stage-discharge relationship is usually curvilinear and very simple to observe, as it mostly depends on channel discharge. However, ice-jam water-level conditions are challenging and difficult to monitor because they are controlled by many additional parameters, rather than stream discharge only. These parameters include various river ice parameters (e.g. ice roughness, strength, porosity, volume, ice-cover type), river width, ice jam toe location and length, and flow thresholds. These parameters are often difficult to measure during ice jam conditions and their impacts on river hydraulics are chaotic; therefore, for a given discharge, a range of water levels can be possible for both freeze-up and breakup jams.

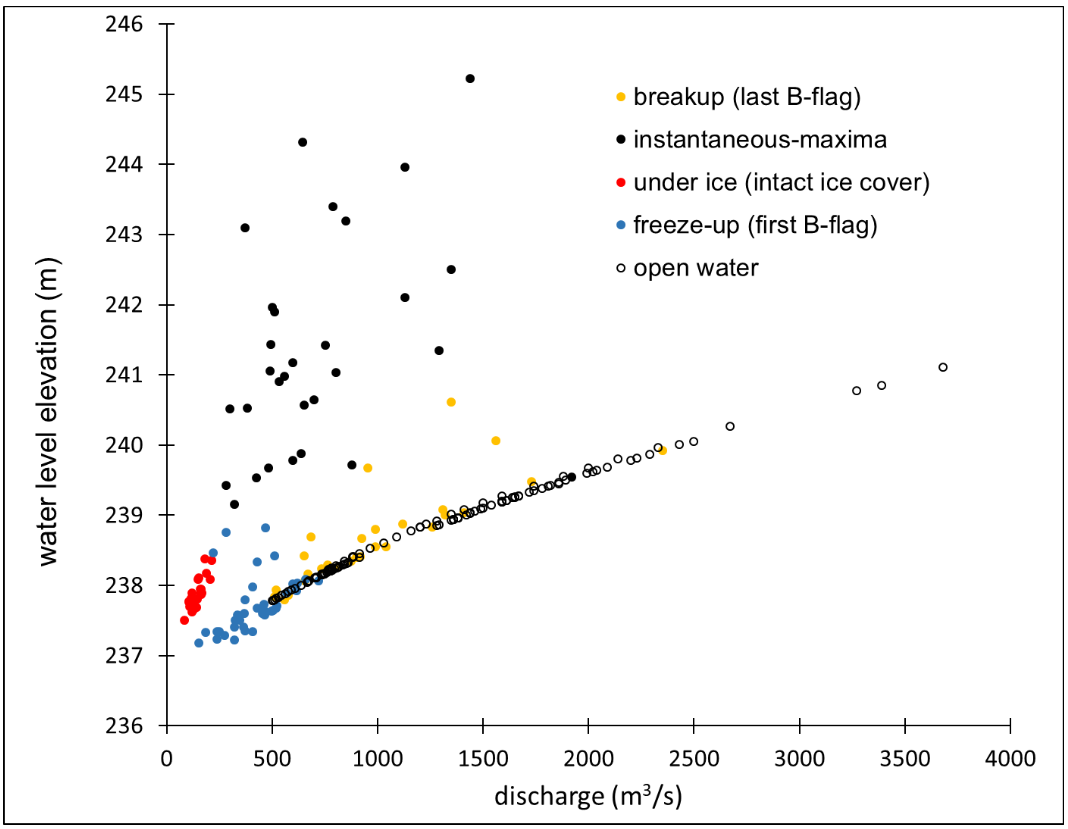

Figure 2.1 Stage-discharge relationships at Water Survey of Canada's gauging station along the Athabasca River below Fort McMurray.

The magnitude of water level rise due to the presence of ice can be described by the following equation (Beltaos, 1982).

$$\frac{H_c}{H_o} \approx \left[\left(1 + \frac{n_i}{n_b}\right)^{3/2}\right]^{2/5} + 0.92\ \frac{t_i}{H_o} \text{ .... } (2.1)$$

which H_o and H_c are the water depths under open-water and ice-covered conditions, respectively; n_i and n_b are the hydraulic roughness coefficients for the ice cover and river bed, respectively; and t_i is ice-cover thickness. The changes in water level or backwater height due to the ice cover can be estimated from the difference between ice-covered and open-water depths, (H_c - H_o). Under an equivalent discharge, a large ice-cover thickness and roughness can raise water levels to twice or three times the open-water depth. This effect is usually higher during freeze-up and breakup. At freeze-up, ice floes start to accumulate to form an initial ice cover and also, they could protrude downward considerably into the flow under a certain hydraulic condition, hence significantly increasing flow resistance and constricting flow. Over the progression of winter, thermal smoothing and deposition of frazil ice reduce the underneath ice-cover roughness. The largest river ice effect often occurs during the spring ice-cover breakup when the flow of broken rubble ice is arrested causing ice jams to form in the river channel, as breakup ice jams tend to be thicker and rougher compared to freeze-up. Freeze-up usually occurs during low flow conditions, when precipitation stops contributing to runoff, as it starts to accumulate in the form of snowfall. The low river flow conditions are usually consistent throughout the winter period due to reduction in flow contribution from upstream storage and groundwater fluxes. The amount of flow can be modified due to ice-cover formation in three ways – reduction of groundwater supply due to freezing, loss of a portion of flow volume due to ice-cover formation and thickening, and hydraulic storage or flow abstraction due to ice-cover progression in the upstream direction (Prowse and Beltaos, 2002). This stored water eventually melts during spring breakup and may make a significant contribution to the spring freshet.

Ice jamming and subsequent flooding during the ice-cover breakup period can damage property and infrastructure, interfere with ship traffic, and hinder hydropower generation and hydrometric gauging (Beltaos, 2008). Extreme ice jams are one of the major sources of physical disturbances that are detrimental to many instream aquatic species and their habitats (e.g. severe fish mortality and loss of spawning grounds) (Peters et al. 2016). Adjusting for inflation on previous estimations of damage, French (2018) reported that the annual cost of river ice jams in North America is about USD 300 million (in 2017 value). However, ice jam flood (IJF) events have also been found beneficial to high elevation floodplains in some deltaic environments, where high water staging attained by ice jamming replenishes perched basins with essential moisture and sediments, and maintains water balances that are more favourable to these ecosystems (Peters et al., 2006).

It is now firmly established that the temperature of the world's climate system has significantly warmed, which has been impacting many hydrological and meteorological processes over the last several decades (IPCC, 2014). Implications have been significantly greater in the Northern Hemisphere compared to the Southern Hemisphere (Feulner et al., 2013) due to interhemispheric temperature asymmetry. Several studies have demonstrated shifts in the timing and magnitude of total precipitation and river discharge, a decreasing trend in snow cover, melting of sea ice glaciers, thawing of permafrost, earlier river ice-cover breakup and changes in many biological and geomorphological processes (DeBeer et al. 2016; Serreze et al., 2000; Hinzman et al., 2005; White et al., 2007; Prowse et al., 2009b; Callaghan et al., 2011a; Derksen et al., 2012; Bush et al., 2014). In Canada, studies suggest that these climate related changes could contribute to many extreme events such as widespread forest fires, prolonged droughts/dry conditions and severe flood events (Bush et al., 2014). In 2011, these extreme events led to $1.7 billion of insured losses for Canadian insurance companies due to property damages. Although the climate change-related findings on river ice are sparse, a study suggests that climate change will increase the frequency and/or intensity of the extreme events in the coming years in northern regions (Warrend and Lemmen, 2014).

Since many Canadian communities are located along the banks of major rivers and these rivers are ocasionally affected by ice jams during spring ice-cover breakup, changes in ice regimes may result in wide-ranging consequences from severe damages to human fatalities or the reduction in ice-jam flood frequency to prolonged dry periods. The 2020 ice jam flood event along the Athabasca River at Fort McMurray is a recent example of the severity of ice jam flooding. This event may or may not have been directly connected to climate change impacts; however, it resulted in one human fatality and millions of dollars in property and business losses for the community. Therefore, with the current implications and projected future changes, it is necessary to assess the future frequency and severity of IJFs. Although there has been some research related to the duration of the ice-cover period (Prowse et al. 2011; de Rham 2019; Lemmen et al. 2008; Magnuson et al. 2000) and frequency analysis (Das et al. 2020), appropriate modelling approaches to assess climate change impacts are not well defined. Therefore, given the broad economic and environmental significance of IJFs and their sensitivity to changing climate, a clear understanding of current modelling capabilities for simulating climate change impacts is necessary. Thus, the main objective of this review is to investigate the current modelling capabilities for quantifying the impacts of climate change. The specific objectives are to (i) assess the current status of research related to climate change impacts on river ice regimes and associated extreme events; (ii) evaluate current modelling capabilities for simulating future climate impacts on river ice processes; and (iii) provide recommendations for future research.

2.2 Climatic control of river ice processes

2.2.1 Climate change in the Northern Hemisphere

The global climate system is changing, with changes to climatic behavior (mean and variability) projected beyond the 21st century (IPCC, 2014). Compared to the southern hemisphere, the average annual surface air temperature in the northern hemisphere is 1° to 2°C higher due to increased ocean heat transport and reduced snow/ice albedo (Feulner et al., 2013). The interhemispheric temperature asymmetry (i.e. temperature difference between the northern and southern hemispheres) has grown with a significant warmer trend, especially since 1980 (Friedman et al., 2013). This asymmetry, which is considered to be an emerging indicator of global climate change, has also been attributed to the decline in sea ice and snow cover in the Northern Hemisphere (Stouffer et al., 1989).

In a warming climate, precipitation is more likely to occur as rainfall event while overall snowfall may be decreased in coming future. A study by Kapnick and Hall (2012) showed that the recent snowpack changes in western North America have been caused by regional-scale warming. This is contrary to prediction that a shift from snow toward a rain dominated regime does not significantly affect the mean streamflow. Berghuijs et al. (2014), in their study of the contiguous United States, found that a shift in precipitation from snow towards rain leads to a decrease in mean streamflow. On a global scale, the largest changes in the hydrological cycle due to warming are predicted for the snow-dominated basins of mid- to higher latitudes, because adding or removing snow cover fundamentally changes the capacity of the snowpack to act as a reservoir for water storage (Nijssen et al., 2001).

In Canada, a statistically significant rise in air temperature has been observed. Recent analyses show a statistically significant 1.5°C rise in annual air temperature across Canada between 1950 and 2010 (Vincent et al., 2012). Even after removing the effects of climatic variability, Vincent et al. (2015) found a statistically significant increasing trend in air temperature. This has led to widespread permafrost thaw and a northward migration of the southern limit of discontinuous permafrost (Jorgenson et al., 2001). Permafrost thaw has the potential to fundamentally alter the cycling and storage of moisture inputs by altering the type and relative proportions of the major land-cover types (Connon et al., 2014).

An assessment of future scenarios using multi-model ensembles from phase 3 (B1 and A2 scenarios) and phase 5 (RCP 4.5 and 8.5) of the Coupled Model Intercomparison Project (CMIP) revealed that interhemispheric temperature asymmetry is likely to increase in all future scenarios (Friedman et al., 2013). Another assessment of 20 global climate models from the CMIP5 under the RCP 8.5 scenario projects strong warming (> 8 °C) in high latitude regions (north of 60°N) with moderate warming (5 to 7 °C) in the mid-latitudes (40 to 60°N) of the Northern Hemisphere (Feng et al., 2014). Other studies (e.g. Peacock, 2012; Miao et al., 2014; Barnes & Polvani, 2015) have also pointed out that warming will accelerate with increasing latitude and, as a result, the Northern Hemisphere is likely to warm disproportionately. The resultant change in environmental conditions will pose risks not only to northern natural systems, but also to local communities that have been historically dependent on these natural systems for livelihood, cultural integrity, and traditional ways of life (Wesche & Armitage, 2014).

2.2.2 Current climate-induced impacts on river ice

Although there are few studies related to climate-induced impacts on river ice, climate-induced changes to river ice could be a good environmental indicator for discerning climate change. There are many factors related to the river ice regime which could be affected by climate-induced changes, such as duration of the ice season, thickness of ice covers and severity of ice jams (Beltaos and Prowse, 2009). The following section summarizes some findings related to climate-induced impacts on river ice.

Most previous studies have found a decreasing trend in the overall duration of the ice-cover season (Beltaos and Prowse 2009). Although there is large spatial variability in freeze-up date, an earlier shift in breakup date is observed along many cold region rivers. Strong trends of later freeze-up and earlier breakup along many rivers in European Russia, West Siberia and the Danube have shortened ice-cover duration by about 20 days per century (Borshch *et al*., 2001). However, an opposite pattern of longer ice-cover duration has been reported in Eastern Siberia (Turcotte et al. 2019, Beltaos and Prowse, 2001; Zhang et al. 2001). Smith (2000) examined long-term river ice data of nine Russian Arctic rivers, in which no significant trends were found in eight data categories, except for the timing of ice-cover melt. One to three week earlier breakup date (shorter ice-cover duration) was observed along the Pechora, Ob, Olenek, Indigirka, and Kolyma rivers, while earlier freeze-up dates resulted in longer ice-cover periods along the Onega, Varzuga, and Yenisei rivers, except for the Mezen River. Several similar ice phenological studies have also been carried out for the rivers of the North-western part of European Russia, Lithuania and Mongolia (Batima *et al*., 2004; Stonevicius *et al*., 2008; Vuglinsky, 2006). The results of these studies found significant trends of later freeze-up and earlier breakup dates. Zachrisson (1989) recorded an earlier breakup date along the Tornealven River in northern Scandinavia.

Many studies have also been carried out in Canada (Williams, 1970; Rannie, 1983; Beltaos, 2002, 2004; de Rham, 2006; Doyle and Ball, 2008; Janowicz, 2017; Chen, Y., & She, Y. 2020) and the USA (Hodgkins et al. 2005; White et al. 2007), which found trends of earlier ice-cover breakup dates and shorter ice-cover durations for many rivers. A recent large-scale study on spatial and temporal variations in spring ice-cover breakup in five river basins in Canada was carried out by Chen and She (2020), which identified overall earlier breakup trends, mainly resulting from warmer air temperatures. Another comprehensive study of trends in river ice in Canada by Lacroix et al. (2005) demonstrated a clear pattern towards earlier breakup in most of the country. However, due to complex spatial variability in freeze-up regimes, it is difficult to discern any clear temporal trends. While all the studies in Alaska and Maine found earlier breakup trends, only two of the studies showed later freeze-up trends (White et al., 2006). Trends toward shorter freshwater-ice durations over much of the circumpolar North closely correspond to the increasing air temperature trends observed over most of this region, and it is most pronounced at the end of the last century (Prowse et al., 2011; Magnuson et al. 2000b).

Although fairly high correlations (r^2 = 0.6 to 0.7) between mean air temperature and ice-cover duration have been found (Ginzburg et al. 1992; Soldatova, 1992), river ice processes cannot be fully captured using heat index parameter, since other climate-dependent parameters, such as snow depth, solar radiation and river discharge, exert large influence on river ice processes.

Borshch et al. (2001) reported that incorporating river discharge and air temperature together can significantly improve the prediction of changes to ice-cover breakup. However, studies (e.g. Bonsal et al., 2006; Schmidt et al., 2019) have also noted the influence of large-scale atmospheric and oceanic oscillations on ice duration, in addition to long-term climate change.

Since the thickness of a river ice cover is difficult and often dangerous to measure, very few studies have been carried out to analyze historical trends and climate change impacts on river ice thickness. A long-term ice thickness data analysis along the Piscataquis River in central Maine, USA detected a total decrease of 23 cm from 1912 to 2001 (Huntington et al. 2003). Vuglinsky (2006) reported that river ice-cover thickness had decreased by 2-14 cm along most Russian rivers, including rivers of European Russia. Significant decreases of 20 – 80 cm in river ice-cover thicknesses were observed in Mongolian rivers from the 1960s to 2000 (Batima et al., 2004; Si et al., 2015). Although climate change impact studies on river-cover thicknesses in Canada are sparse, Beltaos (2004, 2007b) applied an indirect approach to determine maximum ice thicknesses along two Atlantic Canadian rivers, finding no significant trends.

While a larger pool of literature is available on river ice freeze-up and breakup trends and a few studies report on ice thickness trends, very limited work has been carried out to understand the impact of climate change on the severity of extreme ice-jam events.

Researchers have reported that the frequency of mid-winter breakup and associated ice-jam flooding has also increased in Canada and the USA (Beltaos & Prowse, 2001; Prowse et al. 2002; Beltaos et al., 2007a, b; White et al., 2006, Carr and Vuyovich 2014, Newton et al. 2017), as a result of mild weather conditions (temperature above 0 ºC) and winter precipitation (rain-on-snow events). Beltaos (2002) examined long-term hydrodynamic data along the Saint John River in eastern Canada from the 1920s to the 1990s and found a dramatic increase in peak winter flows, as mild days increased during the winter. Mid-winter breakups also reported along the St. Lawrence River, Quebec, Canada (Turcotte et al. 2020), the Picataquis River in Maine, USA (Huntington et al. 2003), the Salmon River near Salmon, USA (White et al. 2006), the Fox and Grande River in the Midwest United States (Carr and Vuyovich, 2014) and Klondike River, Yukon, Canada (Janowicz, 2010). Reported mid-winter breakups and ice-jam formation along these rivers coincided well with the increased trends of mild-winter days and rain-on-snow events (Newton et al. 2017). Turcotte et al. (2019) report that a rise in air temperature and drop in winter precipitation reduces the chances of ice-jam floods, while the rise in winter precipitation (rainfall) exacerbates winter breakups and associated ice jams. However, if thinner ice- covers forms due to warm weather conditions during freeze -up/winter, it will further reduce the chances of ice -jam formation and flooding, as ice simply washes out of the channel. A mid-winter breakup can create several persistent open-water stretches throughout winter that can generate more frazil ice and lead to relatively greater ice-cover thickness. In the Saint John River, Canada, detailed field data measurements after mid-winter breakup events suggest that the ice-cover thickness was significantly higher in locations where jams occurred than the normal ice-cover thickness of the reach (Beltaos et al. 2003). Therefore, the winter ice-jam formation can be responsible for aggravating the spring ice-cover breakup by providing more ice in the channel before the spring breakup (Turcotte et al. 2019, Beltaos, 2002).

On the other hand, a rise in spring precipitation has a greater probability of more frequent ice-jam formation during spring breakup, if the other river ice parameters/ and conditions remain favourable (Beltaos and Burrell, 2003). Both increased and decreased spring flow trends have been observed along rivers in northern regions and these trends influence and shift ice -jam regimes in many rivers (Zhang et al. 2001). Studies show that there was an increasing trend in spring flows in southwestern Canada (Zhang et al. 2001); and a decreasing trend in the northwestern United States (Lins and Michaels, 1994). A recent study by Rokaya et al. (2018) reported that there have been distinct shifts in both the timing and magnitude of ice jam floods from 1903 to 2015 in Canada. While an earlier ice jam flood tendency was observed along rivers in the south-eastern and some western parts of Canada, a delayed ice jam flood tendency was observed in Central and Atlantic Canada. Analyses of trends regarding the magnitude of ice jam flooding in rivers show that the severity of flooding has increased along rivers in the northwest and some south-central regions of Canada, while severity decreased in Alberta, Atlantic Canada, southern Ontario and northern regions of Saskatchewan and Manitoba.

A reduction in the frequency of ice jam floods in many deltas in Canada, such as the Peace Athabasca Delta and Slave River Delta, suggests a decreasing trend of ice jam severity since the 1960s. The paucity of ice jam flooding has an adverse impact on delta ecology, such as drying of perched basins and ponds that provide habitat for many aquatic species in the deltas. Although the Peace River is regulated, Beltaos (2014) applied a conditional probability concept and found that only part of the changing signal (drying of Peace-Athanasca Delta) is a result of regulation, whereas some is also climate change. Some researchers have also reported that the frequency of mid-winter breakup and ice jam flooding has also been increasing in Canada and the USA (Beltaos and Prowse, 2001; Beltaos et al., 2007 a, b; White et al. 2006). Although it is still to be determined, climatic conditions may have a major impact on this type of flooding due to warmer days, rainfall events and excessive frazil ice generation caused by extremely cold weather during winter.

2.2.3 Expected climate change impacts on river ice regimes

Although there are a limited number of studies involving a long-term observation of complex ice-cover factors, such as ice thickness and severity of ice breakup and jams, many studies on the long-term changes in freeze-up/breakup timing and duration of river ice covers have been related to the impacts of climate change on ice regimes. Over the years, many studies have examined and identified some foreseeable changes in river ice regimes.

Under a warming climate scenario in the future, it is expected that ice-cover duration in rivers will be shorter due to higher water and air temperatures during freeze-up and spring breakup. A recent study on the future of global river ice by Yang et al. (2020) estimates that global mean river ice duration will likely decrease by 16.7 days under RCP 8.5 and 7.3 days under RCP 4.5 scenarios in future (2080 – 2100), compared to the period of 2009 - 2029. Borshch et al. (2001) estimated expected changes in river ice duration from a uniform 2°C increase in air temperature across various locations in the former Soviet Union. The results from this study showed that freeze-up and spring breakup dates will be delayed by 4-12 days and advanced by 4-10 days, respectively. Several studies have also reported that the expected increase in air temperature of 3 - 7 °C would result in significantly advanced breakup days (15 to 35) in northern Canada (Magnuson et al. 2000; Prowse et al. 2002). A comprehensive analysis of monthly temperature projection for the period of 2040-2069 revealed that the ice-cover duration in many places in Canada will be shortened by approximately 20 days compared to the baseline period of 1961-1990 (Prowse et al. 2007). Modelling work carried out by Andrishak and Hicks (2008) predicted a total of 28 days reduction in ice duration along the Peace River, Alberta, Canada by the mid-21st Century. However, these findings regarding the relationship between ice dates and air temperature may not be reliable under future climatic conditions, as other governing parameters that influence ice regimes, such as river discharge, could also be changed under altered climatic conditions. For example, while increased river flows could delay freeze-up and advance spring breakup, low-flow conditions could advance freeze-up and delay breakup. Andres and Van der Vinne (1998) reported that reduced flow conditions often accelerate earlier ice-cover formation along the Peace River, which is contrary to the expected trend with warmer climatic conditions.

With changes in the timing and duration of ice-cover formation, warmer climatic conditions can change overall ice regimes along the river. An extremely cold climate would promote frazil ice generation and accelerate complete ice-cover formation and a warmer climate would impede both ice-cover formation and frazil ice generation (Prowse and Beltaos, 2002). An increase in flow would enhance turbulence and frazil ice generation and lead to more shoving and thickening of the initial ice-cover formation. The effect of warmer conditions may have a similar effect of an increased flow environment, as warmer air temperatures would reduce the internal strength of an ice accumulation, leading to more telescoping of the ice cover as well.. Thus, the combination of higher flows and air temperature could increase the severity of freeze-up jamming (Beltaos and Prowse, 2009).

It is expected that changes in winter air temperatures could have a significant impact on the total thickness of the ice cover. Warmer air temperatures may produce thinner ice covers, while extreme cold temperatures tend to produce thicker ice covers in rivers. Studies suggest that there will be many rivers that will be fully or partially ice free under the pronounced warmer climatic trends in the future (Beltaos and Prowse, 2009). Overall, it is predicted that, under warming climatic conditions, ice covers will be relatively thin and weak and winter discharge will increase, which could enhance freeze-up consolidation and mid-winter breakup events along many rivers; hence, the severity of mid-winter ice-jam flooding will likely increase. Lamichhane et al. (2019) estimated winter ice-cover thickness along the Grand River, Ohio, USA under various RCP scenarios (2.6, 4.5, 8.5) using Stefan's equation and predicted that thicknesses would decrease considerably in the period of 2015 – 2098.

While warmer climatic conditions would alter the overall ice regimes, they could also affect the severity of ice-cover breakup and jamming. The severity of ice-cover breakup and associated flooding are dictated by the type of ice-cover breakup, i.e. thermal or mechanical. Thermal breakup occurs when mild weather and low flow conditions of the river cause the ice cover to deteriorate gradually. Ice covers break and disintegrate in place and are flushed away by the moderate flow. In this type of breakup, the possibility of ice jam formation is minimal and backwater levels remain low. Mechanical breakup, on the other hand, is triggered by rapid and high run-off conditions, which lead to premature ice-cover breakup before significant thermal ice-cover deterioration occurs. This type of breakup may lead to severe ice-jam formation and has great potential to produce large-scale flooding (Beltaos, 2003). The resulting ice jams from a mechanical breakup can be more persistent, due to the strong mechanical resistance of ice covers, requiring a significant driving force to dislodge the jams. A premature breakup event, which occurs due to the combination of thermal effects and mechanical fracture, can often create extreme flooding.

Changing climatic conditions can modify natural processes of both the driving and resisting forces that govern breakup regimes (Beltaos and Prowse 2009). The driving forces are usually characterized by drag forces exerted by the moving water on the underside of the ice cover, the thrust of moving water on the ice cover, and the vertical component of the weight in the sloping direction acting on the ice cover or ice jam. These forces usually depend on upstream ice conditions and flow discharge, which is mainly affected by the amount of total precipitation (e.g. rainfall and snowmelt) (Turcotte et al. 2019). The resisting forces are usually characterized by ice competence, which depends on ice thickness, flexural strength and freeze-up stage. The first two factors (ice thickness and strength) directly influence the severity of breakup and are strongly controlled by the intensity of atmospheric heat fluxes. For example, a relatively long pre-breakup melt period leads to a greater probability of thermal breakup and lesser probability of mechanical breakup. The pre-breakup melting from atmospheric fluxes also depends on the type of ice cover that forms during freeze-up and the amount of snow on the ice cover at breakup. A higher depth of snow could create strong insulation that reduces the rate of ice-cover thinning; the snow must melt before the underlying ice cover starts to melt. Also, the snow layer reduces solar radiation impinging on the ice cover to weaken it. Changes in the internal strength of ice are usually controlled by the intensity of solar radiation absorption by the ice sheet (Beltaos, 1995). Therefore, a general increase in cloudiness could increase the ice competency (reduce the rate of strength deterioration) due to less shortwave radiation, thus increasing the breakup resistance and probability of severe ice-jam flooding. Rapid snowmelt events and ablation of ice sheets due to a higher magnitude and intensity of atmospheric fluxes can increase river discharge and the probability of a mechanical ice-cover breakup. Hence, freeze-up levels of a season will play a vital role in controlling the frequency of ice-jam occurrences. Higher freeze-up stages mean higher runoff is required to dislodge the ice cover from the banks and other boundary supports at breakup. Therefore, when other factors are in favourable conditions (e.g. relatively less streamflow), high freeze-up levels will reduce the probability of major ice-jam occurrences during breakup in the future.

Since warmer climatic conditions and changing precipitation patterns are very pronounced in the flow regimes in Canada, the severity of ice-jam floods will be highly influenced by these factors. A warmer winter in a future climate scenerio would directly reduce the thicknesses of ice covers and thus the severity of ice jams. While the reduction in winter and spring precipitation will tend to cause fewer mid-winter breakups and less severe ice jam floods, larger winter and spring precipitation may lead to frequent winter breakups, ice jams and dynamic spring breakups, hence increasing the severity of ice-jam floods (Turcotte et al. 2019). Rokaya et al. (2019) show that relatively low flow conditions at breakup will reduce the probability of ice jam flooding along the Athabasca River at Fort McMurray in the period from 2041 – 2070. Another similar study at the same site by Das et al. (2020) also shows that the frequency of ice jam flooding is likely to be reduced in the future. However, both studies concluded that extreme ice-jam floods are still probable under certain climatic conditions.

Apart from these direct climate change impacts on river ice regimes, ice properties and streamflow discharge, there are some indirect factors that could also impact ice regimes and severity of ice-jam floods under future climatic conditions (Beltaos and Burrell, 2008). A higher amount of fall precipitation in the future will increase flows at freeze-up, resulting in higher freeze-up levels. These higher levels may, in turn, increase discharge thresholds (high discharge may require to initiate breakup), thus decreasing the probability of ice jams, especially for low-gradient rivers (Beltaos et al., 2006, Turcotte et al. 2019). The geomorphology of the river can change more rapidly if there is increased open-water runoff. More dynamic ice regimes alter sediment transportation processes, which could change the location of ice jams and modify overall ice- cover and ice-jam processes. Warmer groundwater influx will promote prolonged open-water sections during winter or reduce ice-cover strength along small streams, which could have a greater impact on downstream ice-jam processes, as small streams usually flow into large rivers, such as the Clearwater River into the Athabasca River at Fort McMurray. Moreover, changes in hydrological regimes, permafrost thaw, sea-level rise, land use and infrastructure development will have some level of impact on ice parameters and the severity of ice-jam floods (Turcotte et al., 2019).

2.3 Existing methodologies for determining climate change impacts on river ice regimes

Many approaches exist for assessing the climate change impacts on river ice regimes, including statistical and empirical analyses, and hydrological and hydraulic river ice jam modelling (Turcotte et al. 2020, Chen and She 2020, Yang et al. 2020, Andrishak and Hicks, 2008, Timalsina et al. 2013). Statistical and empirical approaches mainly analyse historical data to determine variability in long-term river ice processes and the correlation between different climatic parameters (including air temperature, snowfall and rainfall) and variables of river ice regimes (such as ice duration, ice thicknesses and ice-jam flood frequency) (Prowse et al. 2007, Beltaos 2002, Lamichhane et al. 2020). Historical data (discharge, water level, ice-in and ice-out dates) is recorded at various hydrometric stations and documented through photographs, satellite imagery and reports. However, river ice processes are often so dynamic and extreme that they can destroy the gauge station and interfere with the collection of ice and water-level information. An empirical approach, such as degree-days of freezing and melting could be applied to estimate ice-in or ice-out dates using Stefan's equation, but it is only approximate estimations and are unable to capture dynamic processes of ice regimes accurately. One of the main downsides of this approach is the large dataset required for both temporally and spatially distributed data along the rivers to fully understand the climate change impact trends. More importantly, projecting a statistically significant historical trend into future climate scenarios may not be all that accurate or reliable. Many studies suggest that climate change impacts on dynamic river ice phenomena are not linear, and analyses require incorporation of evolving meteorological and hydrological variables (Lamichhane et al. 2020, Comfort et al. 2013).

Different hydrological models Modélisation Environnementale communautaire-Surface Hydrology (MESH) and Variable Infiltration Capacity (VIC)) are used to simulate snowmelt and river discharge conditions for both past and future scenarios using a variety of meteorological forcing data from global and regional climate models (Rokaya et al. 2020, Dibike et al, 2018, Eum et al. 2017). Since runoff is an important variable controlling river freeze-up and breakup regimes, hydrographs simulated from a hydrological model can be used to indicate breakup timing by using rising of spring freshets during pre-breakup. Moreover, some hydrological models can simulate the amount of melting water from water stored in the channel (hydraulic and groundwater storage) during winter, which has a large impact on various breakup mechanisms in rivers (Jasek et al. 2005, Beltaos 2018). Although these hydrological models are able to simulate an important river ice governing variable (i.e. stream discharge), they are still unable to simulate river ice processes, ice jam formation and release events. Beltaos et al. (2006) applied the hydrological model WATFLOOD output, which is coupled with the ONE-D hydrodynamic model, to simulate daily flow hydrographs for the historical period along the Peace River in western Canada. Although the hydrological model overestimated spring discharge along the river, the timing of spring runoff was estimated accurately. More recently, Rokaya et al. (2019) and Das et al. (2020) coupled hydrological modelling results (e.g., streamflow) with a river ice hydraulic model to examine the severity of ice jam flooding along the Athabasca River at Fort McMurray under future climatic conditions. Such coupled modelling approaches have been shown to have great potential in assessing the scenarios under future climatic conditions. Moreover, many river ice models exist that could capture river ice and ice jam processes very well, if adequate calibration data are available. River ice hydraulic models range from 1-D steady-state to 1-D unsteady state to 2-D models. The basic theory of the models has mostly been formulated based on studies by Pariset et al. (1966) and Uzuner and Kennedy (1976). A summary of available river ice models is given in Table 2.1. Almost all the models have some common parameter and boundary condition inputs. Some parameters are user-defined, and some are estimated based on empirical equations. Therefore, a good understanding of river ice processes, local climatic conditions, and channel morphology is required to run each model.

Table 2-1 Summary of available river ice models.

Numerical Models	Types	Numerical Scheme	Developer
ICETHK	1-D, Steady-State	Iterative Procedure	U.S. Army
RIVJAM	1-D, Steady State	Runge-Kutta Solution	National Water Resources Institute
ICEJAM	1-D, Steady State	Iterative Procedure	University of Alberta
ICESIM	1-D, Steady State	Iterative Procedure	Acres International

ICEPRO	1-D, Steady State	Iterative Procedure	KGS Group
MIKE-11	1-D, Steady State	Standard Step method	LaSalle Consulting Group
RIVER 1D	1-D, Steady State	Iterative Procedure	University of Alberta
HEC-RAS	1-D, Steady State	Iterative Procedure	U.S. Army
RICE	1-D, Unsteady State	Implicit Finite-element method	Clarkson University
RICEN	1-D, Unsteady State	Implicit Finite-element method	Clarkson University
RIVICE	1-D, Unsteady State	Implicit finite difference method	Environment Canada
CRISSP1D	1-D, Unsteady State	Implicit Finite-element method	Clarkson University
CRISSP2D	2-D, Unsteady State	Explicit Finite-element method	Clarkson University
DynaRICE	2-D, Unsteady State	Explicit Finite-element method	Clarkson University

Although applications of the above-listed models for the assessment of climate change impacts on river ice and ice-jam floods are sparse, some numerical models have been used to predict changes in ice regimes in rivers due to climate change. For example, Andrishak and Hicks (2008) applied the River1D thermal river ice process model to predict the duration and extent of ice covers along a Canadian river for a future climate analogue in a period during the mid-21st century. The Canadian second-generation global climate model (GCM) provided the air temperature input for the model. Although this study shows good potential for using a numerical model to predict ice duration under future climatic conditions, a constant hydraulic boundary condition was assumed, which is very unlikely with continuous changing climatic conditions. Timalsina et al. (2013) applied a gridded HBV (*Hydrologiska Byråns Vattenbalansavdelning*) tool for rainfall-runoff and Mike-Ice for river ice to determine the climate change impacts on river ice regimes. In this study, two GCMs, HadAm3H SRES A2, B2, and ECHAM4 SRES B2 were downscaled to the study reach using an atmospheric regional climate model (RCM) to drive a hydrological model for simulating the future flow regime along a Norwegian river.

Das et al. (2020) and Rokaya et al. (2019) applied the RIVICE hydrodynamic river ice model to assess severity of ice-jam flooding. Input files for the hydrodynamic model were derived using available global climate models (GCMs), the Community Climate System Model (CCSM) and the Third Generation Coupled Climate Model (CGCM3). These were used to drive the Canadian Regional Climate Model (CRCM) to produce regional projections for the future. Both studies used stochastic modelling to simulate hundreds of ice jam scenarios under future climatic conditions.

River ice hydraulic models can also be combined with empirical river ice models (Turcotte et al. 2019) to examine future climate change impacts on river ice regimes. While empirical models can derive some of the important model parameters e.g. the location of ice jams and the magnitude of stream flows, river ice models are required to simulate ice-jam water levels.

Although some geospatial modelling studies have been carried out over the years to understand the current impacts of river geomorphology on ice-cover and ice-jam locations (De Munck et. al., 2016; Lindenschmidt and Das, 2015; Lindenschmidt and Chun, 2014), their application in climate change studies is sparse. Since they consider various geomorphological parameters to understand river ice processes, they can be applied to quantify future changes in river ice regimes or ice jam processes (e.g. ice jam location) if any geomorphological change occurs.

2.4 A conceptual modelling approach to determine future climate change impacts on river ice

Modelling of future climate change impacts on river ice regimes requires reliable estimates of input parameters under future climatic conditions. Common river ice and hydraulic parameters of ice jam models are bathymetry, roughness coefficients of the river bed and ice-cover, ice-cover porosity, thickness of sheet ice cover, strength parameters, river ice erosion and deposition velocity thresholds, stream discharge, the volume of ice cover and ice-jam locations. As a single model or approach is unable to determine these input parameters, a combination of different models and approaches can be applied to assess the severity of the ice-jam scenarios.

Moreover, ice-cover processes can be very vulnerable to destructive conditions, such as ice-jam formation during spring ice-cover breakup. Therefore, studies are mostly carried out to determine ice-jam severity during breakup. However, from the above discussions, it is important to note that river ice covers and hydraulic characteristics have great influence on the severity of breakup and ice-jam flooding along rivers. Therefore, modelling of climate change impacts on the severity of ice-jam flooding should simulate river ice and hydrological processes of the entire winter and spring breakup simultaneously. This approach could also improve current river ice jam modelling capacity and management strategies.

Effort should be concentrated on developing a comprehensive river ice (CRI) model that can simultaneously simulate entire river ice and hydrological processes from freeze-up to break up, incorporate all the historical trends and geomorphological changes, and deal with climatic, hydrological, and cryologic parameter uncertainties to quantify probable climate change impacts on ice jam flooding under future climatic conditions. It would be unrealistic and a huge challenge for a single research group to develop this type of model; thus, multiple model combinations and couplings and collaboration with different experts and research groups may be necessary. Figure 2.2 illustrates a conceptual CRI model flow chart to quantify the severity of ice-jam flooding under a future climate scenario. GCM output can serve as input for hydrological, thermal river ice processes and empirical models, as researchers currently rely extensively on these GCMs scenarios to develop future climate scenarios. However, the GCM models are often unable to simulate the actual climatic conditions. Even with sophisticated downscaling, there are often significant differences between modelled climatic variables (e.g. air temperature) and historically observed data (see Figure 2 of Das et al. 2017). The standard approach is to consider the model-indicated changes between baseline and future values of climatic variables; then apply these changes to observed baseline values to estimate the projected future values. The absolute and relative changes are often applied to baseline values to estimate projected values under future climatic conditions (Lamichhane et al. 2020, Andrishak and Hicks 2008; Eum et al 2017).

From the above sections, it is clear that available hydrological models can simulate future flow conditions based on future air temperature and precipitation trends and a thermal river ice processes model could simulate probable freeze-up level, winter ice thicknesses and ice volumes. This information can be transferred to an ice-jam hydrodynamic model to simulate probable ice jam scenarios. The empirical model can be applied to understand the basic trends such as degree days of freezing and melting, physical ice processes and morphological changes, and then coupled to a geospatial model to identify potential or frequently susceptible ice jam locations and necessary changes in model cross-sections for both thermal river ice and ice jam models.

Since multiple model combinations of CRI models require inputs from various sources, there can be considerable uncertainty in model inputs and outputs. One of the possible solutions is to analyze past climate conditions and associated impacts on river ice using the same model combination to quantify the model bias to historical events (Turcotte et al. 2019). This bias can be incorporated into the entire modelling process when future climate change needs to be derived. Another solution is to explore uncertainty in the model by simulating hundreds of scenarios to identify the most probable distributions (Fu et al. 2014). Recently, a stochastic modelling approach has been introduced by Lindenschmidt et al. (2016b) and used several ice jam flood studies (Lindenschmidt 2020, Das et al. 2020, Rokaya et al. 2019), where hundreds of ice jam scenarios were generated in a Monte-Carlo framework using the RIVICE hydrodynamic model. This stochastic approach can also be applied with the proposed CRI model to create a confidence band or probability distribution of probable ice jam severity under a future climate scenerio.

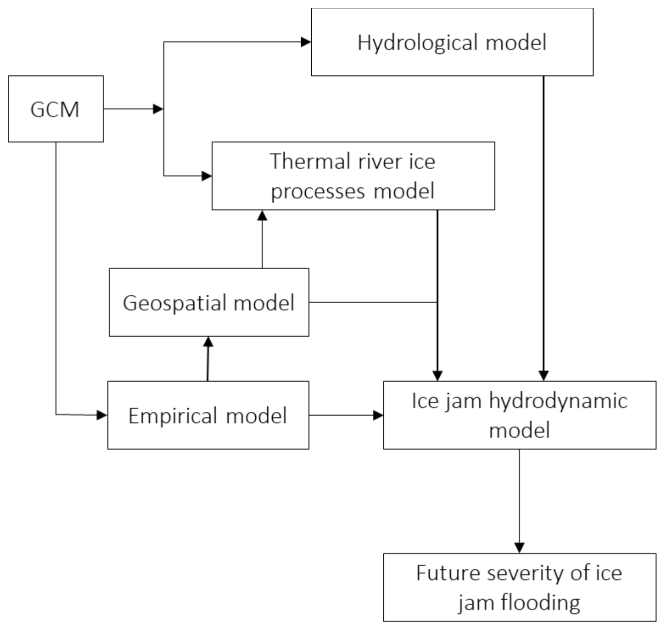

Figure 2.2 A conceptual comprehensive river ice model to assess climate change impacts on the severity of ice jams.

2.5 Limitations and Recommendations

A major limitation in current river ice modelling systems is their inability to incorporate entire river ice processes from freeze-up to breakup. Over the years, many studies have been carried out to simulate river ice and ice jam processes, but there are limitations in predicting mechanical breakup, identifying ice jam locations and characterising hydrodynamic impacts on river ice thicknesses. For example, the rates of hydraulic thickening and deterioration of river ice covers are important parameters for estimating total winter ice thicknesses and identifying ice duration and breakup timing; however, there is no model available that could quantify this hydraulic process.

Although regular monitoring and long-term historical records related to spring ice-cover breakup are available in many locations, there is still many deficiencies in collecting of winter ice-cover data, such as spatial and temporal variations of ice thickness, ice-cover types and strengths. All these parameters are necessary to improve modelling capacity and advance the knowledge in climate change impact modelling and analyses. Moreover, identifying uncertainty is still a big challenge in ice jam modelling, as well as the assessment of future climate change impacts on the severity of ice jam flooding.

To address the above challenges, a collaboration of different research groups is necessary to improve current modelling, monitoring and research capabilities. Education and knowledge dissemination between scientists, engineers and decision-makers would be an important step forward in dealing with this complex natural phenomenon. More monitoring using all available sources and tools, such as satellite imagery, aerial surveys, photography, and knowledge from local residents, is highly recommended.

2.6 Conclusion

Climate change is modifying river ice regimes and affecting the severity of ice jam flooding in cold regions. While it remains unknown whether climate change impacts will lead to more severe or less extreme events, it is perhaps time for more collaboration to quantify the overall climate change impacts on river ice under future climatic conditions.

In this study, both the historical and future climatic impacts on river ice have been summarized. A conceptual model and current modelling capabilities, challenges and limitations have also been discussed. While proposing a conceptual CRI model to assess climate change impacts on river ice-jam events for the future can be an effective means of assessing future climate change impacts, it is very challenging and there are many limitations. Therefore, it can only be done if we can work together and incorporate all possible resources and options for modelling, monitoring and expert collaboration.

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Preface to Chapter 3

CHAPTER 3: CURRENT STATUS AND ADVANCEMENT SUGGESTIONS OF ICE-JAM FLOOD HAZARD AND RISK ASSESSMENT

In this chapter, the current status of ice-jam flood hazard delineation and risk analysis is discussed. The article published to the Journal of Environmental Reviews:

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CHAPTER 3

CURRENT STATUS AND ADVANCEMENT SUGGESTIONS OF ICE-JAM FLOOD HAZARD AND RISK ASSESSMENT

Abstract

In many northern rivers, ice-jam flooding can be more severe than open-water flooding, leading to human casualties, damages to property and infrastructure and adverse impacts on ecology. Therefore, ice-jam related flooding is a major concern for many riverside communities, water authorities, insurance companies and government agencies. Ice-jam flood hazard delineation and risk analysis are important measures for flood preparation, mitigation, and management strategies. Although methodologies and techniques for open-water flood hazard and risk assessment are well established, methodologies and techniques for ice-jam flood hazard and risk assessment are often unavailable or less developed. In addition to this, a considerable number of studies have been conducted in the context of flood management, but a very limited number of studies have been carried out real-time flood risk analysis during operational flood forecasting. In this paper, the current status of ice-jam flood hazard delineation and risk analysis is discussed. A framework for real-time risk analysis for operational flood forecasting is also discussed. Finally, current limitations and future requirements for developing effective ice-jam flood hazard delineation and risk analysis methodologies are provided.

3.1 Introduction

River flooding is one of the most frequent and devastating natural hazards worldwide. Every year numerous riverside communities are adversely affected by floods. A flood event can cause human fatalities, injuries and displacement and losses of millions of dollars of property, infrastructure, and businesses. Floods affect riverside ecology and aquatic environments (Peters et al. 2016). They modify channel geomorphology, water quality and create physical disturbances in the aquatic environment, which are often detrimental to fish and other aquatic habitats. Floods can also be a major source of nutrient supply for many deltaic perched basins and ponds, and maintain water balances within these environments (Peters et al. 2006, Das et al. 2018). River floods often occur when the volume of water overwhelms or crosses a certain level/thresholds along river channels. There are numerous factors that contribute to riverine floods such as rainfall, snowmelt runoff, groundwater, geomorphology and ice jams. Since breakup ice jams are more common and have the highest potential for flooding, they are of great concern because they can be more severe than open-water flooding. For example, under the same or lower discharge, an ice jam can raise water levels two to three times higher than an open-water flood event (Beltaos 2008). This paper mainly focuses on ice-jam flood hazard delineation and risk analysis along northern rivers.

Financial costs from an ice jam flood event can be large; for example, the ice-jam flood damages for North America were estimated to be 300 million USD in 2017 (French 2017). The potential risks of ice jamming in rivers are so high that often heavy machinery (e.g. Amphibex) or sometimes even bombs are deployed to dislodge threatening ice jams within river channels (Beltaos 1995).

Climate change and regulation both significantly affect river ice regimes. Rokaya et al. (2018) presented a clear pattern of climate change and flow regulatory impacts on the magnitude and timing of ice jam floods in Canadian rivers. Beltaos (2014) reported that both climate change and regulation have contributed to the reduction of ice-jam flood frequency along the Peace-Athabasca Delta in Canada. Some previous studies have also observed a general warming trend in the Northern Hemisphere which is changing the timing of freeze-up and breakup, and the duration (generally shortening) of the winter ice cover season in many rivers (Beltaos and Prowse 2001, Prowse and Beltaos 2002, Beltaos and Burrell 2003). There is also evidence of reduced ice jam flood frequencies along rivers (Beltaos et al. 2008). In recent years, mid-winter thaw and breakup events have also been observed in temperate and maritime regions of North America (Beltaos 2002, Beltaos 2004, Beltaos et al. 2008). Although future changes to river ice regimes are highly dependent on local climatic and hydrologic conditions, it is essential that knowledge about these changes be included in flood management strategies for adequate planning and climate change adaptation.

Although open-water flood hazard delineation and risk analysis are widely applied and accepted in conventional flood management strategies, methodologies for ice-jam flood hazard delineation and risk analysis (Lindenschmidt et al. 2018) are not well developed. Therefore, considering the huge economic losses and potential risks, as well as the impacts of climate change and regulation on ice jam flooding, current flood hazard delineation and risk analysis techniques need to be evaluated and potentially extended. Additionally, many studies related to flood hazard delineation and risk analysis in a flood risk management context have already been conducted (Belore et al. 1990, Schanze et al. 2006, Sayers et al. 2013, Lindenschmidt et al. 2016). However, few studies have been carried out related to real-time flood risk analysis in an operational flood forecasting context. Thus, this study also assesses the current capability of real-time flood risk analysis for operational ice-jam flood forecasting.

The main goal of this paper is to assess the current status of the methodologies for delineating ice-jam flood risk and provide an outlook on requirements to advance this field. The specific objectives are to layout the current status of ice-jam flood hazard delineation and risk assessment and suggest requirements for ice-jam flood hazard and risk analysis in the context of operational flood forecasting. The advancement and challenges of ice-jam flood hazard and risk analysis compared to open-water flood modelling is also discussed.

3.2 Ice-jam Flood Hazard Delineation

Identifying and understanding flood hazards are necessary to increase public safety and reduce flood damages (Lindenschmidt et al. 2018, Kovachis et al. 2017). Ice-jam flood hazard can be defined as a probabilistic measure of flood extent, depth, velocity, and the presence of debris (e.g. moving ice sheets) of an ice-jam flood event (Van Alphen et al., 2009).

Although an ice-jam event is the common cause of the peak breakup water level in any given year, peak breakup water level can be the result of a variety of other mechanisms, such as upstream ice-jam releases and presence of sheet ice cover if there is no ice-jam formation during the breakup (Beltaos, 2008). When an ice-jam release due to thermal melts or changes in upstream hydraulic conditions (e.g. flows and water level rise) a steep water wave or surge may travel downstream and may result in the peak breakup water level. As this surge event can rise quickly, it has a great potential of a flooding event.

There are many different approaches that can be used to estimate flood extent and depth for a flood hazard map; however, four basic approaches, in particular, are applied in ice-jam flood hazard delineation: biophysical, flood-envelope, historical flood extent and hydro technical approaches (Burrell et al. 2015). The biophysical approach uses physical characteristics (e.g. vegetation, soils, and debris lines) of topography and ecology to identify the flood extent areas. In order to determine the ice-jam flood extent, vegetation trim lines and ice scars can be used (Lindenschmidt et al. 2018; Gerard 1981). Most often the biophysical approach is used as a preliminary step in flood hazard delineation (NRCC 1989). It can also be used to delineate final flood hazard areas if sufficient biophysical data are available. One of the most convenient approaches for identifying flood hazard areas is historical flood extent. In this approach, field (e.g. high water marks) and photographic (aerial photo, satellite imagery) information from a major past flood event are used to estimate flood extent and depth against river distance (Burrell et al. 2015). The flood envelope approach is similar to the historical flood extent, but the data are collected from multiple past flood events. This approach is useful when the data are limited for the aforementioned approaches to be applied. The hydrotechnical approach is an engineering method for deriving flood hazard using hydrological and or hydraulic models (Burrell et al. 2015). The hydrotechnical approach involves statistical derivation of design floods based on hydrologic analysis of storm and discharge records. The design flood information is then applied to a hydraulic analysis to estimate ice-jam flood profiles. The advantage of this approach is its application in areas where data such as stream flows and ice stages on past flooding is scarce, and it can be applied to statistically derive flood frequency analyses. However, this approach is relatively expensive since it requires extensive amount of field data and computation preparedness, which include all relevant historical data collection, river cross-sections/bathymetry measurements and data analyses and interpretation (Burrell et al., 2015). Hence, if sufficient ice-jam related data and resources are available, the hydrotechnical approach can be most appropriate to delineate ice-jam flood hazard along rivers (Kovachis et al. 2017).

Development of an ice-induced stage-frequency relationship is a necessary task to study ice-jam flood hazard for a specific location (White and Beltaos, 2008, Kovachis et al. 2017). In order to develop this relationship, water stages can be determined from the river discharge via rating curves (White and Beltaos, 2008). However, the formation of ice and ice jams along the river make it challenging to estimate of stages from the discharge. The stochastic nature of ice-jam formation affects the hydraulic characteristics of the flow giving a poor deterministic relationship between stage and discharge (Lindenschmidt 2020, Turcotte et al. 2017). Ice-affected data may be unavailable and inaccurate because hydrometric gauges are often damaged from extreme forces of ice debris and blocks during ice jam formation. Therefore, ice-induced data are not homogeneous and are shorter than the open water records. Since the unavailable gauge data are often associated with extreme events, which are very important for frequency analyses and various types of approaches, alternate sources are required, such as the collection of ice-related data from the nearby station or locations.

Historical ice-related data are collected from various societal and environmental sources. Societal sources include newspaper archives, aerial, satellite, and personal photography, government records, and private agencies. Environmental indications include high water marks, ice scars on trees, damaged vegetation and topographical marks formed from shoving ice. However, caution must be exercised when collecting historical data, to avoid a false indication of peak stages. For instance, ice scars on trees can be formed from the water surface rising during freeze-up and breakup events, which may not be the actual peak stages (Gerard 1981, Gerard and Calkins 1984). The probability of exceedance for an observed or estimated stage can be calculated by assigning the appropriate rank and sample length in a suitable probability formula. Since historical data are not homogeneous, the concept of ‘perception thresholds' or ‘perception stage’, an elevation below which an ice-jam flood events go unnoticed, is considered when collecting the appropriate length and rank for a flood peak flow or stage (England et al. 2019, Beltaos 2008). Moreover, the record length should be assigned separately for all ice-jam peak stages if they have been collected from different sources. The applicable record length for an ice-jam flood peak is equal to the total number of years in which the perception stage does not have that peak. Similarly, the rank of the peak is selected by assigning the group of peaks having a perception stage that does not exceed that peak (Gerard and Karpuk 1979). The quantification of stage-frequency relationships from these historical data is usually developed using a direct graphical method. Additionally, for nonparametric analyses, a graphical method could be replaced by the Kernel estimator, but no application to ice-jam stage frequency has been reported yet (White and Beltaos 2008).

Where the historical data is inadequate, the indirect or synthetic approach can be applied (Beltaos 2010, White and Beltaos 2008). Gerard (1989) proposes a guideline about the indirect approach that combines flow frequency estimates with an ice-affected stage-flow rating relationship to develop a synthetic frequency curve of ice-jam stages. The flow data for an ungauged site are required to be interpolated from records of upstream and downstream gauges or extrapolated from regionalised estimations. However, using the maximum or instantaneous discharges (if available) during ice cover breakup could be the most appropriate data to develop such frequency curves. An ice-jam stage-discharge or rating relationship is usually developed from a fully developed or equilibrium ice-jam. Once the ice-jam rating and discharge frequency estimate curves are combined, the synthetic frequency of a specific stage during a breakup can be easily derived. Another methodology is proposed for estimating ice-induced flood probabilities using a stage distribution approach (Burn 1989). Although in this approach two stage-discharge curves (one for a solid ice-cover and another for ice jam events) are used to develop the frequency curve, this approach is not quite as reliable in extreme ice-jam events (McPherson, 1991).

However, there are still some limitations to the synthetic ice-induced stage frequency analysis since this method is time-consuming and a good understanding of local channel geomorphology and ice jam processes is required. In this context, numerical ice-jam modelling techniques can be applied to synthesize ice-jam affected stages based on a given discharge and the characteristics of ice jams (e.g. toe location, and volume of ice) for a particular location (Beltaos 2010). However, numerical models require many user-defined variables and a good set of calibrated data (Carson et al. 2011). Empirical evidence suggests that, for a given discharge, ice-jams can create a range of stages which do not meet the assumption of the synthetic approach of frequency analysis of ice-jam stages (Beltaos 2012). Ahopelto et al. (2015) also reported that the development of ice-jam frequencies along the Tornionjoki River failed using the indirect approach due to insufficient data. Beltaos (2012) introduced an alternative method for synthetic frequency analysis of ice-jam stages called the distributed-function method (DFM), in which a probability of breakup stage is estimated from a given discharge and a conditional probability function. Although this method provides relatively better results compared to the synthetic approach, there are still some limitations in probability estimates for peak ice-jam stages. The Federal Emergency Management Agency (FEMA) provides detailed guidelines to develop ice-jam flood frequency curves using direct and indirect approaches (FEMA 2018). In this guideline, while a direct approach relies highly on historical ice-jam stages, an indirect approach is mainly based on equilibrium ice-jam or ice-jam thicknesses that completely block the channel.

A threshold of flows can also be applied based on certain hydraulics and ice cover breakup characteristics (Tuthill et al. 1996). Note that these threshold values are very site-specific and change from year to year due to local hydro-meteorological conditions, ice characteristics and rates of thermal deterioration of the ice cover which all have a strong influence on stream flows during pre-breakup and breakup periods. Additionally, the threshold values solely represent the mid-points of the values extracted from the field (White and Beltaos 2008).

In recent years, some progress has been made in ice-jam flood frequency analyses using a stochastic modelling approach (Lindenschmidt. 2020, Lindenschmidt et al. 2016b, Lindenschmidt and Rokaya, 2019, Das et al. 2020, Rokaya et al. 2019, Rokaya et al. 2019). In this approach, a one-dimensional fully dynamic river ice model is used to simulate thousands of ice-jam water level profiles within a Monte-Carlo framework. From the ensemble of water level profiles, the peak stages for a particular location are extracted to derive exceedance probabilities and stage-frequency distributions. These distributions are then used to determine flood hazard for a specific return period of a flood. However, in this approach, there are various limitations associated with the selection of the modelling parameters such the toe of ice-jam locations are not always uniformly distributed and volume of ice-cover is not always independent to flow magnitude. Moreover, this approach only deals with the peak water level elevation during ice-jam events.

Ice-jam stage-discharge relationships can be developed using a variety of analytical and numerical models. Most of the theoretical concepts of these models were advanced by Pariset et al. (1966) and many others over the years. These models include both steady-state and dynamic models and can range from simple one-dimensional to complex two-dimensional configurations. For example, HEC-RAS by the US Army Corps of Engineers, RIVICE by Environment Canada (ECCC, 2013), River 1D and River 2D from the University of Alberta, RIVJAM by Environment Canada, MIKE 11 by LaSalle Consulting Group, now GCL-NHC, ICESIM by Hatch Energy, and DYNARICE, CRISSP1D and CRISSP2D by Manitoba Hydro and Clarkson University (Kovachis et al. 2017).

The numerical river ice models require some hydro-meteorological and geomorphological parameters and boundary condition inputs to simulate the ice-jam formation and associated flooding (Kovachis et al. 2017). Some parameters and boundary conditions are based on empirical information, field data collection and GIS information. Every model has some constants and user-defined parameter inputs, depending on their algorithms. Moreover, uncertainties are inherent in every model when selecting values for ice parameters (e.g. ice volume, roughness and type of ice cover), river bathymetry (e.g. cross-sections spacing) and topographic data (e.g. DEM resolution).

3.3 Ice-jam Flood Risk Analysis

Flood risk analysis is a combination of flood hazard and vulnerability assessment, that identify the probability of potential consequences of a flood event (Figure 3.1) (FEMA 2018). The potential consequences can be included as financial damages, loss of life and environmental degradation. The flood hazard identifies the intensity and the flood probabilities, while vulnerability provides the information related to the exposure and susceptibility. The flood hazard map presents the intensity (flood extent and depth) for different flood exceedance probabilities with different vulnerability information. Vulnerability includes exposure (e.g. buildings, population, land use, and infrastructure) and susceptibility, which estimates the financial damages as a function of flood depth, velocity and other factors (e.g. moving debris) (Lindenschmidt et al. 2006). The relationship between flood inundation and the damages caused by that inundation establishes a flood depth-damage curve (Lindenschmidt et al. 2006).

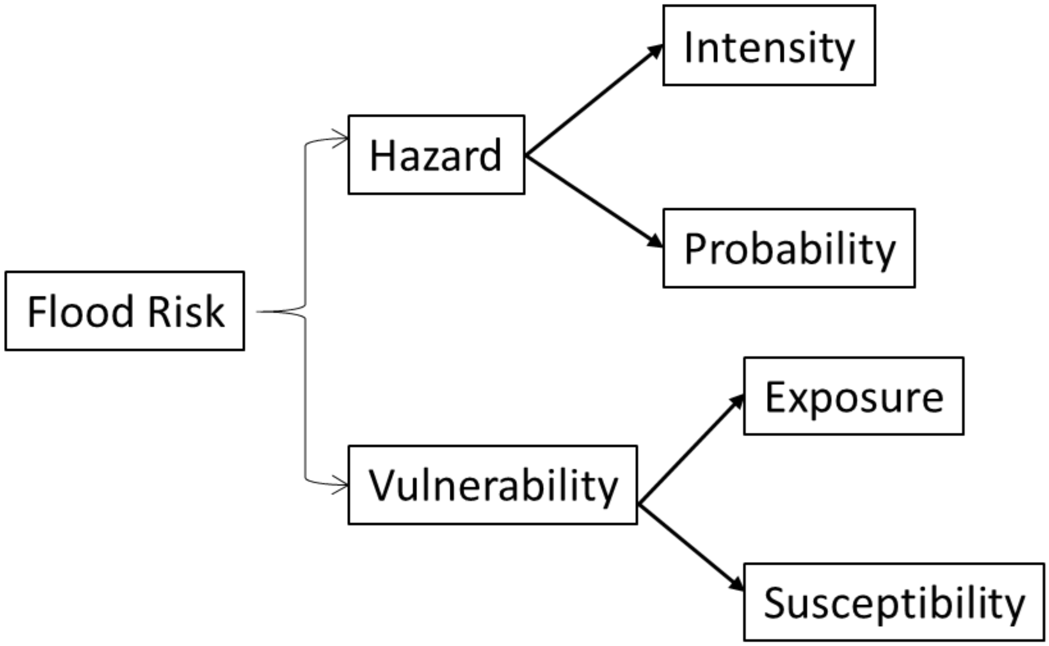

Figure 3.1 A flow chart of flood risk analysis.

Flood damages can be divided into the categories of tangible and intangible damages (IBI-Group 2015). Tangible damages usually refer to financial damages that can be measured in monetary terms and intangible damages mainly consider social or environmental implications that cannot be measured in monetary terms, such as emotional stresses or loss of life. Tangible damages can be further divided into direct and indirect damages. Direct damages occur due to direct contact with flood water, which is directly quantifiable, such as damages to buildings and their contents. Indirect damages occur due to interruption of some activities due to the flood water, such as business closures and traffic disruption.

Ice-jam flood risk analysis is a probabilistic manner of estimating the potential consequences, such as direct and indirect damages or the number of people who would be affected by specific flood events (Lindenschmidt et al. 2006). Lindenschmidt et al. (2016) calculated direct damages to the structure and content of buildings for two ice-jam extreme events with 1:100 and 1: 200-year return periods. The expected damages for these two extreme events were combined to calculate the total expected flood risk per unit area over a 200 year period. To date, very few studies have been attempted to estimate ice induced flood risk, since most risk analyses are limited to open-water floods. In this method, a stochastic modelling approach is applied to simulate hundreds of ice-jam water level profiles. The ensemble of hundreds of ice-jam profiles is then used to estimate the ice-jam flood hazard in a probabilistic manner (Lindenschmidt et al. 2016). The probability of flood hazard is finally combined with the vulnerability information to estimate flood risk. Although it is a great advancement in ice-jam flood risk estimation, the method still needs to be extended to consider additional ice-jam flood hazard information, such as freezing conditions, rate of rise and ice debris. During ice-jam floods, damages can result from moving ice sheets and freezing of flooded water. The impacts of the rate of water level rise and the duration of the flood should also be considered (Das and Lindenschmidt 2019, Burrell et al. 2015). The water level during a breakup ice-jam formation can rise rapidly leaving very little time to implement any mitigation or evacuation measures. This may increase the risk to people and infrastructure.

In the case of freeze-up jams, flood water remains on the floodplain longer due to the freezing of flooded water (Burrell et al. 2015). The freezing of flooded water may cause extra damages and pose additional risk to property and industrial production, and lead to traffic disruption. Ice jams can also result in adverse ecological impacts (Peters et al. 2016). Although these impacts are difficult to account for in flood risk analysis, a method should be developed to determine the ice-jam flood risk for riverside ecology.

3.4 Ice-jam Flood Forecasting

Ice-jam flood forecasting is a challenging task because ice-jam formation processes involve very complex and nonlinear hydrological, meteorological and geomorphological factors. Some empirical, statistical, and artificial intelligence approaches have been applied to develop breakup and ice-jam forecasting models (Mahabir et al. 2002, White 2003, Mahabir et al. 2006). Empirical approaches are highly dependent on local conditions and tend to have a high rate of false-positive errors about flooding, resulting in very limited success of ice-jam forecasting. Although statistical approaches improve the accuracy of false-positive errors, the accuracy in predicting ice-jam forecasting is still not satisfactory. Artificial intelligence techniques such as neural network and fuzzy logic may be able to capture non-linear processes of ice-jam formation and have the potential to predict ice-jam flooding accurately (Guo et al. 2018). Mahabir (2008) was able to predict all the ice-jam flooding events observed along the Athabasca River at Fort McMurray for the past 25 years using fuzzy logic techniques; however, there was still some false positive predictions of ice-jam flooding. Additionally, these techniques only focus on temporal processes and are unable to consider the spatial processes of ice-jam formation. Sun and Trevor (2018) showed how the accuracy of predicting maximum breakup water level can be improved by combining different forecasting methods, such as adaptive neuro-fuzzy systems, artificial neural networks, and multiple linear regression. The combination of different models may not always be feasible in the operational flood forecasting context because it requires several different groups of experts and long computation times. Some hydraulic models such as River2D (Brayall and Hicks 2012) and HEC-RAS (Tang and Beltaos 2008, Beltaos et al. 2012) have also been applied to predict ice-jam backwater levels deterministically; however, it is challenging to incorporate the stochastic nature of ice-jam formation in these models.

Zhao et al. (2015) developed a data-driven fuzzy logic system to predict the severity of ice-jam floods. Although this model was effective in making forecasts with limited historical data, some uncertainties still existed when breakup occurred before the peak snowmelt runoff. Similar to other predictive models, this model also provides only yes/no outcomes for possible flood occurrences, which can be dangerous if the wrong action or no action is carried out in managing a flood, in the case of false-negative results (Lindenschmidt, 2020). To avoid this kind of false-negative situation when resources for data collection are limited, a probabilistic forecasting approach was recently applied along the Athabasca River at Fort McMurray by Lindenschmidt et al. (2019). In this approach, a hydraulic model was applied in a stochastic framework to simulate an ensemble of ice-jam water level profiles. From these profiles, probabilities of flood extents and depths were estimated for the flood-affected areas. A similar approach was designed by Warren et al. (2017), where a river ice numerical model was used to determine the near real-time ice-induced flood hazard along the Exploits River in Newfoundland.

3.5 Ice-jam Flood Risk Analysis in Operational Forecasting

Since the current flood forecasting system is mostly limited to flood hazard mapping, there is an opportunity to improve the emergency response by incorporating real-time risk analysis in flood forecasting. Once the probable flood-prone areas are identified for a given probability of occurrence in real-time flood forecasting, the possible consequences, such as the total affected population and economic flood damages, can be evaluated simultaneously (Molinari et al. 2013, Dottori et al. 2017). Although some experimental research projects have already attempted to assess real-time flood impacts during flood forecasting in Europe (Rudari 2015, Schulz et al. 2015, Saint-Martin et al. 2016), application of these assessments into operational forecasting is sparse.

Dottori et al. (2017) introduced an operational procedure for real-time flood risk assessment in Europe. In this approach, event-based flood hazard maps were integrated with vulnerability information to estimate the affected population, infrastructure and urban areas as well as direct economic damages. Lindenschmidt et al. (2019) and Kögel et al. (2017) provide a checklist of requirements for the development of an ice-jam flood forecasting system for the lower Oder River, extending along the border between Germany and Poland.

A few studies have recently attempted to map and assess real-time ice-jam flood hazard along the Athabasca River at Fort McMurray (Lindenschmidt et al. 2019, Lindenschmidt 2020) and Exploits River at Badger (Warren et al. 2017). An ice-jam numerical model (RIVICE) was used in these studies for real-time ice-jam flood forecasting and both studies have the potential to provide the basis for real-time ice-jam flood risk analysis and provide a better understanding of ice-jam flood risk to property and inhabitants.

A hydrological model can be applied to generate streamflow forecasts using a daily weather or meteorological forecast for the next 10 days (Lindenschmidt 2020). The hydrological model can identify the peak discharge along the river (Dottori et al. 2017). In order to produce flood hazard maps, this information may only be adequate for open-water flood forecasting. Ice-jam flood forecasting requires additional boundary conditions and parameter inputs. The information on boundary conditions and parameters can be provided from simulation results of other models (e.g. hydrologic models), historical data, satellite and aerial photography, field surveys and hydrometric gauging records.

A river ice hydraulic model can be used for flood forecasting using river ice boundary conditions and parameters to compute near real-time ice-jam flood water profiles for an affected area. Hundreds or thousands of expected ice-jam water level profiles can be generated if the stochastic approach is applied; however, it may depend on the operational timeline. A probability of flooding can be estimated from the ensemble of ice-jam water level profiles and a GIS tool can translate the probability of flooding into a real-time hazard map (Lindenschmidt et al. 2015, 2019b).

A real-time flood hazard map can be combined with exposure and vulnerability information to assess economic damages and affected infrastructure, urban areas and populations. The stage-damage function for a particular location can be gleaned from previous studies, government records and government agencies (Lindenschmidt et al. 2016, IBI-Group 2015). The number of inhabitants in each household can be collected from the census record and can be updated from the local government every year.

3.6 Advancement and Challenges

Ice-jam formation and associated flooding mechanisms are a dynamic and complex interaction of hydro-meteorological and geomorphological parameters (Beltaos 2008). A comprehensive understanding of these mechanisms is required to develop an appropriate method for flood hazard and risk assessment mapping. Collecting historical data and real-time ice monitoring is crucial for understanding these processes and modelling (model calibration) ice-jam floods along rivers. However, field data collection and continuous monitoring of ice-jam formations are often challenging tasks because of remote locations, adverse weather conditions, safety issue when working with ice and high cost (Chu et al. 2015). Therefore, methods should be developed to collect field data from multiple sources (e.g. remote sensing, local residents and media) and to use this information to determine input parameters (e.g. ice-jam location, ice-jam extent, backwater level, etc.) for numerical models.

Ice-jam flood modelling requires sufficient data for river ice parameters and boundary conditions. Many of these parameters and boundary conditions are usually collected from historical data, empirical relations, and modellers' experience. However, some of the boundary conditions are very difficult to predict due to their stochastic nature (Lindenschmidt 2017). For example, an important boundary condition for the ice-jam simulation is the volume of inflowing ice, which is difficult to estimate because of the uncertainties in the ice cover thicknesses and random and continuous movement of ice fronts during an ice jam-release/run progressions. Although a few methods have already been applied to determine ice volume (Lindenschmidt 2017, Zhang et al. 2017), more case studies are still required to establish an appropriate method.

Comprehensive ice-jam flood hazard delineation requires water depth and velocity of the overbank flow in the floodplain (Kovachis et al. 2017). While a hydraulic model can be applied to simulate ice-jam water level profiles, a digital elevation model is required to extend the flood water levels from the river to the floodplain to estimate the flood hazard (Das et al. 2020). Therefore, a comprehensive river ice model to simulate both flood depths and flow velocities simultaneously is required. In addition to this, a 2D hydrodynamic ice-jam simulation model can be developed to simulate both ice-jam flood water levels and flood hazard maps simultaneously.

Ice-jam flood risk assessments require an accounting of the damages due to moving ice sheets and freezing of flooded water (mid-winter breakup) during an ice event (Burrell et al. 2015). Flow velocity can drive ice blocks into the floodplain and cause damage to property and infrastructure. In order to determine whether ice blocks can flow into the floodplain and calculate the total damages due to transported ice blocks, five factors should be assessed: (i) flood depth above the bank; (ii) ice block thickness; (iii) intensity of flow velocities on the floodplain; (iv) size and mass of the ice blocks on the floodplain; and (v) the presence or absence of obstacles on the banks (e.g.

trees, vegetation, structures and snow layers) (Burrell et al. 2015, Kovachis et al. 2017). In addition to these, variability in flood duration can affect the severity and consequences of the flood event. The information related to these kinds of damages is still sparse. Therefore, future research should focus on how these damages can be calculated and incorporated in the risk analysis.

Although plenty of studies have already provided information to assess economic damages (IBI-Group 2015, Lindenschmidt et al. 2016), studies related to assessing the affected population are sparse. DEFRA (2006) provided a detailed guideline for assessing flood risk for the population. Some factors need to be considered while calculating the flood risk to people. These include flood depth and flow velocity, types of building (e.g. multi-story or single-story), timely issuance of flood warning, appropriate or inappropriate response to flood warning, the rate of flood formation, and the vulnerability of people (the elderly, disabled and sick). The number of people at risk combines the flood hazard rating (conditions when people can be drowned or swept away in a flood), the vulnerability of the area (chance of people being exposed to flood water) and people's vulnerability (the ability of people to respond to a flood). The following equations can be used to calculate the risk to people.

$$\textit{Flood hazard rating (HR)} = d \times (v+0.5) + DF \; \ldots \; \ldots \; \ldots \; \ldots \; (3.1)$$

where d is the depth of flooding (m), v is the velocity of flood waters (m/sec) and DF is the debris factor depending on the characteristics of the land use and ice blocks in the case of ice-jam flooding.

$$\textit{Area of vulnerability (AV)} = SO + NA + FW \; \ldots \; \ldots \; \ldots \; \ldots \; (3.2)$$

where SO is the score for the speed of onset, NA is the score for nature of the area and FW is the score for flood warning.

People vulnerability score (Y) = % residents suffering from long-term illness + % residents aged 75 or over … … … … … (3.3)

The details about the method for calculating flood risk to people can be found in DEFRA (2006).

Figure 3.2 shows a conceptual diagram to forecast real-time ice-jam flood risk. There are three components in real-time ice-jam flood risk analysis which need to be considered. First, a river ice-hydrodynamic model can be applied to simulate an ensemble of ice-jam water level profile for the study area, expressed for different percentiles (10^{th}, 50^{th} and 90^{th}) of flood depth. Second, GIS can be employed to generate expected flood depth, floodplain flow velocities and presence of debris (score) maps. Finally, the expected economic and population risks can be estimated using the stage-damage and census report, respectively.

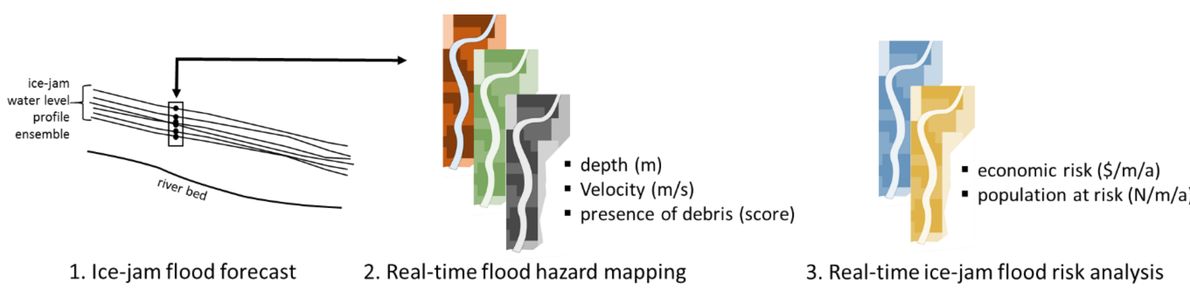

Figure 3.2 A conceptual diagram of the real-time ice-jam flood risk assessment.

Since a warming climate is changing ice regimes and the severity of ice-jam formation (Beltaos et al. 2006, 2008, Das et al. 2020), it is important to evaluate if the current modelling approaches for ice-jam flood hazard delineation are adequate for determining the impacts of climate change. For example, one of the important input parameters of ice-jam hydraulic modelling is the volume of ice forming ice jams which may change with future climatic conditions, hence a hydro-technical approach should be developed to determine such parameters to evaluate future ice-jam flood risks.

Such research should be done to identify additional factors that may need to be incorporated into the hydro-technical modelling system to capture breakup dynamics and characteristics in the future.

3.7 Summary and Conclusion

Ice-jam flood hazard delineation and risk analysis is an important requirement for an effective flood management strategy in cold regions. Although several methods have been developed for delineating ice-jam flood hazard, such as ice-induced stage frequency calculations, most of the methods still rely extensively on historical data. Historical data is often unavailable or insufficient. While the synthetic method can be an alternative in the case of inadequate historical data, this method has some limitations. A stochastic method can be another effective approach to capture the stochastic nature of river ice processes and developing stage-frequency distributions for ice-jam backwater staging. However, all of these hydro-technical approaches require an improved understanding of river ice processes and appropriate methods for determining river ice parameters and boundary conditions (e.g. inflowing ice volume).

The incorporation of real-time ice jam flood risk analysis in operational flood forecasting could be an effective advancement in this field of study. Rapid flood risk analysis during an event could help to identify the number of affected people and expected damages for a study area. This information could then be applied to making decisions regarding implementation of emergency measures and evacuation strategies. However, application of new methodologies, improvement of modelling capabilities and field observation strategies are still required to determine ice-jam flood hazard and risk accurately.

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Preface to Chapter 4

CHAPTER 4: EVALUATION OF THE SENSITIVITY OF ICE-JAM FLOOD DELINEATION TO HYDRAULIC MODEL PARAMETERS, BOUNDARY CONDITIONS AND DIGITAL ELEVATION MODELS

In this chapter, the influence of model parameters, boundary conditions and digital elevation models (DEM) on ice jam flood hazard is estimated using a novel stochastic framework. The article published in the Journal of *Cold Regions Science and Technology* for publication:

Das, A., & Lindenschmidt, K. E. (2020). Evaluation of the sensitivity of ice-jam flood delineation to hydraulic model parameters, boundary conditions and digital elevation models. *Cold Regions Science and Technology*.

Contribution of Authors: Apurba Das carried out all the data analyses and wrote the manuscript. Karl-Erich Lindenschmidt conceptually helped to develop the paper and reviewed the manuscript throughout the process.

CHAPTER 4

EVALUATION OF THE SENSITIVITY OF ICE-JAM FLOOD DELINEATION TO HYDRAULIC MODEL PARAMETERS, BOUNDARY CONDITIONS AND DIGITAL ELEVATION MODELS

Abstract

Model parameters and boundary conditions characterizing flood domains in riverine flood modelling play an important role in the delineation of the flood hazard along rivers. Since the digital elevation model (DEM) is an integral part of the delineation of flood hazard, it is necessary to determine the influence of the DEM, alongside hydraulic model parameters and boundary conditions, on model outcomes. This study provides a novel framework to include the DEM in the sensitivity analysis of a river ice hydraulic model. It is the first study to consider a DEM as a factor in a global sensitivity analysis. The result demonstrates that ice-jam flood delineation is highly sensitive to DEMs' (flood depth and extent). While flood hazard delineation is low to moderately sensitive to all the model parameters, it is highly sensitive to almost all the boundary conditions. The Athabasca River at Fort McMurray in Canada is presented as a test site.

4.1 Introduction

Model parameters and boundary conditions of riverine flood modelling play an important role in the delineation of flood hazard along rivers. Model parameters and boundary conditions serve as input to a hydraulic model to simulate water-level profiles. These parameters and boundary conditions include many climatic (e.g. air and water temperature), hydraulic (e.g. water level and discharge) and geomorphological (e.g. channel cross-section and bed roughness) characteristics of rivers. In ice-jam flood modelling, river ice parameters include hydraulic roughness of the ice-cover underside, deposition and erosion velocity of ice along the bottom surface of the ice cover, thickness and porosity of the ice cover and incoming ice floes and inflowing ice volume (Beltaos and Burrell, 2010, Carson et. al. 2011, Fu et. al. 2014, Lindenschmidt et al. 2012). Many of these parameters are estimated empirically and some of their values may require the extensive effort of field data collection. For these reasons, river-ice boundary conditions are difficult to estimate deterministically; hence, the stochastic modelling approach has been used to calibrate their frequency distributions (Lindenschmidt, 2017, Rokaya et. al. 2018).

Since the 1960s, a significant number of studies have introduced static and dynamic numerical river ice models, such as HECRAS (Carson et al. 2001), RICE (Lal and Shen, 1991), RICEN (Shen et al., 1995), RIVJAM (Beltaos, 1996), ICEPRO and ICESIM (Carson et al., 2001), DynaRICE (Shen et al., 2001), CRISSP1D (Chen et al., 2006), RIVICE (EC, 2013), and YRIDM (Fu et al., 2014). While these models perform well when calibration data are available, performance of the models is unsatisfactory in uncalibrated or blind mode (Carson et al. 2011). This is mostly due to a wide variation in model parameters (open-water vs. river-ice parameters). River ice-jam modelling requires a variety of river-ice and open-water parameters (e.g. porosity, ice thicknesses, roughness, ice erosion and deposition velocities thresholds, and bed roughness) to simulate ice jams. Moreover, different models adopt different parameters and ranges of values (Carson et. al 2011), leading to high uncertainty in their values**.**

To overcome these challenges of uncertainty, characterization of the influence and role of different parameters on ice-jam flooding mechanisms is required. Global sensitivity analysis (GSA) is applied to determine the most important components of the model that control the ice dynamics and model performance. Hence, in practice, GSA can be applied in river-ice modelling to adjust the optimum parameter and boundary condition settings. Several studies have already been carried out using GSA in river-ice modelling. Lindenschmidt and Chun (2013) carried out GSA to determine the influence of river ice parameters on different ice-cover formation processes using regional sensitivity analysis. Sheikholeslami et al. (2017) conducted a comparative study of two GSA methods, variogram analysis of response surfaces (VARS) and conventional regional sensitivity analysis (RSA), to investigate the effect of river-ice parameters on the model's behaviour. Both of these studies found backwater level outcome is most sensitive to the values of ice porosity and upstream discharge. Lindenschmidt (2017) extended these GSA approaches by using stage frequency distributions as objective functions in the sensitivity analysis. One main advantage of the GSA approach is its ability to assess the impact of model parameters and boundary conditions on different flooding events. Although all of these studies were able to estimate the impacts of model parameters and boundary conditions on model performance based on ice-jam backwater levels, studies on how these factors affect ice-jam flood hazard delineation are sparse. Ice-jam flood hazard delineation typically has two main components: hydraulic ice-jam modelling and flood hazard mapping.

The DEM is a key component in ice-jam flood hazard mapping. Flood damage can be calculated as a function of flood depth; hence, accurate ground elevation data is vital for assessing risk and potential damages. However, accurate ground elevation data acquisition and GPS surveys are very costly, time-consuming and difficult to carry out in many remote areas. Therefore, modellers rely mostly on remotely acquired DEMs. The most common sources of DEM within the latitude of our along the Athabasca River in Canada are the Shuttle Radar Topography Mission (SRTM), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Canadian Digital Elevation Model (CDEM) and Light Detection and Ranging (LiDAR) (Ali et al., 2015). SRTM and ASTER are the only global DEMs that cover most of the areas in the earth, with the finest resolution being 1 arc second (30 m) for both of these DEMs (Nikolakopoulos et al., 2006). The CDEM, ground or reflective surface elevations, is available for almost all of Canada, with a resolution varying from 0.75 to 3 arc seconds depending on the geographic location (GC, 2016). The LiDAR DEM is commonly used for hydraulic and hydrological studies, as it provides the finest resolution and most accuracy compared to other DEMs (Cook and Merwade, 2009, Haile and Rientjes, 2005, Zhang and Montgomery, 1994). As the various DEMs are made available with different resolutions and accuracies, quantification of the influence of the DEM on model performance should be properly addressed. GSA can then be used to determine the importance of the DEM in ice-jam flood delineation. The main purpose of this research is to present a novel framework for relative sensitivity analysis of different components of flood delineation. To the author's knowledge, it is also the first study that incorporates the DEM as a parameter in the GSA. The specific objectives of this study are to:

I. assess relative accuracy of different DEMs for ice-jam flood hazard delineation.

II. quantify the relative sensitivity of flood hazard to the river ice hydraulic model parameters/boundaries and DEM;

III. identify where data collection resources should be directed in the future e.g. parameter estimation or boundary condition determination or base data such as DEM refinement.

4.2 Methodology

4.2.1 Study site

The Athabasca River at Fort McMurray in Canada was selected as the test site for this study (Figure 4.1). The Athabasca River originates in the Rocky Mountains at the Columbia Icefield and flows approximately 1538 km northeastward before draining into the Peace-Athabasca Delta (PAD) in northern Alberta. Approximately 280 km upstream from the PAD, the Town of Fort McMurray (TFM) is situated at the confluence of the Athabasca and Clearwater rivers. Historically, this location is one of the ice jam flood-prone areas along the Athabasca River due to the river's morphological characteristics at this location. Here, along the flow direction, the river is characterized by abrupt changes in slope (from 0.001 to 0.0003) and width (between 300 and 700 m) and an increase in the presence of islands and sand bars. The Clearwater River has an additional impact on ice-jam flooding at the TFM by being an additional source of water and ice, which can exacerbate an ice-jam event along the Athabasca River. Since the 1870s, a total of twenty-four ice-jam events have been documented in the vicinity of the TFM (Robichaud, 2003). The mechanism of flooding along the Athabasca River at the TFM is unique. During spring breakup, ice jams often form along the Athabasca River downstream from the confluence of the Athabasca and Clearwater rivers, resulting in high backwater flows along the Clearwater River that flood the downtown area of the TFM. Backwater flooding along the Clearwater River has also been documented, particularly the floods which occurred in the springs of 1977, 1979, and 1997.

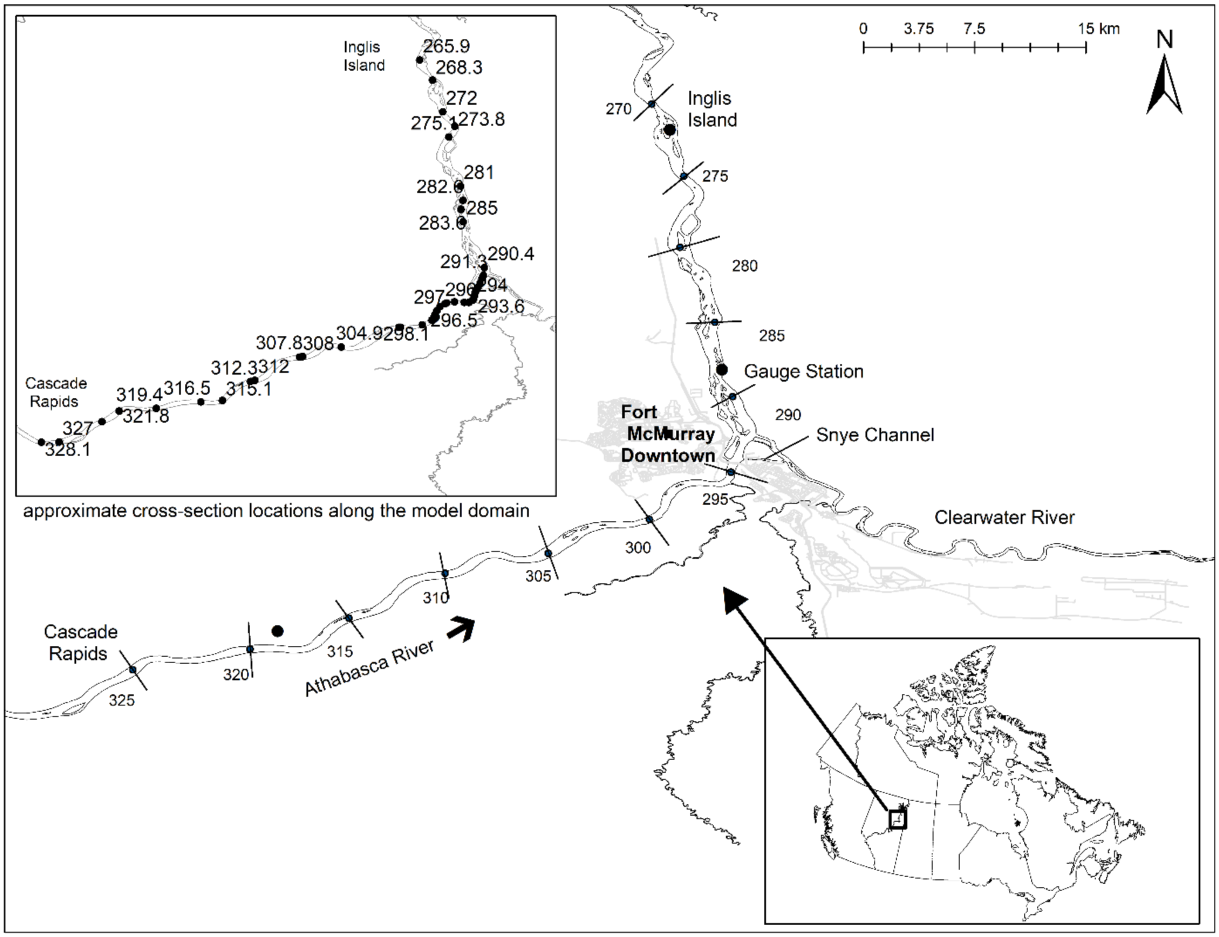

Figure 4.1 The Athabasca River at Fort McMurray and approximate cross-section locations of the RIVICE hydrodynamic model. The km values along the Athabasca River indicate the distances from the mouth of the river.

4.2.2 RIVICE Model and Monte-Carlo Setup

The 51 km model domain along the Athabasca River extends from Cascade Rapids to Inglis Island (Figure 4.1). The surveyed cross-sections were available to set up the one-dimensional hydraulic model domain. The observed water flows from 1957 to 2019 were obtained from the gauging station on the Athabasca River downstream of Fort McMurray (07DA001, see also Figure 4.1 for the location of the gauge), operated by Environment and Climate Change Canada (ECCC)'s Water Survey of Canada (WSC). The study examines ice-jam backwater flooding, and flooding at the TFM which usually occurs due to ice jam formation downstream of the confluence of the

Athabasca and Clearwater rivers. Ice jams occurring downstream of the confluence causes water to back up into the Clearwater River channel, which could then flood the downtown area of the TFM. Therefore, an important boundary condition is the toe of the ice jam, which was selected to be downstream of the confluence of the Athabasca and Clearwater rivers to examine the ice jam effects at the TFM (Table 4.1).

The hydraulic model RIVICE (EC, 2013) was used to simulate ice-jam formation along the study site. RIVICE is a one-dimensional hydrodynamic model that uses various ice parameters and boundary conditions to simulate ice-jam backwater profiles (Figure 4.2). The parameters include porosity of the ice floes *PS* and ice cover *PC*, thickness of the ice floes *ST* and ice cover *FT*, flow velocity thresholds for ice erosion v_{er} and ice deposition v_{dep}, coefficient of hydraulic roughness underneath the ice cover n_{8m} (Manning n-value at an ice thickness t = 8 m, please see the RIVICE user manual to find the detail explanation about this parameter (EC 2013)), and a hydraulic flow roughness or Manning coefficient for the river bed n_{bed}. Boundary conditions include the upstream supply of incoming volume of ice V_{ice}, upstream volumetric discharge Q, downstream water level W and the location of the toe x of the ice jam. The model setup for this study site was extracted from Lindenschmidt (2017).

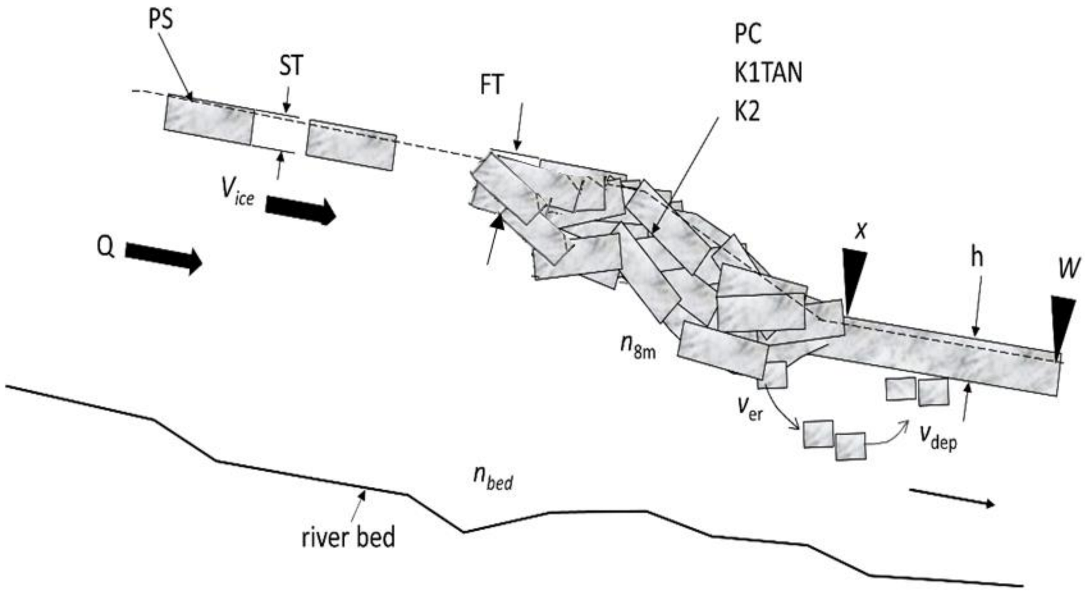

Figure 4.2 A conceptual diagram of the parameters and boundary conditions used in the RIVICE model.

The RIVICE model was embedded in a Monte-Carlo (MOCA) framework in the Parameter Estimation Program (PEST) to simulate an ensemble of ice-jam backwater level profiles (Lindenschmidt et al. 2016, Lindenschmidt 2017, Rokaya et al. 2019, Das et al. 2020). The ensemble of the ice-jam backwater profiles was used for the GSA. For the MOCA, parameter values and the location of the ice-jam toe were extracted randomly from uniform probability density functions (pdf) within certain ranges (minimum and maximum) and the certain boundary condition values (e.g. upstream discharges and volume of incoming ice) were generated randomly from Gumbel pdf with certain statistical properties (location and scale) for each (Table 4.1). Random values of observed upstream discharge were extracted from a Gumbel distribution. A Gumbel distribution of incoming ice volume was calibrated using MOCA by comparing distributions created from simulated water levels at the Athabasca River gauge location, downstream of Fort McMurray, with observed instantaneous maxima recorded at the gauge. The calibrated RIVICE model in the MOCA framework was run using an approximately assumed ice-distribution and observed flow-frequency distribution to match the observed stage-frequency along the Athabasca River at Fort McMurray. After each MOCA simulation, the simulated stage-frequency distribution was compared with the observed stage-frequency distribution. If they did not coincide with one another, the corresponding ice distribution was adjusted and the MOCA was repeated. The process was repeated until an agreement was attained between the two stage-frequency distributions. Once an ice distribution was calibrated, additional sets of MOCA runs were carried out to create an envelope of the ice distributions.

Since the gauge is sometimes rendered inoperative during extreme ice jam events during breakup, instantaneous peak water level data were not recorded. Some of these gaps were filled from previous studies. Peters (2003) and Mahabir et al. (2008) reported maximum water level data along the Athabasca River below Fort McMurray gauge station.

Table 4-1 Probability density functions used in the model with the corresponding ranges and values.

Parameter/ boundary conditions	**description**	**units**	**sampling type**	**minimum/ location***	**maximum/ scale***
Parameters					
PS	Porosity of slush		uniform	0.3	0.7
ST	Thickness of slush pans	m	uniform	1	1.5
PC	Porosity of ice cover		uniform	0.4	0.6
FT	Thickness of ice cover front	m	uniform	1	1.5
h	Downstream ice thickness	m	uniform	0.8	1.2
v_{dep}	Deposition velocity	m/s	uniform	1.1	1.3
v_{er}	Erosion velocity	m/s	uniform	1.7	1.9
n_{8m}	Nezhikhovskiy ice roughness	$s/m^{1/3}$	uniform	0.11	0.13
n_{bed}	Manning bed roughness	$s/m^{1/3}$	uniform	0.024	0.028
K1TAN	Lateral: longitudinal stresses		uniform	0.15	0.22
K2	Longitudinal: vertical stresses		uniform	7	8

Boundary conditions					
x	Ice jam toe chainage location	km	uniform	293	280
V_{ice}	Incoming ice volume	m^3	Gumbel	Calibration	
Q	Upstream volumetric discharge	m^3/s	Gumbel	Observed	
W	Downstream water level elevation	m	Rating Curve	Calibrated	
Base data					
DEM	Digital elevation model		uniform		
*minimum/maximum for uniform distribution, location and scale for Gumbel distribution					

The downstream water level elevations at the end of the model domain were estimated using a calibrated rating curve. RIVICE simulates partially developed ice jams, which eventually may attain an equilibrium condition. Under this condition, the downstream water level is usually controlled by the upstream discharge and the characteristics of the still intact ice cover which lodges the ice jam in place. However, changes in ice-cover characteristics, such as thickness and roughness are insignificant, therefore the downstream water level is mostly controlled by upstream discharge. Since the observed water level data at the downstream end of the model domain was unavailable, the RIVICE hydraulic model was used to relationship between upstream discharge and water level elevation at the downstream end of the model domain (Figure 4.3). The model was run using a constant ice cover thickness (0.8 m) from the gauge station to Inglis Island and different flow conditions such as 100, 500, 1000, 1500, 2000 and 2500 m^3/s. In each simulation, the downstream water level under a specific flow condition was selected based on equal slope between downstream bed slope and water level slope. After each simulation, the model result were visually examined to make sure that at the downstream cross-sections flows are approximately uniform (normal). Figure 4.3 shows the stage-discharge (rating curve) relationship at the downstream of the model domain, which will be using to estimate the downstream boundary conditions for the ice-jam simulations in this study.

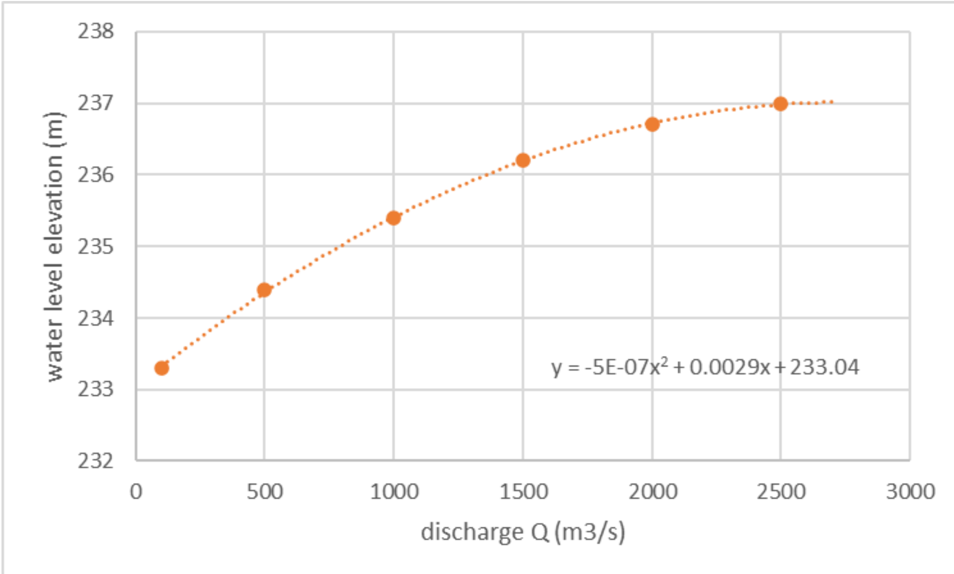

Figure 4.3 Stage-discharge (rating curve) relationship at the downstream end of the model domain under a stable ice-cover condition.

4.2.3 Flood Hazard Delineation

Ice-jam water level profiles simulated in RIVICE were transferred to a GIS tool to map flood hazard within the downtown area of the TFM. The flood hazard map presents information on flood extents and depths of a flood within the floodplain. Flood depth was marked as the difference between the floodwater surface elevation and the floodplain surface elevation, while flood extent of a flood hazard map was marked as the outer limit at which flood depth was greater than zero meters. In order to produce the flood hazard maps, the ground surface elevation from the DEM was subtracted from the ice-jam water surface elevation. Das et al. (2020) presented that the water level at the confluence of the Athabasca and Clearwater rivers is a good representation to produce flood hazard maps for the downtown area of TFM. Therefore, the simulated ice-jam water surface elevation along the Athabasca at the confluence was extrapolated as a flat surface along the Clearwater River to produce flood hazard map at the downtown of Fort McMurray. The positive values in the subtracted DEM represent the flood extents and depths of the ice-jam flood event.

4.2.4 DEM Evaluation

The study used four different DEMs – LiDAR, ASTER, SRTM and CDEM – to generate flood hazard maps for DEM evaluation and GSA. Table 4-2 provides detailed specifications of all the DEMs. The finest resolution LiDAR DEM (15 × 15) was selected as the "true" elevation for our study site and used as a basis for evaluating the performance of the test DEMs – CDEM, ASTER and SRTM. Since the resolutions of all test DEMs differ from one another, the resolution of the test DEMs were converted to the same resolution as the "true" elevation DEM to estimate the errors in the flood hazard maps. The nearest-neighbor sample method was applied to convert the grid size of all test DEMs. In this method, no new values were created, therefore, there is no change in the pixel elevation values.

Table 4-2 Summary of various DEMs used in this study.

DEMs	Name	Horizontal Resolution and Datum	Data Source	Generation/ Distribution	Year of survey
ASTER	The Advance Spaceborne Thermal Emmission and Reflection Radiometer	25 x 25 m WGS84	Spaceborne radar	The Ministry of Economy, Trade, and Industry (METI), Japan, the United States National Aeronautics and Space Administration (NASA)	2011
SRTM	The Shuttle Radar Topography Mission	25 x 25 m WGS84	Spaceborne radar	The German Aerospace Center (DLR), the Italian Space Agency (ASI), NASA/JPL (USA)	2015

CDEM	Canadian Digital Elevation Model	18 x 18 m NAD83(CSRS)	Ground based survey and remote sensing	Natural Resources Canada (NRC)	2016
LiDAR	Light Detection and Ranging	15 x 15 m NAD83(CSRS)	Laser Equipment (aircraft)	Alberta Environment and Parks (AEP)	2016

The root mean square error (RMSE) was used to evaluate the overall vertical accuracy of all the test DEMs by comparing with "true" elevation DEM (LiDAR). The lower the RMSE, the higher the vertical accuracy of the DEM. The equation for the RMSE is as follows:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(D_{test} - D_{true})^2} \text{ .... (4.1)}$$

where $D_{test,}$ is an elevation from the test DEM, $D_{true,}$ is the elevation from the "true" elevation DEM and N is the number of sample points.

The deviations of the flood hazard maps were derived to evaluate the performance of the test DEMs by comparing the flood hazard maps derived from "true" DEM (LiDAR). The deviation of a flood hazard map was defined as the error in flood extent and depth of the flood hazard map produced by the test DEM compare to the flood hazard map produced by the "true" elevation DEM. The overall deviation in flood depth maps was estimated by calculating RMSE, using equation 4.1. The deviation in the flood extent map (horizontal accuracy) was measured by estimating the error using equation 4.2.

$$e_{flood\ extent} = abs\left(\frac{n_{true} - n_{test}}{n_{true}} \times 100\right) \text{ .... (4.2)}$$

where n_{true} = number of cells in the flood extent map of the true elevation, and DEM n_{test} = number of grids in one of the flood extent maps from the test DEMs.

The 1977 ice-jam flood event along the Athabasca River at the TFM was simulated using RIVICE and this simulated result was used to evaluate all test DEMs. This was a severe ice-jam event recorded for the site. The ice-jam occurred just downstream of the confluence of the Athabasca and Clearwater rivers, which blocked the flow from the Clearwater River. The water then backed up into the Clearwater River to overtop its banks by as much as 2.5 m (Andres and Doyle, 1984). A GIS tool was developed to produce deviation maps of flood extent and depth for evaluating all the test DEMs. Similarly, the 1500 ice-jam water level profiles simulated from the MOCA framework were used to map flood hazard for GSA. The details of the procedure for GSA is described in the following section.

4.2.5 Global Sensitivity Analysis (GSA)

This study applied the regional sensitivity analysis (RSA) proposed by Hornberger and Spear (1981). In this approach, an objective function is selected to compare a single simulated result to an observed result. In RSA, the main concept is to generate behavioral and non-behavioral distributions for each parameter and then compare the similarities between the distributions. The behavioral and non-behavioral sets are selected based on a predefined threshold (a goodness of fit measure) of the model output. Behavioral sets are those whose outputs closely represent the expected results or observed values (i.e deviations are less than a threshold value), while non-behavioral parameters are designated to have deviations (model outputs are not closely aligned with the expected results or observed data) greater than the threshold value. The total parameter set without any distortion (observed or reference data) is called an *a priori* parameter set (Ballard et al. 2011) (Figure 4.4). The maximum vertical distance between behavioral and non-behavioral values indicates the degree of influence of a factor on the modelling output. Finally, the empirical cumulative distribution functions (CDFs) of the model outputs are used to compare the behavioral parameters with the non-behavioral parameters for identifying the significant differences between both groups. The dissimilarity between the CDFs of an input parameter of behavioral and non-behavioral set indicates the degree of sensitivity of the parameter to the modelling output. In RSA, the Kolmogorov-Smirnov (K-S) test is applied to estimate the maximum deviation (maximum vertical distance) between behavioral and non-behavioral parameter sets (Figure 4.4). If the absolute maximum difference of these two CDFs is large, then the corresponding parameter is judged to be a sensitive parameter. The K-S test is carried out using the following equation:

$$K\text{-}S_{max} = max\,|F_b(x) - F_{nb}(x)| \ldots\ldots\ldots\ldots\ldots\ldots \; 4.3$$

where, $F_b(x)$ is the behavioral distribution and $F_{nb}(x)$ the non-behavioral distribution.

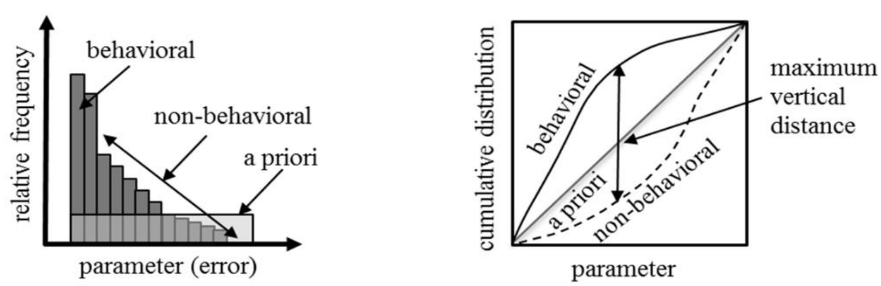

Figure 4.4 A conceptual sensitivity analysis procedure, indicating the relative frequency of the deviations and cumulative distribution functions for a model parameter.

In this study, a GSA was carried out on model parameters, boundary condition values and DEMs in order to determine the parameters to which flood hazard was most sensitive. The approach was carried out here by comparing the flood hazard map generated from a randomly chosen test DEM and the flood hazard map generated from the true elevation DEM. In order to select an objective function, the study assumes the flood hazard map generated from the true elevation DEM to be observed and the flood hazard map generated from a test DEM to be the simulated case. Two objective functions, the deviations in flood depth and extent, were estimated from two flood hazard maps using Equations 4.1 and 4.2. Based on a certain threshold value of the deviation, the parameters were divided into two groups – behavioral and non-behavioral (Figure 4.4). The maximum vertical distance between behavioral and non-behavioral values indicates the degree of influence of a factor on the modelling output, in this case, flood water extent and depth.

To carry out the GSA of the model parameters, boundary conditions and DEMs, a total of 1500 ice-jam backwater level profiles were simulated along the study site using the MOCA framework. The automated GIS tool was used to generate flood hazard maps for both randomly chosen test DEMs and the "true" elevation DEM. The GIS tool compared all the test flood hazard maps generated from test DEMs with the 'true' flood hazard maps generated from the 'true' elevation DEM (LiDAR) to calculate the deviation. The deviation was calculated for two objective functions applied to flood extent and depth. Ten percent of the best performing flood hazard maps were selected as the behavioural subset and the rest (90%) served as the non-behavioural subset. The GSA was carried out by comparing cumulative distribution curves of the behavioural sets of factors (parameter, boundary conditions and DEM) and the cumulative distribution curves of the non-behavioural sets of factors.

4.3 Results and Discussion

4.3.1 Evaluation of DEMs for ice-jam flood delineation

The RMSE was estimated to assess the vertical accuracy of all the DEMs. First, the RMSE was calculated by comparing the test DEMs directly with the 'true' DEM to assess the vertical accuracy of the test DEMs. The study estimated that the RMSE of the ASTER DEM is much higher than the CDEM and SRTM. The RMSE for the CDEM, SRTM and ASTER are 1.1, 1.7 and 4.18 m, respectively. Therefore, the CDEM has the highest vertical accuracy at the study site among all the test DEMs. This accuracy assessment is also reflected in the following section of the assessment on DEMs for ice-jam flood delineation.

The RIVICE simulated results for the 1977 ice-jam flood event along the Athabasca River at Fort McMurray is shown in Figure 4.5. This was one of the most severe ice-jam events recorded for the site. The ice jam occurred just downstream of the confluence of the Athabasca and Clearwater rivers, which blocked the flow from the Clearwater River (Das et al. accepted).

The model results were extracted and transferred to the GIS tool to generate a flood hazard map using the LiDAR DEM. The true flood hazard map was used as the basis for estimating the deviation of the results derived from the test DEMs. A close comparison of an aerial photo and simulated flood hazard map of the 1977 ice-jam flood event shows good agreement with the flood water extent in the downtown area of Fort McMurray (Figure 4.6).

The centre area of the map may underrepresent the amount of flooding compared to the historical aerial photograph. There are several sources of uncertainty that may lead to some of the discrepancies. One is that we are using a DEM surveyed in 2016, and there has been additional development (e.g. road close to and parallel to the river) in the floodplain since 1977 that will influence topography and, hence, floodwater flow paths and extents. The error can be as much as approximately 42 cm (estimated from the simulated ice-jam water level profiles) and becomes greater in very flat areas, as is the case of the floodplain surfaces immediately adjacent to the river.

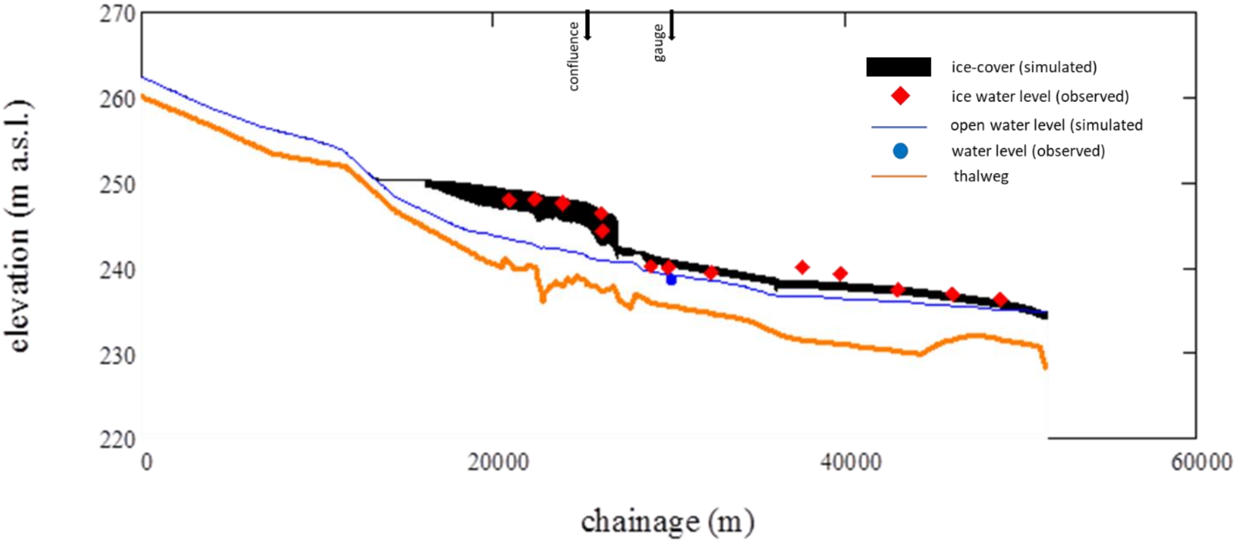

Figure 4.5 The RIVICE simulated results for the 1977 ice-jam flood along the Athabasca River at Fort McMurray, the observed data has been adopted from Andres and Doyle (1984)), 0 m in the x-axis indicates the 325 km along the Athabasca River at the Cascade Rapids in Figure 4.1. (The figure is adopted from Das et al. 2020, with permission).

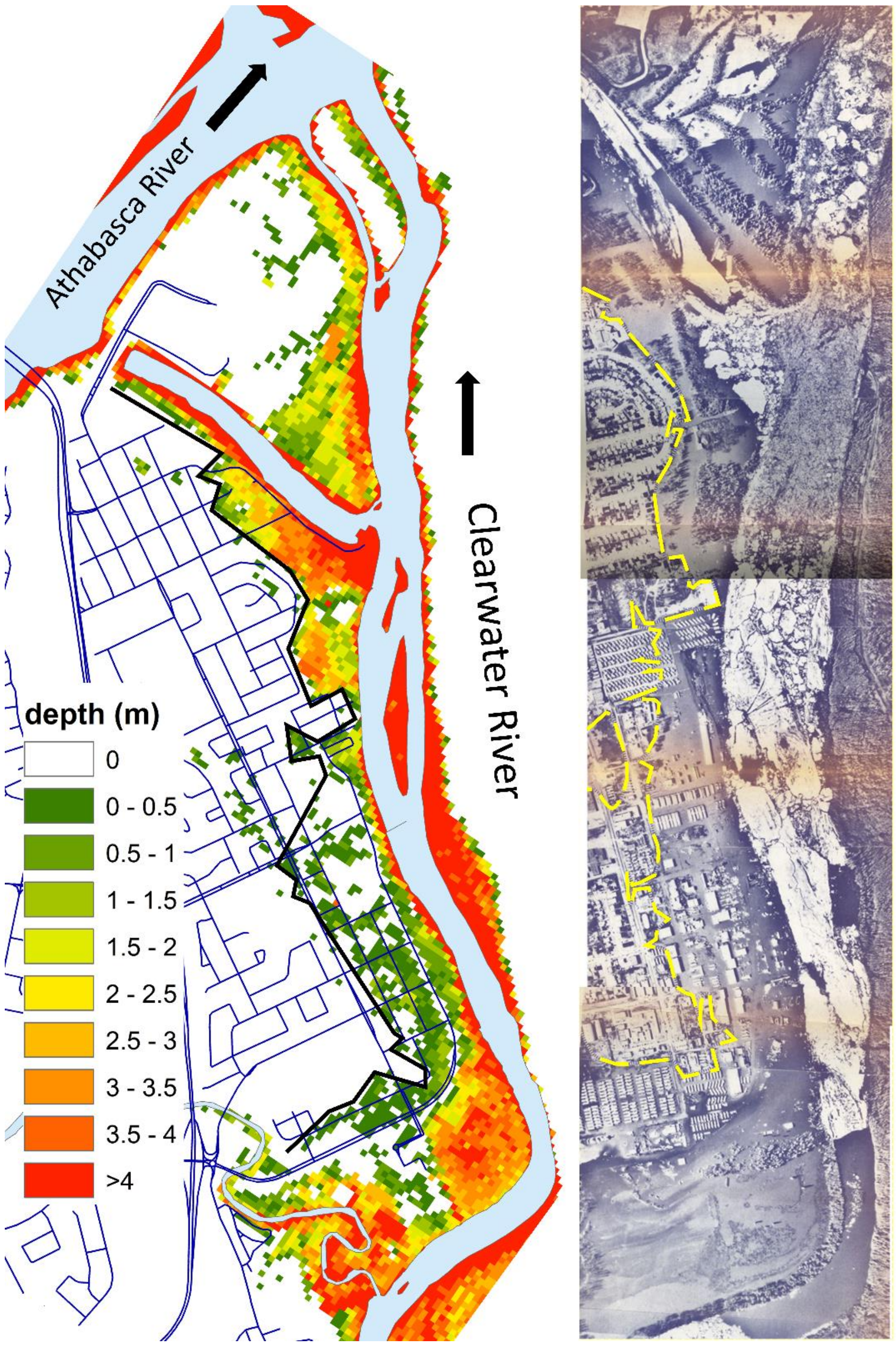

Figure 4.6 The 1977 ice-jam flood hazard map using LiDAR and aerial photo along the Athabasca River at Fort McMurray, the black line indicates the approximate flood hazard area of the event (photo courtesy of the Government of Alberta, adapted with permission).

Figure 4.7 shows the deviations in flood extent and depth of CDEM, ASTER and SRTM DEMs from the map produced by the LiDAR DEM. The deviation using the CDEM map is least for flood extent estimation (4.3%), which may be a reflection of the high spatial resolution and good compatibility with the true elevation DEM. On the other hand, the deviation in flood extent using SRTM and ASTER is relatively greater, such as 25% and 42%, respectively. The deviation in flood depth estimations was assessed using the RMSE in flood depth maps from test DEMs, compared with the flood depth maps from the LiDAR DEM. The maximum deviation is for flood depth estimations using ASTER, with a RMSE of 8.1 m. Relatively low deviation was identified in CDEM and SRTM flood depth maps, with RMSE values of 1.9 and 3.1 m, respectively. Therefore, the relatively low deviation in CDEM flood hazard maps identifies CDEM as the most accurate DEM among the test DEMs to produce flood hazard map at the study site.

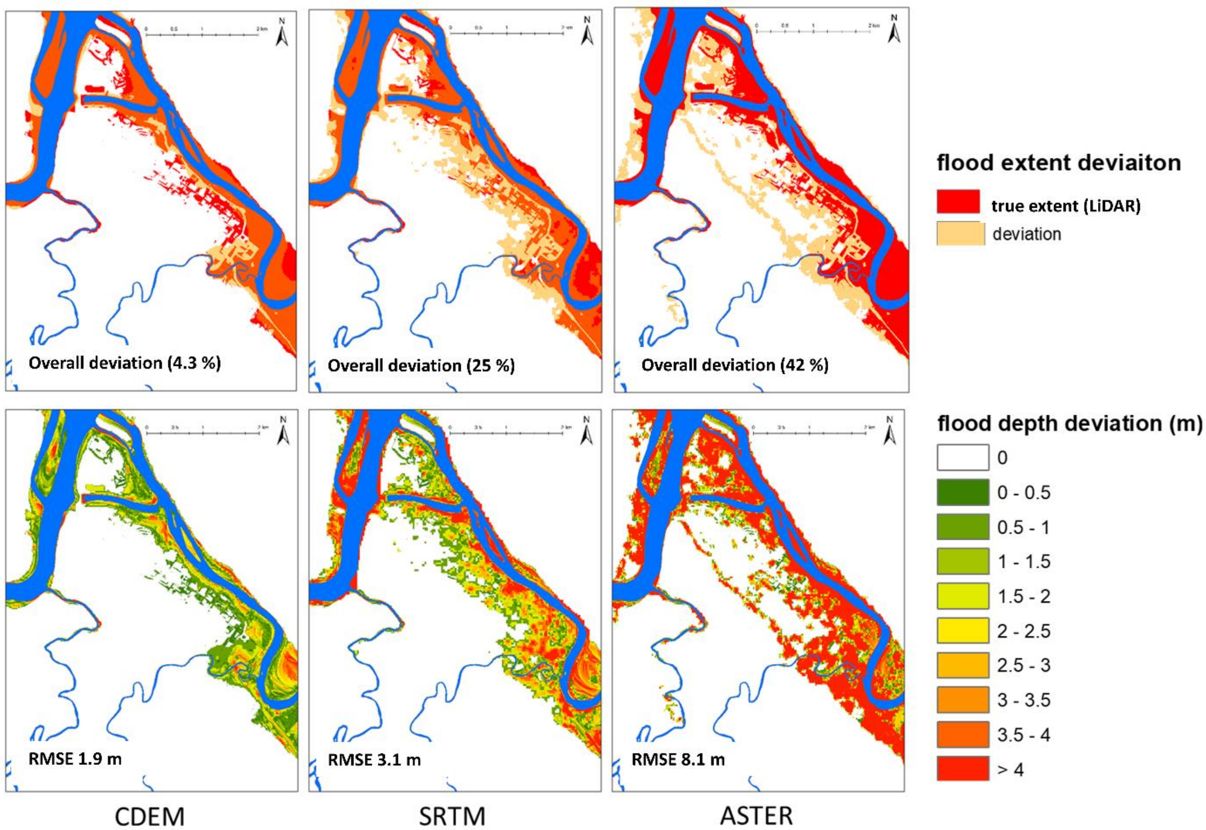

Figure 4.7 The deviations in flood extent and flood depth of different DEMs for the 1977 flood event along the Athabasca River at Fort McMurray.

The validation of the 1977 ice-jam flood hazard map was limited to an aerial photo, where flood extent areas were identified successfully. Since the study only intended to assess the impact of different types of DEMs on flood hazard mapping, accurate field validation was not necessary. The results found that the accuracy in flood extent and depth varies using different DEMs; thus, the absence of a good DEM can affect the identification of actual flood hazard areas and estimation of flood damages for risk analyses.

4.3.2 Global Sensitivity Analysis and Rankings

Figure 4.8 illustrates flood extent and flood depth sensitivity to all studied parameters, boundary conditions and DEMs for ice-jam flood hazard mapping. The cumulative distribution plots provide information about the sensitivity of the entire distribution of the samples, which helps to identify the subranges of the model parameters and boundary conditions that have lower and greater impacts on the results. Relatively higher deviation of the behavioural distribution from the non-behavioural distribution indicates greater sensitivity of model results to the parameters. Figure 4.8 illustrates that both flood extent and depth are very sensitive to almost all the model boundary conditions, while both flood extent and depth are less sensitive to most of the model parameters. In highly sensitive parameters and boundary conditions, the cumulative distribution function (CDF) curves reveals a strong dissimilarity between behavioural and non-behavioural curves, while the CDFs show strong similarities in insensitive or less sensitive parameters and boundary conditions. The Kolmogorov–Smirnov (K-S) test was used to determine the magnitude of the maximum difference between the two cumulative distribution curves, which is indicative of the degree of sensitivity to each parameter, boundary condition and DEM (Figure 4.9). The degree of sensitivity to each parameter was selected based on the following categories: high sensitivity ($K\text{-}S_{diff} > 0.12$), moderate sensitivity ($0.06 < K\text{-}S_{diff} \leq 0.12$) and low sensitivity ($K\text{-}S_{diff} \leq 0.06$). The K-S test values of the parameters, boundary conditions and DEM and the degree of sensitivity (high, moderate and low) are provided in Figure 4.8. These results can be useful to further ice-jam flood hazard studies and guide implementation of any mitigation measures along the river. For example, both flood extent and depth are moderately sensitive to the ice cover properties, *PC* and *FT*, indicating that winter ice cover characteristics have a fairly strong influence on the severity of ice-jam flooding. Thus, it is necessary to monitor the characteristics of the winter ice cover to determine the severity of ice-jam flooding. Moreover, flood extent has a moderate to high sensitivity to both rubble ice properties, *PS* and *ST*, which indicates that the properties of the incoming ice floes have a considerable impact on the extent of a flood event. Flood depth has low sensitivity to adjustments in *PS* and moderately sensitivity to changes in *ST*, indicating that porosity of the incoming ice floes has less influence on the ice-jam backwater level elevation during ice-jam formation than the thickness of the incoming ice floes. In both cases, under-ice transportation properties, v_{dep} and v_{er}, have moderate and low levels of influence, respectively. While flood extent is less sensitive to thickness of the ice cover downstream of a jam *h*, ice roughness coefficient n_{8m}, and later to longitudinal stresses *K1TAN*, flood depth is moderately sensitive to these parameters. Furthermore, both cases are moderately sensitive to n_{bed} and *K2*. Both flood extent and depth are highly impacted (high sensitivity) by the three boundary conditions: location of the ice jam toe *x*, upstream volumetric discharge *Q* and incoming ice volume V_{ice}. These results show the great importance of the boundary conditions of the model setup; therefore, efforts should be given to acquiring or selecting these model values accurately. Moreover, both flood extent and flood depth are highly sensitive to the DEM. In the ranking table, the DEM holds the highest sensitivity ranking for both objective functions. Although sensitivities to all the parameters, boundary conditions, and the DEM were based on the maximum difference (K-S test) between two cumulative curves, the sensitivity rankings were chosen subjectively. The K-S test values for the DEM are significantly higher in comparison to the values for the parameters and boundary conditions. This is due to the fact that vertical inaccuracies of the test DEMs are high compared to the "true" elevation DEM. All of the test DEMs (CDEM, ASTER and SRTM) were converted to the resolution of "true" elevation (LiDAR), although their spatial resolutions were different. Using two objective functions for the GSA provides a means of selecting and optimizing different parameter sets for flood extent and flood depth estimation in flood hazard mapping. The most influential parameters can be selected carefully to improve model performance and reduce uncertainty. For example, vertical accuracy in flood depth estimation is important for calculating flood damage because the flood damage is usually estimated by depth-damage function. Therefore, to delineate the flood depth more accurately along a floodplain, the model parameter set can be selected based on the degree of sensitivity.

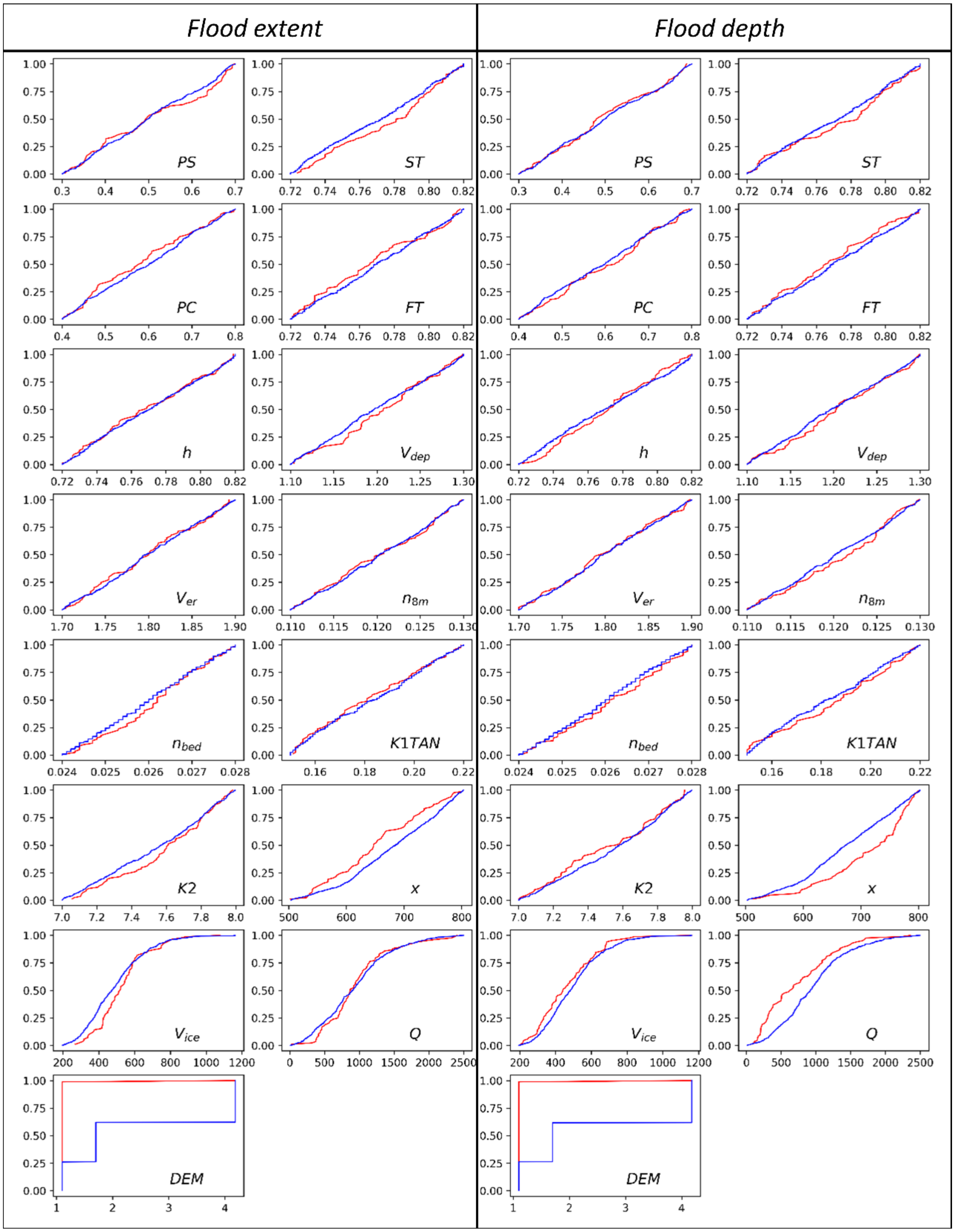

Figure 4.8 Cumulative distribution plots of behavioural (red) and non-behavioural (blue) for the model parameters, boundary conditions and DEM.

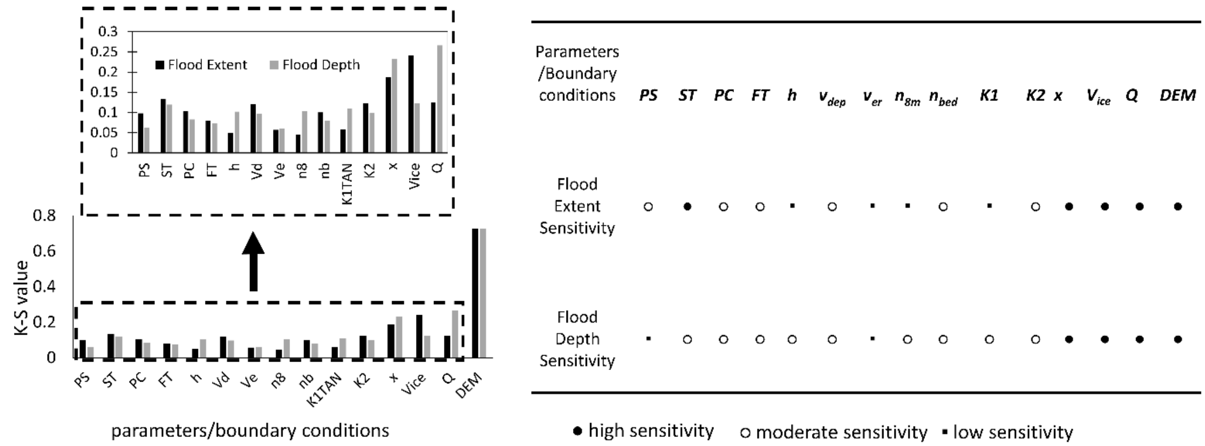

Figure 4.9 The K-S values and ranking for the model parameters, boundary conditions and DEM.

4.4 Conclusion

A simple assessment of various DEMs and a GSA of the model parameters, boundary conditions and DEM are demonstrated in this study. The evaluation of different DEMs for a specific ice-jam flood event fulfilled the first objective and the sensitivity rankings derivation fulfilled the second objective of the study. The relative sensitivity analysis of the river ice model helped to identify the most important factors influencing model output and determine where resources should be directed in the future, which addresses the third objective of the study.

The impact of the large inaccuracies in both the horizontal (flood extent) and vertical resolutions (flood depths) of the test DEMs compared with the “true” elevation DEM was clearly shown in the study results. The DEM evaluation for ice-jam flood delineation revealed that a DEM affects the accuracy of both extent and depth of ice-jam floods. The deviation in CDEM data is the lowest in both flood extent and depth maps and therefore the CDEM seems to be the more accurate DEM for ice-jam flood delineation at the study site, as compared to other tests DEMs such as SRTM and ASTER. Although the deviation in ASTER is less than the deviation in SRTM, the deviation in flood depth is much higher in ASTER compared to SRTM. Since the inaccuracies in ASTER and

SRTM are relatively high, this can increase the degree of uncertainty for both flood depth and flood extent estimations. In order to minimize the uncertainty for a flood hazard study, a DEM should be selected carefully based on an evaluation of both the flood extent and depth estimations. The GSA of the model parameters, boundary conditions and DEM revealed that the DEM is one of the most sensitive components of ice-jam flood hazard delineation. Therefore, the selection of an appropriate DEM is very important for accurate flood hazard delineation. Most of the boundary conditions also have a high degree of influence on model output, e.g. the location of the toe of the ice jam, incoming volume of ice and upstream volumetric discharge. A GSA study carried out by Lindenschmidt (2017) focused on backwater staging, not floodplain delineation, at the same study site. The study found the stage frequency distribution had low sensitivity to boundary conditions in less extreme staging events, while the stage frequency distribution was moderately to highly sensitive to all the boundary conditions in extreme staging events. The sensitivity rankings of the boundary conditions in less extreme staging are low because higher magnitudes of the boundary condition values have a significant influence on ice-jam backwater staging. In contrast, most of the boundary conditions have the highest sensitivity ranking in this study because the resolution of the DEM has a significant impact on the floodplain delineation.

The results of this study can be used for a variety of purposes, such as to reduce the uncertainties of the model results by selecting parameter values based on their sensitivity assessment, for example less-sensitive parameters can be selected as constant variables to simulate a particular event. The assessment of various DEMs could help in the selection of the appropriate topological data for ice-jam flood delineation. A GSA approach to a river ice model and DEM can be applied to direct resources for future research. Resources should be assigned to regularly update DEM and ice-jam information to keep flood hazard assessments as current as possible. The higher the sensitivity ranking of a parameter, the greater impact it has on model results; hence, modellers should be careful to select parameters with the highest sensitivity ranking for calibration.

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4.6 Appendices

Appendix A RIVICE Model and Monte-Carlo Setup

Table. A-1 Available peak water-level during spring ice cover breakup along the Athabasca River below Fort McMurray gauge station.

Year	Peak water-level (m)	Source
1964	239.423	WSC
1967	241.170	WSC
1968	239.158	WSC
1969	244.312	WSC
1970	241.344	WSC
1971	241.892	WSC
1972	241.036	WSC
1973	240.524	WSC
1974	243.959	WSC
1975	239.722	Peter (2003)
1976	242.100	Peter (2003)
1977	243.197	Peter (2003)
1978	240.573	Peter (2003)
1979	245.221	WSC
1980	241.420	Peter (2003)
1981	241.061	WSC
1982	240.984	Peter (2003)
1983	239.883	WSC
1984	240.908	WSC
1985	239.541	WSC
1986	241.960	WSC
1987	242.500	WSC
1988	240.513	Peter (2003)
1989	243.100	Peter (2003)
1990	240.641	Mahabir et al (2008)
1991	239.669	WSC
1992	239.537	WSC
1993	243.400	WSC
1994	241.436	Mahabir et al (2008)
1995	240.555	Peter (2003)
1996	243.176	WSC
1997	247.000	WSC
1998	244.800	Mahabir et al (2008)
1999	239.679	Mahabir et al (2008)
2004	239.669	WSC
2005	241.406	WSC
2012	238.413	WSC
2013	239.481	WSC
2015	241.627	WSC
2017	238.553	WSC
2018	239.923	WSC

Preface to Chapter 5

CHAPTER 5: ICE-JAM FLOOD RISK ASSESSMENT AND HAZARD MAPPING UNDER FUTURE CLIMATE CONDITIONS

In this chapter, a novel stochastic framework has been developed to quantify the severity of ice jam floods under future climatic conditions along the Athabasca River at Fort McMurray.

Contribution of Authors: Apurba Das carried out all the simulations and data analyses and wrote the manuscript. Prabin Rokaya provided the streamflow data from the hydrological simulation and reviewed the manuscript. Karl-Erich Lindenschmidt conceptually helped to develop the paper and reviewed the manuscript throughout the process.

CHAPTER 5

ICE-JAM FLOOD RISK ASSESSMENT AND HAZARD MAPPING UNDER FUTURE CLIMATE CONDITIONS

Abstract

In cold-region environments, ice-jam floods (IJFs) can result in high water levels in rivers leading to devastating floods. Since climatic conditions play an important role in ice-jam flooding, there is great concern among property developers, insurance companies, government agencies and communities reading future IJF probabilities, especially in the context of changing climate. This study presents a stochastic framework for future IJF risk assessment and hazard mapping. Future hydrological conditions derived from a physically-based hydrological model (forced with meteorological inputs from a Canadian regional climate model driven by the Third Generation Coupled Climate Model (CGCM3) was coupled to a fully dynamic hydraulic river ice model to evaluate ice-jam scenarios and subsequent backwater level profiles for the 2041-2070 period along the Athabasca River at Fort McMurray. The delta change is derived from the hydrological model output and then applied to the historical observed (baseline period) values to estimate the projected streamflow values. Although there are some uncertainties in the modelling approach, the modelling results show that mean stage frequency distribution (SFD) is projected to be lower for relative delta change and higher for absolute delta change under the projected changes in climate in the period of 2041-2070 compared to the baseline period of 1971-2000.

5.1 Introduction

Flooding is one of the most devastating natural hazards for riverside communities and ecosystems. Floods can cause damage to property, infrastructure and businesses, interfere with ship navigation and threaten human life (US Army Corps of Engineers, 1998). Floods can also play an important role in the supply of necessary sediment and nutrients, and in maintaining water balances in deltaic ecosystems. In cold-region environments, flood dynamics in a river are usually driven by various hydro-meteorological factors that include, but are not limited to, runoff caused by rainfall, snowmelt, rain-on-snow events and river ice processes. Ice jams form in a river when the flow of ice pieces stemming from upstream of the jamming site is arrested and the ice chunks accumulate along a river reach to cause damming of the river. Ice jams can be many kilometers long and can raise water levels significantly higher than open water floods for the same or even lower discharges (Beltaos, 1995).

Ice-jam floods (IJFs) are more common during spring breakups along northern rivers that experience seasonal effects of ice. They also occur occasionally during mid-winter breakups. IJFs are unpredictable and sudden, often leaving little time for emergency warnings and evacuation (Mahabir et al., 2006). Therefore, IJF risk assessment and hazard mapping are important elements of government policies to ensure public safety, to mitigate the costs of flood damages and to reduce ecological impacts. To date, a considerable number of field studies and modelling work have been carried out to determine the mechanism of ice-jam formation and associated flooding (e.g. Lier, 2002; Beltaos, 2003; Beltaos & Carter, 2009; Buzin & D'yachenko, 2011; Beltaos et al., 2012; Lindenschmidt et al., 2012; Ahopelto et al., 2015; Aaltonen & Huokuna, 2017; De Munck et al., 2017; Koegel et al., 2017; Garver, 2018; Wang, 2018). These studies have been instrumental in providing site-specific understanding of the mechanisms of ice-jam formation. However, a complete understanding of the processes of ice-jam flooding, to guide the selection of appropriate flood mapping methods, is still necessary for emergency management and long-term planning in communities that are prone to IJFs.

One of the key factors of IJF management is the development of ice-induced stage-frequency distributions for an ice-jam prone location (Lindenschmidt et al., 2016). Ideally, these relationships are developed using historical data. However, most often, the historical data is sparse and inadequate. Previous studies suggest that, with changing climatic conditions, a stage-frequency curve based on historical data may not apply in the future (Lindenschmidt et al., 2018). However, Das et al. (2017) applied a stochastic hydraulic modelling approach to simulate ice-jam backwater levels within a Monte-Carlo Analysis (MOCA) framework and developed stage-frequency distributions (SFD) under future climatic conditions. Their study used meteorological forcing data from the North American Regional Climate Change Assessment Program (NARCCAP) to derive river flows for the future (2041 – 2070) using a physically-based hydrological model MESH. The future flows, along with projected climate data and river ice parameters, were incorporated into a one-dimensional hydrodynamic numerical river ice model, RIVICE, to simulate the envelope of probable ice-induced backwater levels at the Town of Fort McMurray (TFM) under future climatic conditions. This study extends the methodology to develop future flood hazard maps for the TFM using future SFDs.

Future climate is one of the most challenging factors in understanding possible changes in ice regimes. Many studies have already confirmed that river ice duration, ice thicknesses and flood extents are already changing due to climate change (Beltaos & Prowse, 2001; Beltaos & Burrell, 2003; Beltaos & Prowse, 2009; Das et al., 2017). As a result, climate change could potentially shift temperature zones, change precipitation distributions and alter hydrological regimes. Rokaya et al.

(2018a) have already reported changes in the frequency and magnitude of IJFs in Canada, especially in small basins. The impact of climate change on ice regimes is also a concern for property developers, insurance companies, government agencies and communities that require such information to carry out effective planning, flood mitigation measures and flood risk analyses. Although a considerable number of studies have already been carried out to understand ice-jam formation and mitigation of the impacts of flooding (Beltaos and Krishnappan, 1982, Kowalczyk and Hicks, 2003, She et al., 2009, Unterschultz et al., 2009), only a limited number of studies have evaluated the impacts of climate change on the severity of ice-jam flooding.

The main objective of this study is to investigate the implications of future climate on ice-jam flooding along the Athabasca River in Fort McMurray. Rokaya et al. (2019) reported significant hydro-climatic variability in the Athabasca River, which has implications for river ice processes. They analyzed future flow conditions in the Athabasca River and found that, while average winter flows may increase by about 25%, late spring flows may be reduced by approximately 50% in the 2041-2070 period compared to the historical baseline period of 1971-2000. Their study concluded that the increased freeze-up flows and decreased breakup flows may lower the probability and magnitude of IJFs in the future, but extreme ice-jam flood events are still probable. Further research was recommended to quantify future IJF risk by coupling an output of the hydrological model with hydraulic models. This study builds on the work of Rokaya et al. (2019) and investigates future IJF risk assessment and hazard mapping using a stochastic framework that accounts for uncertainty in parameters and boundary conditions. This chapter, particularly focuses on future IJF risk assessment and hazard mapping within a stochastic framework. The specific objectives are: (1) to develop ice-jam stage frequency distributions (SFD) under future climatic scenarios along the river at Fort McMurray, and (2) to produce a future 1:100-year IJF hazard map for the downtown area of Fort McMurray.

Since climate change impacts are significantly affecting river-ice phenology, a reliable method for assessing future IJF risk is necessary for effective water resources planning and management. Design of suitable mitigation and adaptation measures, new infrastructure, and floodplain development should be based on the estimation of ice-jam flood risk under future climatic scenarios (Beltaos 2008). The estimation of future ice-jam flood risk provides an opportunity to assess the usefulness of an existing flood protection system under future climatic conditions, to evaluate, in particular, whether it is adequate to accommodate future flood risks (Simonovic, 2003). Predicting ice-jam frequency and severity of associated flooding can also help in allocating resources more efficiently for an ice-jam flood mitigation program for the future (Yoe, 1984; Turcotte et al., 2019). Additionally, a sustainable ice-jam flood management strategy should focus on both current and future impacts of hydro-climatic variations on river ice-jam regimes to ensure required flood protection, to implement the most efficient flood mitigation strategies and to preserve natural ecosystems and resources (Das et al., 2018, Rokaya et al., 2018b).

In this study, potential IJF hazard along the Athabasca River at Fort McMurray under future climatic conditions was examined. Future hydrological conditions, derived from a physically-based hydrological model forced with meteorological inputs from a Canadian regional climate model (RCM) driven by an atmospheric-ocean general circulation climate models (GCM), was coupled to a fully dynamic hydraulic river ice model to evaluate ice-jam scenarios and subsequent backwater level profiles for the 2041-2070 period along the Athabasca River at Fort McMurray. Simulation of ensembles of water levels allowed the establishment of envelopes of SFDs for each climate model. The 1:100-year flood water levels were then extracted from each SFD envelope to map flood hazard in the TFM.

5.2 Data and Method

5.2.1 Study Site

The TFM is a location prone to IJFs in Alberta, western Canada. Since the 1870s, a total of 24 ice-jam events have been documented in the vicinity of the TFM (Robichaud, 2004). Many of these jams led to severe flooding resulting in millions of dollars in property and infrastructure damages to the town. The Athabasca River (**Figure 5.1**) originates in the Rocky Mountains of southern Alberta and flows approximately 1,538 km before emptying into Lake Athabasca in northern Alberta. The TFM is located at the confluence of the Athabasca and Clearwater rivers. The Athabasca River, immediately downstream of the TFM, is characterized by numerous sand bars and islands. The width of the river from the Cascade Rapids to downtown Fort McMurray varies from approximately 400 to 900 m and the channel slope varies from 0.001 to 0.0003. The river stretch upstream of the TFM is steeper, with a series of rapids.

Spring ice cover breakup along the river is usually triggered by the thermal deterioration of the ice cover, the fracture of ice sheets and subsequent ice runs generated by water and ice surges caused by upstream ice jam releases (Andres and Doyle, 1984). Thermal ice deterioration and snow melting increase river flows and surges of ice, leading to temporary ice jams which release to move downstream along the river. The river reach in the vicinity of the TFM has a high potential to arrest the flow of these ice runs due to the mild river bed slope and numerous islands that reduce the velocity of the ice runs. An ice jam occurring downstream of the mouth of the Clearwater River may cause water to back up into the Clearwater River channel and flood the town (Robichaud, 2004, Andres and Doyle, 1984). This type of backwater flooding along the Clearwater River has been documented for several floods which occurred during the spring breakups of 1977, 1979 and 1997.

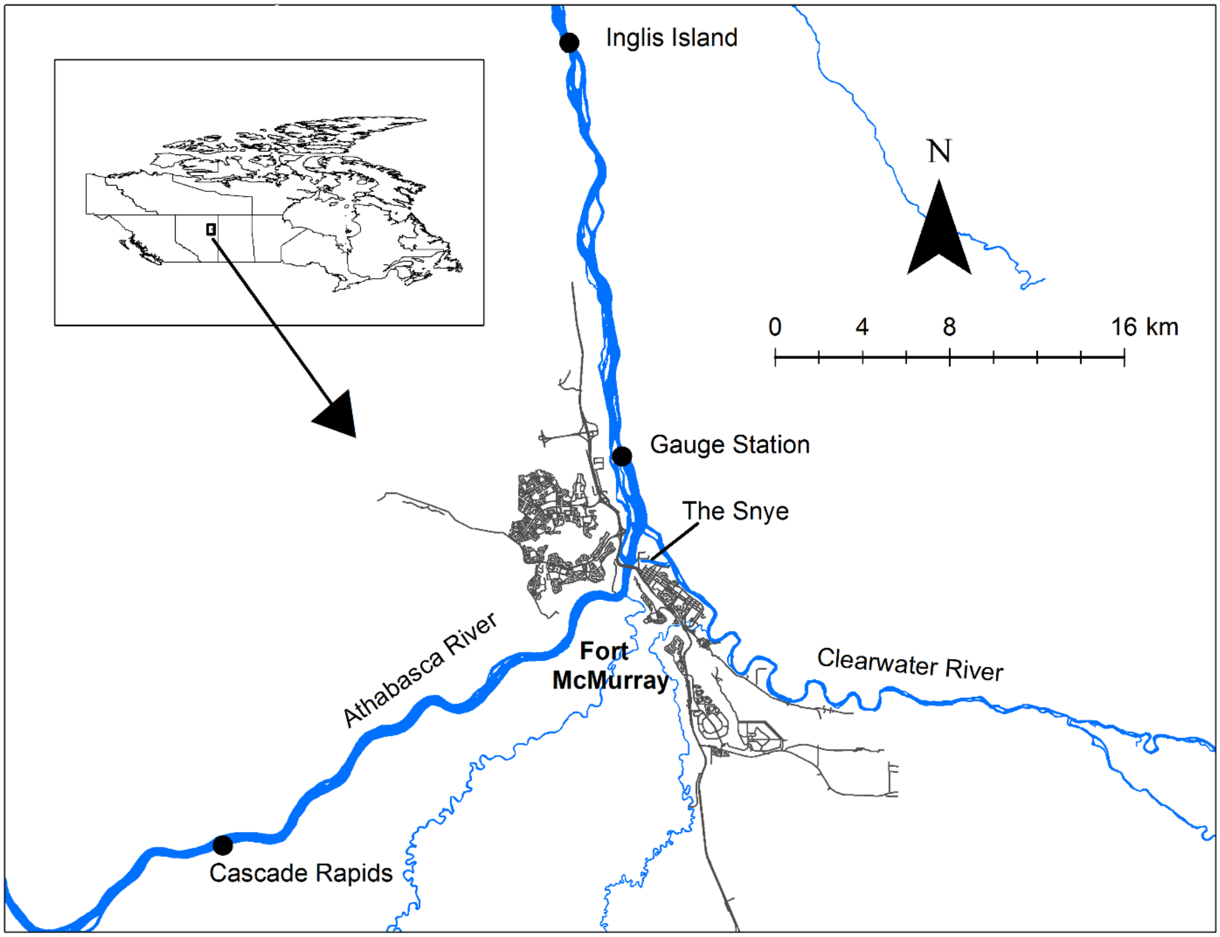

Figure 5.1 Study site along the Athabasca River at Fort McMurray.

The TFM has a continental climate with a mean annual temperature of 0.47 °C and a total annual precipitation averaging 435 mm per year. The mean annual flow of the Athabasca River at the Fort McMurray gauge (07DA001) is 600 m^3/s. Freeze-up of the river usually occurs between late October and mid-November, and ice cover breakup occurs between mid-April and early May (Morales-Marin et al., 2019). However, a substantial change has been observed more recently in the hydrological and meteorological conditions along the Athabasca River. Since the 1960s, a significant decreasing trend in the mean annual flows has been observed along the Athabasca River

Basin (Bawden et al., 2014), whereas the mean annual air temperature along the river area has significantly increased (1 – 2 ºC). Previous studies have shown that these hydro-meteorological changes can affect river ice processes and increase uncertainty in spring ice cover breakup patterns (such as breakup timing) and ice-jam formation along the river (Beltaos and Burrell, 2003, Beltaos and Prowse, 2009, Beltaos and Prowse, 2001).

5.2.2 Hydrological Data

The observed water flows for the historical period were obtained from the gauging station on the Athabasca River downstream of Fort McMurray (07DA001, see also Figure 5.1 for the location of the gauge), operated by Environment and Climate Change Canada's (ECCC) Water Survey of Canada (WSC). At this station, the maximum daily mean flows during spring breakups for the historical period (1971-2000) range from 298 to 2290 m^3/s and the instantaneous peak water levels range from 247.0 to 239.5 m a.s.l. When water level data was missing due to the gauge recording being interrupted by ice during breakup, the missing data was filled based on estimates from previous studies (see Appendix 4.6). The peak water level data at the confluence of the Athabasca and Clearwater rivers was also extracted from the literature (Winhold and Bothe 1993; Turcotte et al. 2019) (see Appendix 5.6).This study used the streamflow data derived by Rokaya et al. (2018) to assess the implications of future climate on river-ice processes. They used a semi-distributed physically-based land surface-hydrological modeling system, MESH (Pietroniro et al., 2007), to simulate daily flows along the Athabasca River for the 2041-2070 period using meteorological inputs from the Canadian Regional Climate Model (CRCM) driven by a GCM, the Third Generation Coupled Climate Model (CGCM3). This meteorological dataset is available from the North American Regional Climate Change Assessment Program (NARCCAP) (Mearns et al., 2012; Mearns et al., 2009). For further details on hydrological model setup, calibration, validation and discussion of model performance, readers are referred to Rokaya et al. (2019).

5.2.3 Meteorological Data

Daily mean temperature data is required to quantify climate impacts on ice-jam flooding at the TFM. The observed daily mean air temperature was obtained from ECCC weather office website (https://weather.ec.gc.ca/) for the station Fort McMurray A, which is located in the study site. This station has long-term temperature data from 1944 to 2017. Potential impacts of future climate on IJF frequencies at the TFM were determined using NARCCAP datasets. NARCCAP consists of a set of RCM which is driven by GCM simulated over consistent time periods, i.e. from 1971 to 2000 for the historical period and from 2041 to 2070 for the future period. The observed and simulated daily mean air temperature data for the historical period has been presented and discussed in Das et al. (2017). NARCCAP uses the A2 emission scenario, which is at the higher end of the SRES emission scenarios (but not the highest) and most relevant based on the impact and adaptation view (NARCCAP, 2016). Among different RCMs and GCMs, CRCM+CGCM3 was selected for further analysis for two reasons. First, CRCM+CGCM3 is comparatively closer to the median of all 30-year day-averaged outputs from all models available from the NARCCAP (see Figure 3.2 of Rokaya 2018) and relatively accurately represents historical observed air temperature at the study site (see Figure 2 of Das et al., 2017). Second, the data was used by Rokaya et al. (2019) to derive future streamflow, which was used as a boundary condition for hydraulic modelling in this study. A comparison study by Mearns et al. (2012) also found CRCM to perform reasonably well compared to other RCMs.

5.3 Development of Future Air Temperature and Streamflow Conditions

Air temperature and streamflow under the future climatic conditions were developed by using a delta change method. The delta change is derived from the GCM output and then applied to the historical observed (baseline period) values to estimate the projected values. The delta is defined as the difference between the model simulated 30 - year weekly mean of a parameter (e.g. streamflow and temperature) in the future and the historical period.

For the future period, the weekly mean changes (delta) in temperature and flows given by the climate model CRCM + CGCM3 were calculated with respect to baseline data of the same climate model. The observed 30-year weekly average flows for the historical observed and the simulated MESH/CRCM+CGCM3 for the baseline period (1971 -2000) is given in Figure 5.2.

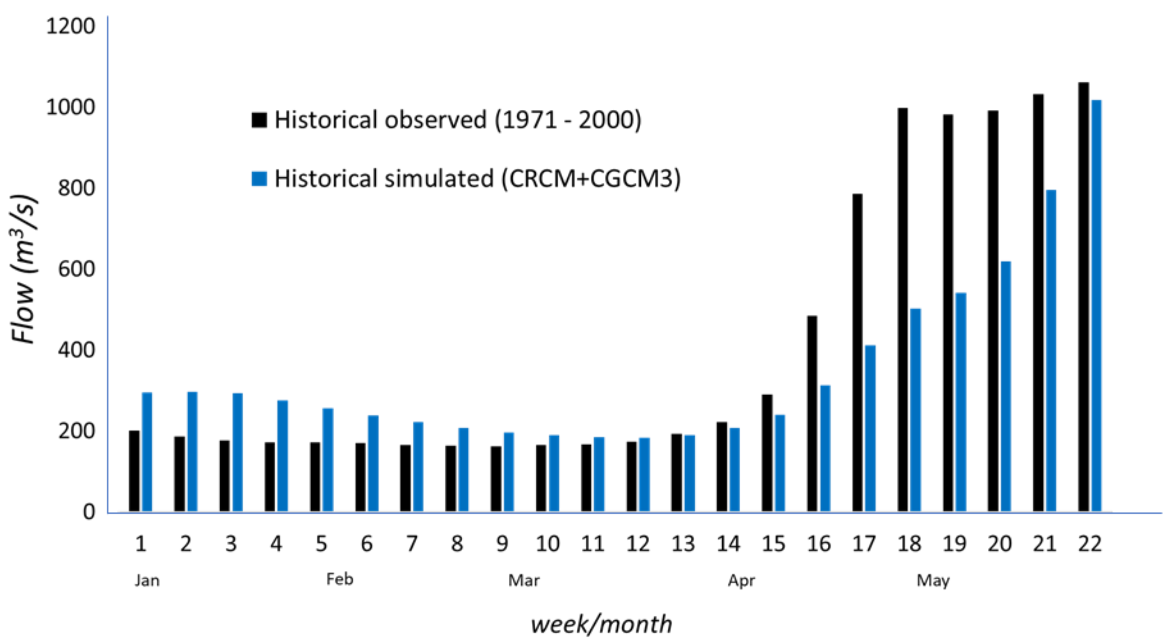

Figure 5.2 The observed 30-year weekly average flows for the historical observed and the simulated MESH/CRCM+CGCM3 for the baseline period (1971 -2000).

The absolute differences for projected air temperatures and both the absolute and relative changes were applied to estimate projected streamflow conditions using Equation 5.1, 5.2 and 5.3, respectively. Although the relative change approach has been widely adopted to estimate projected precipitation in climate-change research (Andrishak and Hicks, 2008, Navarro-Racines et al. 2020, Eum et al. 2017, Räty et al. 2014, Sunyer et al. 2015), the absolute change approach has also been used in recent years to project future climate scenarios (Hudson and Thompson, 2019, Baker and Huang, 2012). Since streamflow also depends on temperature, which is projected based on the absolute change, the estimation of projected streamflow with absolute change can add a counter-intuitive perspective to the analysis. Besides it may help us to understand/assess the associated uncertainties in these approaches to evaluate the severity of ice-jam flooding under the future climatic conditions. One of the main advantages of the relative change approach is to avoid arriving at negative values in streamflow when applying the delta values to observed data. A disadvantage can be an unrealistic magnification of climate-change effects on spring flows, deriving from large relative differences between small quantities.

The delta equations are:

$$\Delta T_m = T_{Fm} - T_{Hm} \text{ ………….. } 5.1$$

where ΔT_m is the mean weekly temperature change, T_{Fm} is the mean weekly temperature in the future period derived from GCM, and T_{Hm}, is the mean weekly temperature in the historical period derived from GCM in the week *m*., and

$$(\Delta Q_{abs})_m = Q_{Fm} - Q_{Hm} \text{ ………… } 5.2$$

$$(\Delta Q_{rel})_m = \frac{Q_{Fm} - Q_{Hm}}{Q_{Hm}} \dots\dots\dots\dots\dots\dots 5.3$$

where ΔQ_{abs} and ΔQ_{rel} is the mean weekly absolute and relative flow change, respectively, Q_{Fm} is the model simulated mean weekly flow in the future period, and Q_{Hm}, is the model simulated mean weekly flow in the historical period in the week m. Figure 5.3 shows the weekly mean changes (delta) in temperature and streamflow using the above equations.

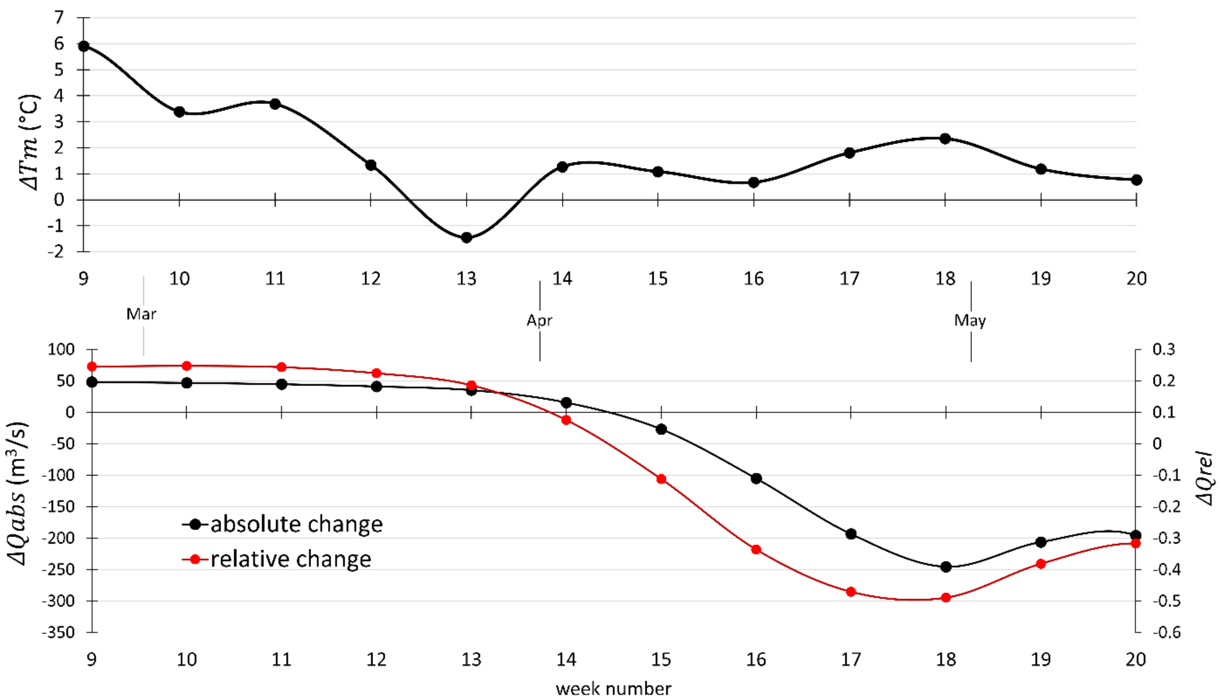

Figure 5.3 weekly mean changes (delta) in temperature and streamflow given by the climate model CRCM+CGCM3 with respect to baseline data of the same climate model. The week-number tick mark refers to the beginning of the week and the beginning of months indicated between top and bottom panels of the figure.

Finally, the mean weekly changes in the temperature obtained from the climatic model and streamflow obtained from climatic model forced hydrological model simulation were added to the daily historical observed temperature and streamflow data to derive the future temperature and streamflow values using Equation 5.4, 5.5 and 5.6.

$$T_p = T_{OB} + \Delta T_m \text{ .... } 5.4$$

T_p is the projected daily mean temperature in the future climate, T_{OB}, is the mean daily temperature in the observed historical period.

$$Q_{p\_abs} = Q_{OB} + \Delta Q_{abs} \text{ .... } 5.5$$

$$Q_{p\_rel} = Q_{OB} \times (1 + \Delta Q_{rel}) \text{ .... } 5.6$$

Q_{p_abs} and Q_{p_rel} is the projected daily mean flow in the future climate from absolute and relative change, Q_{OB}, is the mean daily flow in the observed historical period.

After estimating the corresponding future air temperature values for the 30 - year period, the cumulative degree-days of melting (CDDM) for each year was derived. The CDDM was calculated by adding all the daily mean air temperatures above -5°C from February 1 to May 31. The B-flags from the TFM gauge (07DA001) were used as proxies for the ice-on/ice-off dates for the historical period. The B-flags were provided by WSC along with hydrometric data to indicate backwater effects due to the presence of ice. Thus, the first B-flags indicate the beginning of ice effects on streamflow at freeze-up at/ or near the gauge location, while the last B-flags indicate the end of the ice effects on the water level. Typically, the first B-flag marks a time several days before a complete ice cover formation and the last B-flag marks a time several days after the ice cover has moved out from the gauge station.

The future CDDM values were then compared with the historical observed CDDM distribution to extract the probable range of the last B-day in the future. The CDDM distribution of observed historical period at the last B – flags is shown in Figure 5.4. Since the future ice jam simulation in a stochastic framework requires a flow-frequency distribution to estimate the maximum streamflow during the breakup, the CDDM distribution can help to identify the end of breakup days (last B-flags) for the river.

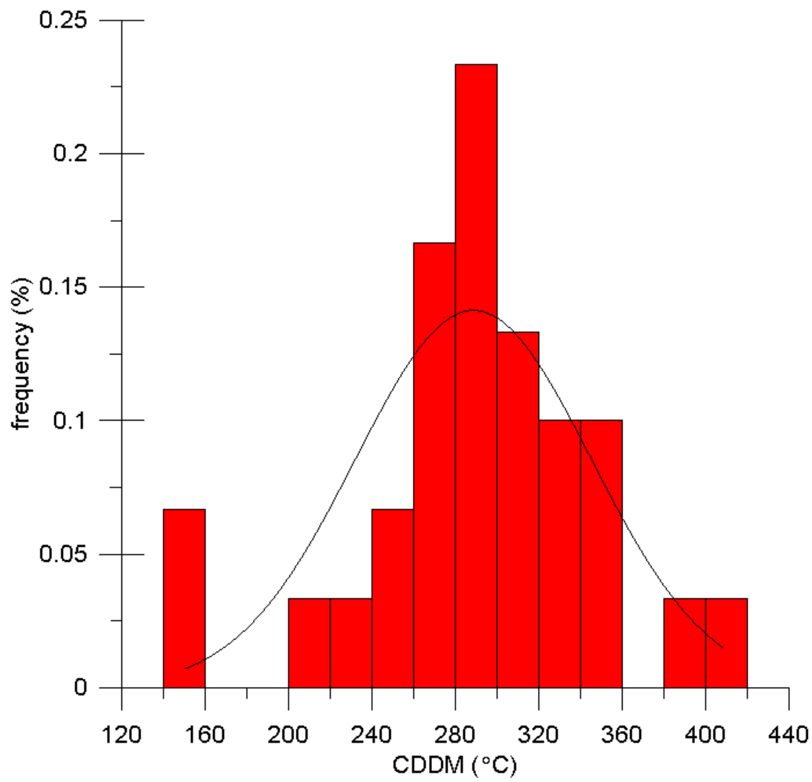

Figure 5.4 Historical observed CDDM distribution at last B -flags along the Athabasca River at Fort McMurray from 1971 - 2000.

To develop flow-frequency distributions of the maximum flows during the breakup for the future climatic conditions, two triggering factors – the rising of the spring freshet and CDDM distributions at the last B- flags were used.

For future climatic conditions, it is difficult to predict the exact breakup initiation date and the end of the breakup for a particular year. The rising of the spring freshet often initiates river ice breakup, while the last B – flag indicates the end of ice effects on stage. Since the historical CDDM distribution at the last B – flags can be derived from the observed air temperature, it can be easily applied as a boundary to estimate the maximum breakup flows in the future. For example, after the spring freshet begins, the CDDM on the day of maximum breakup flow can be extracted and compared with the historical CDDM distribution. If the CDDM value on the day of the maximum breakup flow is within the range of the historical CDDM distribution, the maximum flow can be selected to develop the flow-frequency distributions.

An example of the estimation of the maximum flow during the breakup under future climate conditions is shown in Figure 5.5. Since the observed historical CDDM values range from 200 to 410 °C, the maximum flows after the spring freshet within this CDDM range for the absolute and relative changes are 605.8 m^3/s (CDDM 404.68 °C) and 423.39 m^3/s (CDDM 392.27 °C), respectively. Similarly, the maximum flows for the 30 - year were extracted in the future for both climate models. However, occasionally projected maximum flows have been estimated beyond the overserved CDDM range if the maximum flow occurs before/after the lower/higher limit of the observed CDDM range is attained (Figure 5.6, left panel). Moreover, some negative values were calculated in the projected flow estimation when the absolute change was applied, but the small negative values in the hydrograph do not affect the breakup flow magnitude (Figure 5.6, right panel). Hence the applicable peak breakup flows were recorded for analyses.

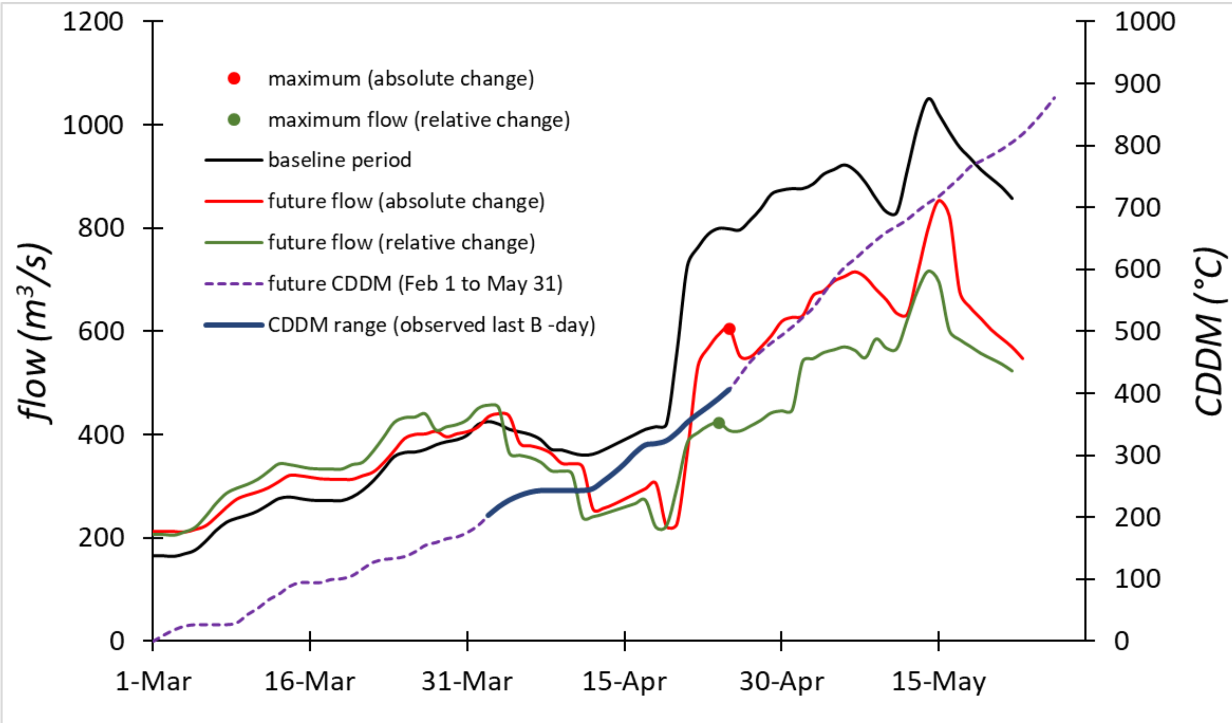

Figure 5.5 An example of the estimation of the maximum breakup flows under the future climatic conditions for a particular year.

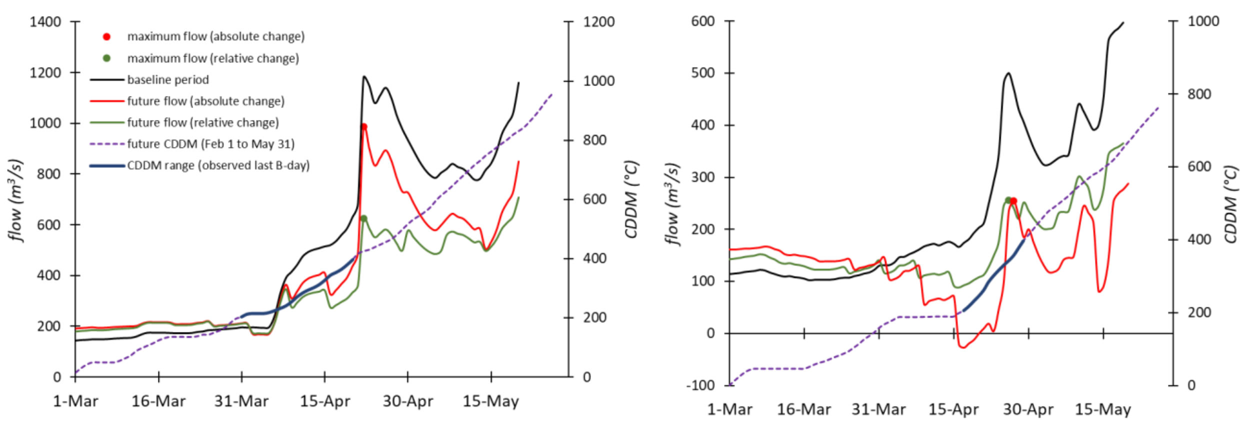

Figure 5.6 Examples of maximum breakup flow beyond the CDDM range (left panel) and occurrences of negative value (right panel) in absolute change approach under future climatic condition.

5.4 RIVICE Model Setup

RIVICE is a one dimensional fully dynamic model which simulates river ice processes using an implicit finite-difference numerical method (Environment Canada, 2013). RIVICE was used in this study to assess the hazard of ice-jam formation at the TFM under future climatic conditions. RIVICE uses various river ice parameters and boundary conditions to simulate ice-jam formation and corresponding backwater level profiles along the river channel. The parameters of RIVICE include porosity of the ice floes and ice cover, thickness of the ice floes and ice cover, a coefficient of hydraulic roughness underneath the ice cover, hydraulic flow roughness or Manning coefficient, and flow velocity thresholds for ice erosion and ice deposition. Boundary conditions include the upstream supply of inflowing ice, upstream and tributary discharges, downstream water level, and the location of the toe of the ice jam (see Table 4.1 for the list of parameters and their ranges). A more detailed description of the RIVICE model can be found in Environment Canada (2013) and Lindenschmidt (2017a).

The modelling domain of this study extends along the Athabasca River from the Cascade Rapids to Inglis Island (see also Figure 5.1). A set of model parameter values were drawn from Lindenschmidt (2017a) and boundary conditions were extended in this study from historical to future scenarios based on empirical relations and modelling results, which are described in the succeeding paragraphs. The Monte-Carlo (MOCA) runs were performed to run sets of 30 RIVICE simulations using PEST (Model-Independent Parameter Estimation Program). Sets of 30 simulations were used because the study analyzed the impacts of climate change on IJF frequency for a 30-year period (2040-2070) using CRCM+CGCM3 outputs. The boundary conditions used in the historical and future MOCA simulations are discussed below.

Upstream discharge: Historical discharge data from the gauging stations were applied to construct a historical extreme value discharge distribution for the upstream boundary of the model domain. The Gumbel extreme value distribution *F(x)* is often used to assess flood frequency distributions:

$$F(x) = 1 - e^{-e^{-[\frac{u+x}{\alpha}]}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(5.7)}$$

where the distribution's parameters, location u, and scale α, can be derived from the series mean μ and standard deviation σ by:

$$\alpha = 0.7797\sigma \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(5.8)}$$

$$u = 0.5772\alpha - \mu \ldots\ldots\ldots\ldots\ldots\ldots \text{(5.9)}$$

Extracted maximum flows using the delta change approach were then used to develop the flow frequency distributions under future period (Figure 5.7). The flow-frequency distributions from absolute and relative changes were then used to generate the random flow values for the future ice jam simulations in the stochastic framework.

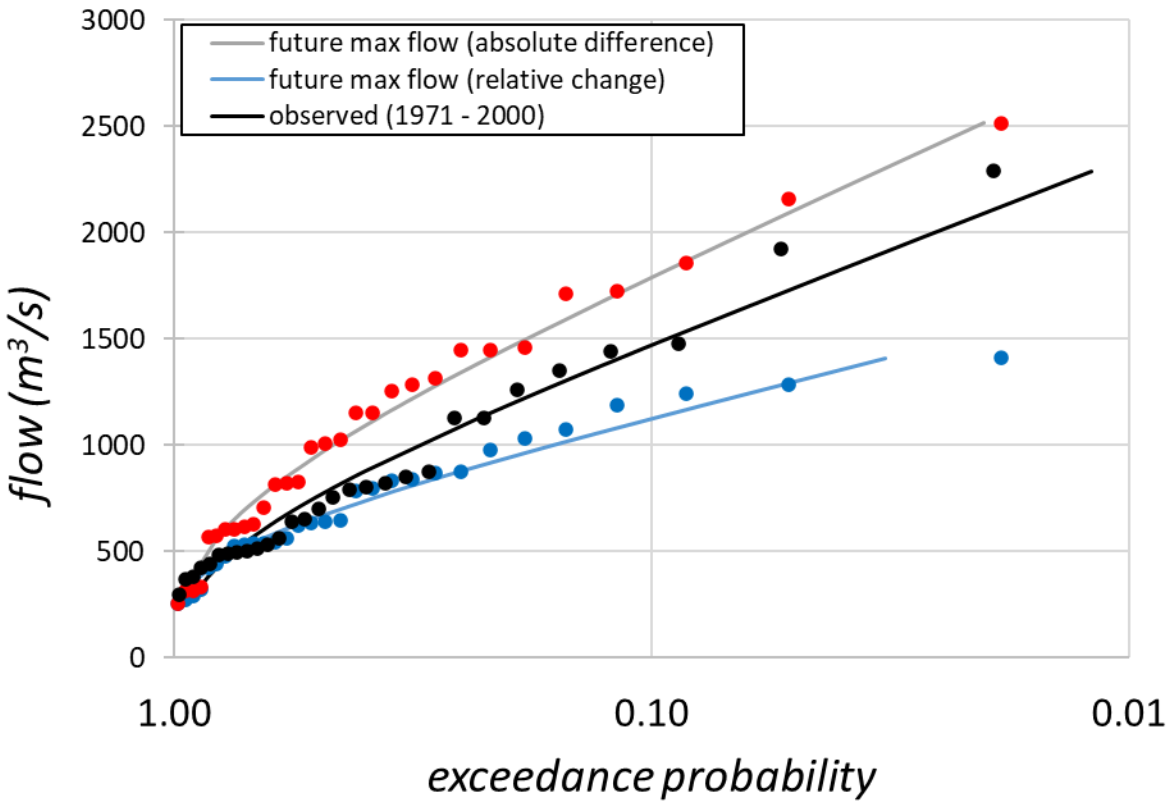

Figure 5.7 Probable flow-frequency distributions during breakup under the future climatic conditions for both models.

Downstream water level: Water levels at the downstream boundary during spring ice cover breakup are required to accurately simulate ice-jam formation along the river. The estimated rating curve was used to generate the downstream water level based on upstream discharge for MOCA simulations (see Figure 4.3).

Inflowing ice volume: The upstream supply of inflowing ice (e.g. rubble ice) is an important factor in determining the progression and severity of ice jams. In this framework, an estimation of the V_{ice} distribution using a set of 30 values was used as input to simulate ice-jam water level profiles. The simulated water levels located at the Athabasca River gauge downstream of Fort McMurray were extracted from each run to construct a stage-frequency distribution (SFD). The simulated SFD was then compared with the observed SFD. The MOCA analysis was repeated with adjustments to the input distribution until the simulated SFD matched the observed SFD. The calibrated inflowing ice volume distribution (Figure 5.8) was then used as input to the MOCA simulations.

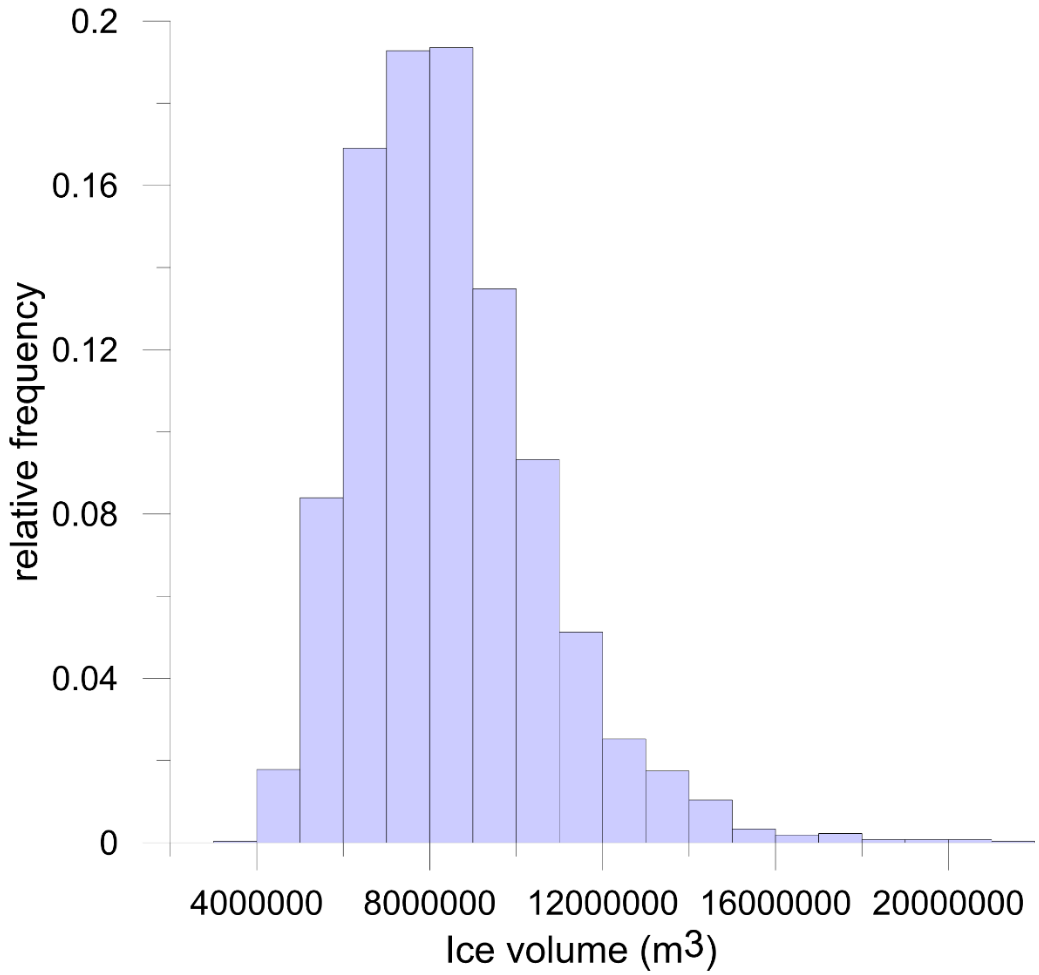

Figure 5.8 Calibrated ice volume along the Athabasca River at Fort McMurray.

Toe of the ice jam: Due to the geomorphology of the river stretch downstream of Fort McMurray, there is a higher potential for the toe of the ice jam to form in this location. The toe locations of ice jams were selected from the confluence of the Athabasca/Clearwater rivers to downstream of the TFM gauge (293 km to 280 km). Although there are some preferred ice-jam locations along the river such as Stony and Poplar Islands, ice jams can also form at several other locations downstream from the Athabasca and Clearwater rivers confluence (Friesenhan 2004, Das and Lindenschmidt 2019). A map of the toe locations of historical ice jam events is presented in Appendix 5.9 B. Since it is difficult to predict the exact location of the toe of the ice jam for any year, a simplified uniform distribution of the river chainage downstream of the gauge was applied for the random selection of the toe locations of ice jams along the model domain for MOCA simulations. The implementation of multimodal distributions for ice-jam toe locations is a subject of future work.

5.5 Flood Hazards Mapping

RIVICE provided flood water levels to determine flood hazard in the downtown region of Fort McMurray. In order to produce the flood hazard map, a method proposed by Lindenschmidt et al. (2016) was adapted. In this method, the ice-jam flood water level is subtracted from the digital elevation model (DEM) of the area to produce the flood hazard map. Flood hazard maps incorporate both extents and depths of flood water in the floodplain. Flood depth in a floodplain is defined as the difference between the flood water surface elevation and the floodplain surface elevation. The floodplain surface elevation was determined from a Lidar DEM at 15 m spatial resolution. A GIS tool was then applied to the flood water level elevations to produce a raster data set that contains the flood water level elevations in each cell. To delineate the flood extent and depths, the Lidar DEM was subtracted from the flood water surface raster of the study area. The positive cell values in the subtracted raster represent the flood extents and depths.

This method was first applied to the 1977 IJF event, which was one of the severest IJF events recorded in the study area. RIVICE was able to successfully model this ice-jam event and its backwater level profiles. This study found that the water level at the confluence of the Athabasca River and the Snye Channel provides a more accurate and conservative representation of the flood hazard areas, based on an aerial photograph of the flooding event in 1977 at the study site. Similar processing steps were then applied to derive the 1:100-year flood hazard map for both historical and future periods.

5.6 Results and Discussion

5.6.1 RIVICE Calibration and Flood Hazard Mapping Validation

The RIVICE model previously calibrated and validated by Rokaya et al. (2019) for the TFM was used in this study for the MOCA simulations to develop ice-jam SFDs. However, the one important boundary conditions of the model, inflowing ice volumes, were calibrated using observed daily maximum discharges. In this calibration, the Gumbel extreme value frequency distribution of inflowing ice volumes at the TFM during ice jam events was developed to extract random values for the MOCA simulations. Based on the calibrated parameters and boundary conditions, the model was able to develop a stage-frequency distribution for the historical period. The simulated historical SFD from the MOCA analysis matches well with the observed historical SFD (see **Figure 5.9**). Gringorton's formula ($P(X \geq x) = (m-0.44)/(n+0.12)$) was used to estimate the plotting positions for the stage-frequency distribution of historical period (Gringorten, 1963), where m is the rank (1, 2, … n) of a descending, sorted series of a total number of n extreme values.

To delineate the flood hazard map of Fort McMurray under future climatic conditions, we first tested a historical IJF event that occurred along the Athabasca River at the town in 1977. **Figure 4.5** shows the longitudinal simulated ice jam and corresponding backwater level profiles for this flood event. An ice jam formed just immediately downstream of the Clearwater River mouth, which blocked flow from the Clearwater River. The water backed up into the Clearwater River to overtop its banks by as much as 2.5 m and flooded a large portion of the town.

In the model, the toe of ice jam was set downstream of the confluence of the Athabasca and Clearwater rivers. The boundary conditions, upstream discharge and downstream water level were set to 1000 m^3/s and 235 m a.s.l., respectively. The inflowing ice volume was estimated to be approximately 20.4 million m^3. The longitudinal profile of the simulated water level shows good agreement with the observed water levels extending along the river chainage. The water level at the confluence of the Athabasca River and the Snye Channel was extracted from the 1977 simulated ice-jam water level profile to produce a flood hazard map for Fort McMurray's downtown area. **Figure 4.6** shows an aerial photo and the flood extent map for the 1977 IJF event. There is good agreement between the flood water extent observed in the aerial photo and the simulated flood inundation map of the town.

5.6.2 Ice-jam Stage Frequency Distributions (SFD) Under Future Climate Conditions

Figure 5.9 shows the ice-jam stage-frequency distribution (SFD) curves for the historical and future periods along the Athabasca River at the Fort McMurray gauging station using the climatic model CRCM+CGCM3. The results reveal that the mean SFD for the climatic model developed by considering both delta changes (weekly mean relative and absolute changes for 30-year periods) will be less extreme in the future compared to the historical SFD. The extrapolation of these SFD curves indicates that, while the 1:100-year flood water level at the Fort McMurray gauge station for the historical period is about 247.5 m a.s.l, the mean 1:100-year flood water levels under future climatic conditions for the absolute and relative changes are 247.01 and 245.31 m a.s.l, respectively. Moreover, while the maximum 1:100-year flood water level under future climatic conditions for the relative change is predicted to be lower, it can be more severe for the absolute change compared to the historical period. Many sets of thirty MOCA simulations were run within the MOCA framework using random selections of flow, ice volume, toe location and river ice parameters. A frequency analysis was then performed on the resulting water levels from each MOCA set to produce an ensemble of simulation SFDs. Finally, mean, maximum and minimum SFD lines were estimated from the ensembles of simulation SFDs to perform the analysis. Some of these ensembles of simulation SFDs at different locations along the model domain are shown in Appendix 5.9 C.

The projected scenarios in flood water levels along the river at Fort McMurray are a result of projected river flows estimated from the CRCM+CGCM3 climatic model using relative and absolute changes (Figure 5.7). While the historical maximum daily river flows ranges from 298 to 2290 m^3/s during spring ice cover breakup, the projected river flows for the future range from 254 to 2514 m^3/s and 256 to 1411 m^3/s for the absolute difference and relative change, respectively (Figure 5.7). As the projection of change in ice-jam backwater peaks with the absolute change is much higher than the relative change approach, therefore it can increase the overall spring IJF risk and current flood hazard areas in the town under future climatic conditions.

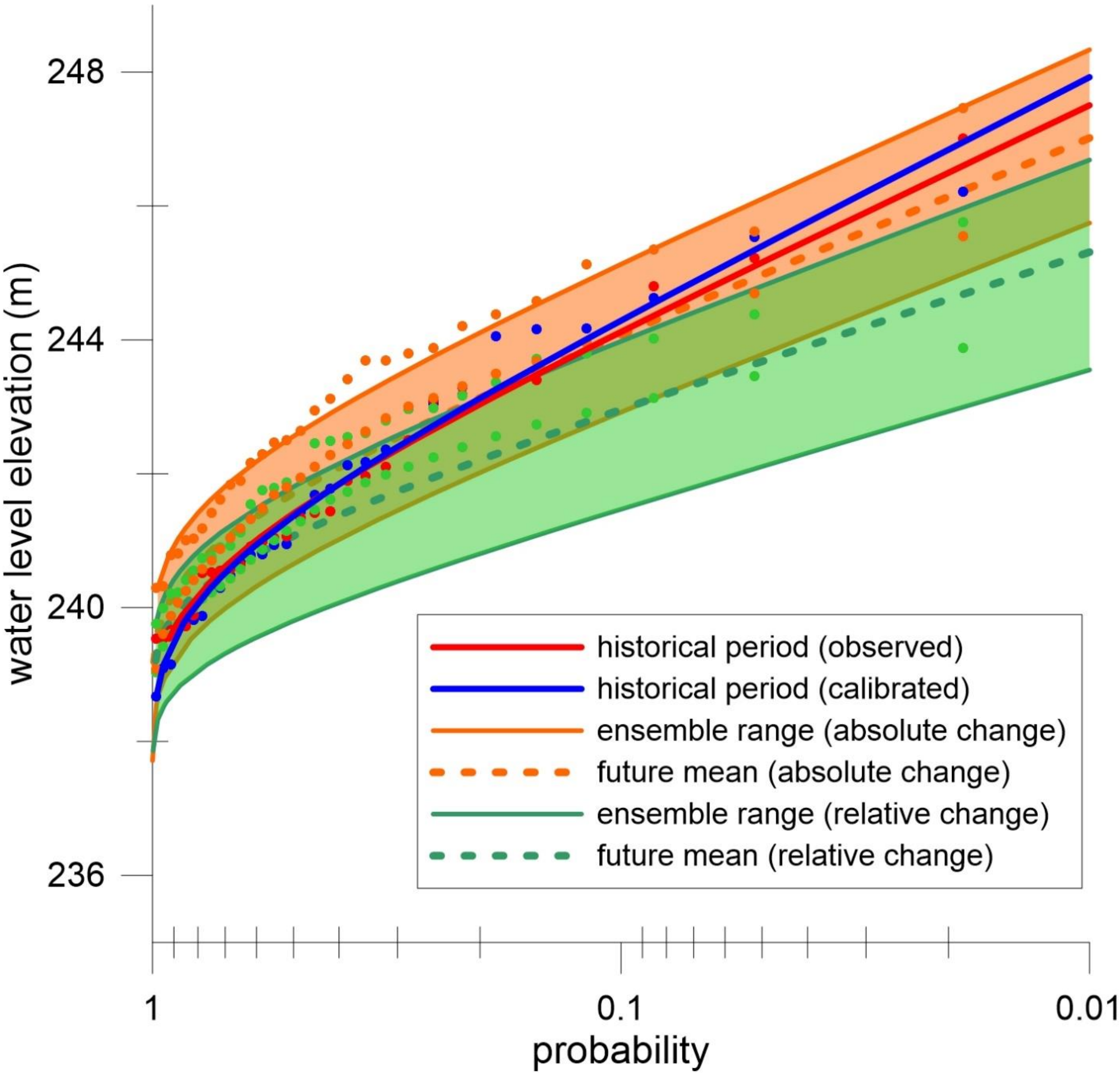

Figure 5.9 Ice-jam stage frequency distribution along the Athabasca River at Fort McMurray gauge station.

Although a contradictory result in ice jam water levels along the river at Fort McMurray has been quantified based on the two delta approaches (absolute and relative change), there may be a certain level of uncertainty in the results associated with the climate, hydrological and river ice models and the assumptions were carried in the whole framework. For example, a study by Eum et al. (2017) projected an increased freshet flow condition in spring due to an increase in precipitation and earlier snowmelt under warming climate conditions in the future, which is aligned with the results estimated from the absolute change approach. However, the streamflow estimated from the relative model predicted a decrease in spring freshet condition. This contradictory result of hydrological model simulation highlights the pertaining uncertainties in one of the important boundary conditions (e.g. upstream discharge) input in the hydraulic model to simulate ice-jam scenarios. Moreover, the hydrological model does not consider the effects of winter ice cover in the simulation, so that simulation results may not fully reflect the actual streamflow conditions along the river. Also, the degree-days method applied to derive future spring breakup dates may not be entirely aligned with the present conditions. River ice processes and characteristics are also governed by many geomorphological features of the river that can also change in the future. However, considering all these uncertainties, the stochastic approach has been used in this study represents a reasonable solution, as a vast range of parameters and boundary conditions are used in the simulations, which may be able to consider the effect of each parameter on the ice jam processes. Moreover, this approach provides a probability band (envelope) of the probable ice jam severity along the river, which may further help to determine confidence intervals of the model output.

5.6.3 Ice-jam Flood Hazard Mapping under Future Climate Conditions

To assess the 1:100-year IJF hazard under future climatic conditions at Fort McMurray, the historical 1:100-year flood hazard map is required. The simulated and observed SFDs of the historical period at the confluence of the Athabasca River and Snye Channel is presented in Figure 5.10. There is a good agreement between observed and simulated SFDs at the Fort McMurray.

The water levels at the confluence of the river and channel were extracted from each MOCA setup under future climatic conditions to produce ensembles of SFDs at the town. From the ensemble of future SFDs, an envelope of maximum, minimum and average SFDs was developed for each approach. The 1:100-year flood water levels were then extracted from these SFDs to map the flood hazard of the town for both historical and future periods. The envelopes of future SFDs from absolute and relative changes at the confluence of the Athabasca River and Snye Channel are shown in **Figure 5.10**. A similar result at the TFM gauge station was found, as at the confluence, an extreme severe SFD with absolute change and a less severe SFD with relative change in the future compared to the historical SFD.

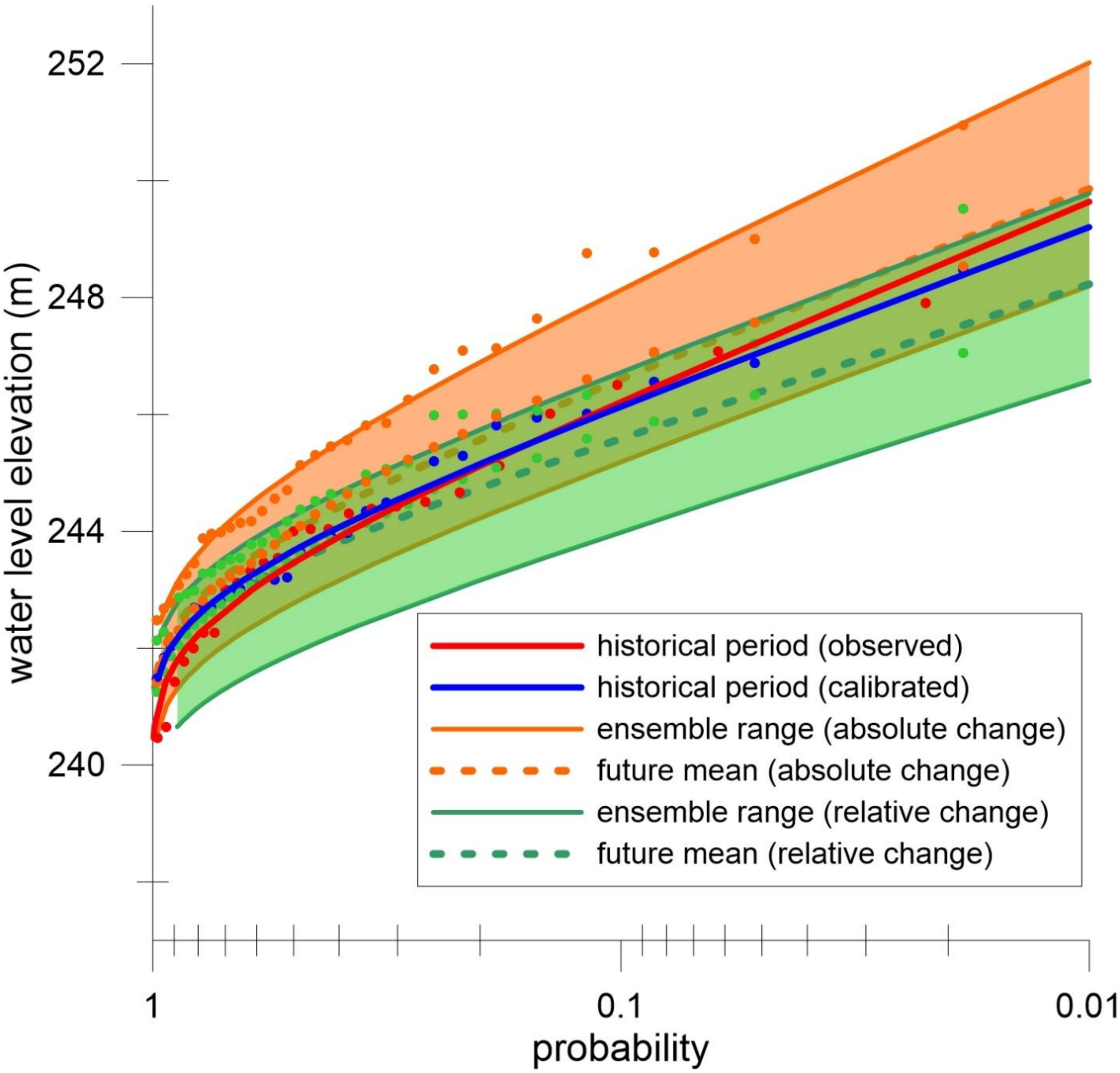

Figure 5.10 Stage frequency distributions for the historical and future periods at the confluence of the Athabasca River and Snye Channel near Fort McMurray's downtown area.

The 1:100-year IJF hazard map for the historical period is shown in **Figure 5.11**. The 1:100-year flood water level at the Fort McMurray was estimated to be 249.64 m, based on historical observed ice-induced water level at the confluence of the Athabasca and Clearwater rivers (Figure 5.11). In the historical (1971-2000) 1:100-year flood event, major portion of the downtown area at Fort

McMurray could be flooded. This flood level could affect a considerable number of residential and commercial areas of the town, leading to damages in the millions of dollars.

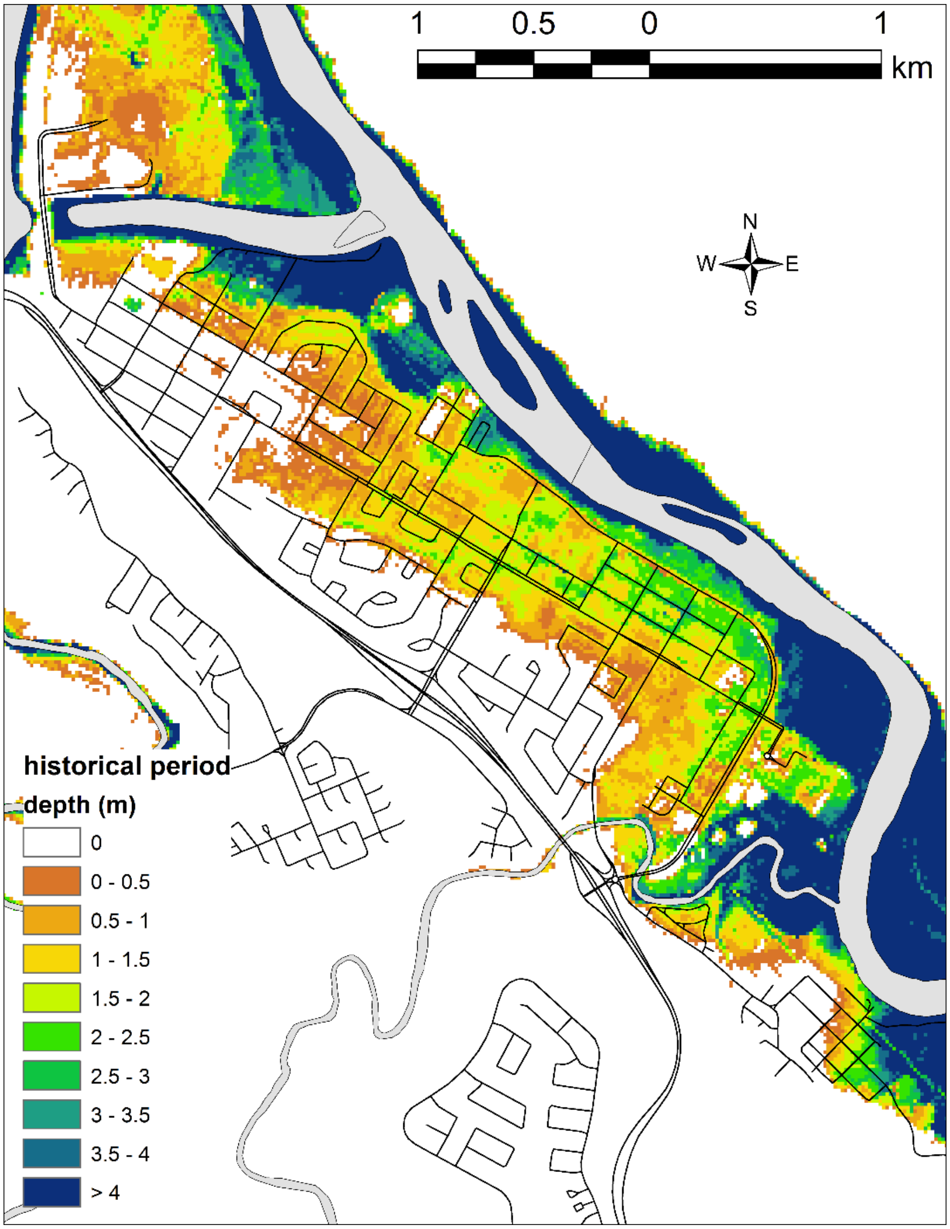

Figure 5.11 The 1:100-year flood extent area for the historical period.

Figure 5.11 illustrates the 1:100-year flood extent area of the town under future climatic conditions (2041 – 2070). The results show that in absolute change, the flood extent area is likely to increase in the future for the maximum 1:100-year flood water levels, while it is likely to be more or less similar to the relative change approach compared to the historical period.

Overall, a relatively small portion of the town may be flooded from the average 1:100-year flood water level predicted by the relative change approach, but a considerable portion of the town could still be flooded from the average 1:100-year flood water level predicted by the absolute change approach (Figure 5.12). The average 1:100-year flood water level is the mean value of the ensemble of simulated SFDs, while the maximum 1:100-year flood water level represents the extreme simulated SFD. As the maximum 1:100-year flood water level represents an extreme ice-jam event and may result in maximum flood damages, most flood design criteria often consider the higher historic flood event (Burrell et al., 2015, Vogel and Stendinger, 1984); hence, flood managers may use this future flood hazard information for decision making.

It is also noticeable that, under the absolute change method, the average flood extent area is much larger than the flood extent area under the relative change method. This is due to the higher number of extreme ice-jam events predicted in the first approach compared to those of the latter one. This output is also reflected in SFDs at both the town and gauge station, with the average SFD of the absolute change being higher than the average SFD of the relative change. The difference between the two approaches may be related to equilibrium climate sensitivities and how boundary conditions are defined, or whether any coupling/adjustment was carried out (Randall et al., 2007). Moreover, the climate models are estimated based on the projections of future greenhouse gases and aerosol emissions. Since these emissions are usually depend on society's developmental trend and various anthropogenic factors, which are unknown, it is difficult to ascertain the actual level of atmospheric greenhouse gases and aerosol emissions for the future and to capture the entire range of natural variability in the analyses, hence projected ice-jam severity estimated in this framework involve uncertainties.

A study investigated the impacts of ice jam formations downstream of the gauge station near the downtown area of Fort McMurray, not the ice jam formations further upstream from the confluence (Das et al. 2020). The study does not consider model bias and indicates that overall severity of the ice jam flooding along the river will be less extreme compared to the historical period. This result is more aligned with the results of mean ice jam flood water levels predicted with the relative change approach in this study. A number of studies along the adjacent Peace River basin have also shown similar trends, that IJF frequency will be reduced significantly under future climatic conditions (Beltaos et al., 2006a, Beltaos et al., 2008).

Although the severity of ice-jam flooding is projected to be lower, the hydraulic model results show that ice jam formation along the Athabasca River will continue to lead to flooding and flood damages. While there are no similar hydraulic assessments of the Athabasca River for comparison, a study by Eum et al. (2017) projected an increased freshet flow condition in spring due to an increase in precipitation and earlier snowmelt under warming climate conditions in the future.

Moreover, some hydrological studies have shown that snowmelt runoff is likely to decrease in the future due to less snowfall in winter and increased runoff in winter and early spring (Dibike et al., 2018a; Dibike et al., 2018b). Reduced streamflow conditions are likely to lessen extreme flood events as previous studies have shown and, with all other factors remaining equal, reduced breakup flows and higher freeze-up stages can lower the probability of IJFs (Beltaos et al., 2006b). Since different projections are obtained under the assumed absolute and relative delta methods, further investigations/research are needed to fully understand the future climatic condition's impacts on the severity of IJFs.

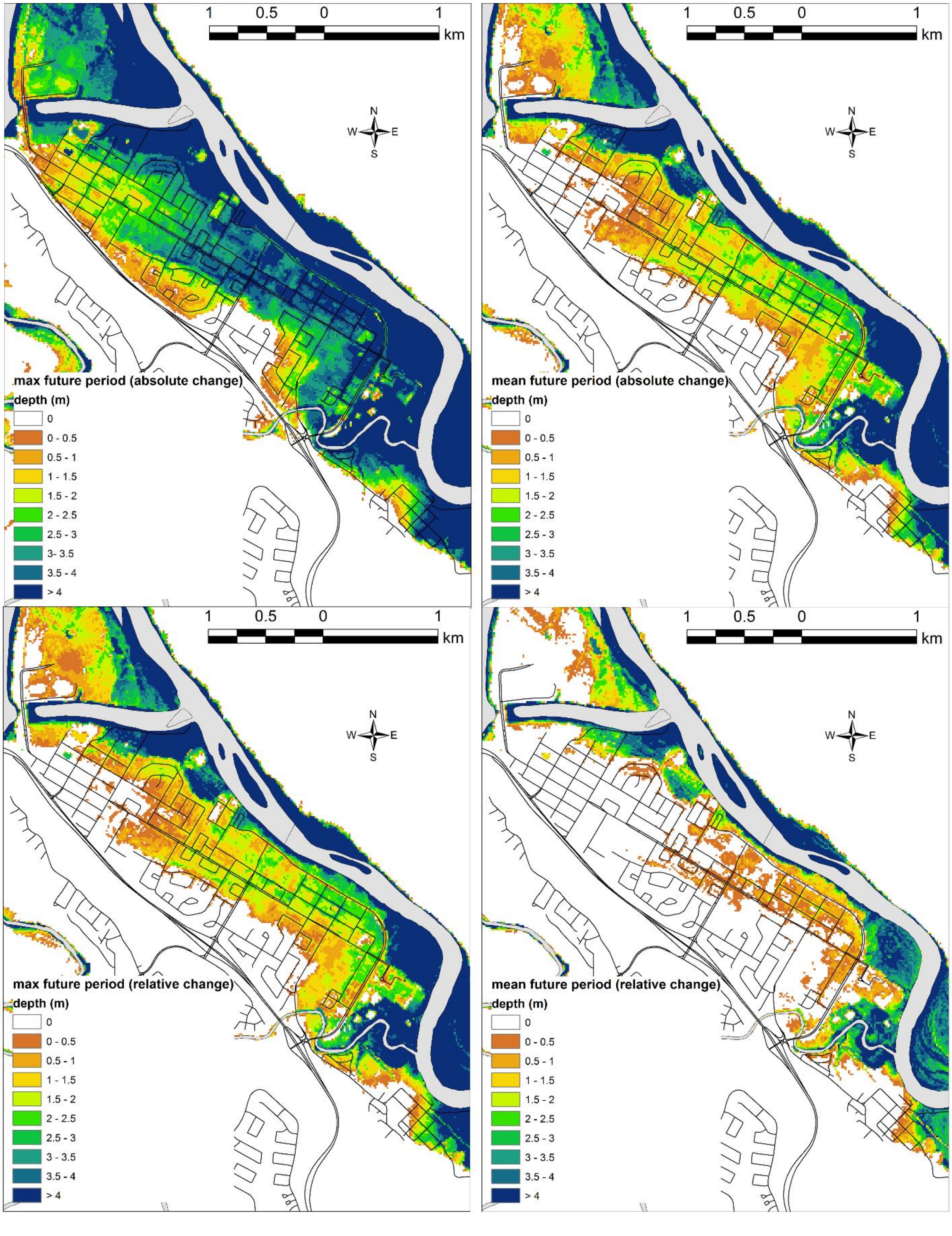

Figure 5.12 The 1:100-year maximum and average flood extent area in the downtown area of Fort McMurray under the projected ice-jam scenarios.

5.6.4 Implications for Planning and Management

The modelling framework of this study will be useful for land-use planning and design of hydraulic structures and other mitigation measures against ice jam flooding under future climatic conditions. The stochastic approach of flood hazard mapping for the town under future climatic conditions can help with the development of an effective IJF risk management strategy to reduce vulnerability of people and property that may be subjected to ice-jam floods. The maps can also be used to calculate potential financial damages and assist in disseminating the information regarding costs associated with future ice-jam flood events. The flood prone areas can also be identified by the maps to avoid further development in those areas. This approach of this study can also assist flood managers in determining the capacity of current flood protection systems along the river and whether they are sufficient to protect against future ice-jam flooding. Overall, the stochastic framework can be a reliable approach for water resources managers to evaluate climate change impacts on ice-jam flooding, especially in estimating the future exceedance probability of ice-jam staging during spring ice-cover breakup. A similar approach has already been applied successfully along the Athabasca River at Fort McMurray in an operational flood forecasting context (Lindenschmidt et. al., 2019).

5.7 Conclusion

Overall, this study has provided a new framework to evaluate the impact of future climate conditions on IJFs by coupling hydrological model results in a hydraulic river ice model within a probabilistic framework. Most of the existing climate change studies on river ice are limited to the assessment of future freeze-up/breakup dates or hydrological flow simulations, but this study has advanced the research one step further by incorporating hydraulic modelling for IJF risk assessment and hazard mapping. Such coupling studies that incorporate uncertainties through probabilistic modelling can be useful to both hydrologic and hydraulic engineers to better understand the impacts of hydrological parameters on hydraulic characteristics of the river channel. Although there is and will always be some uncertainty regarding future assessments, a meaningful inference can be drawn from this study. The risk of spring ice-jam flooding along the Athabasca and Clearwater rivers can be more severe in the future compared to the historical period.

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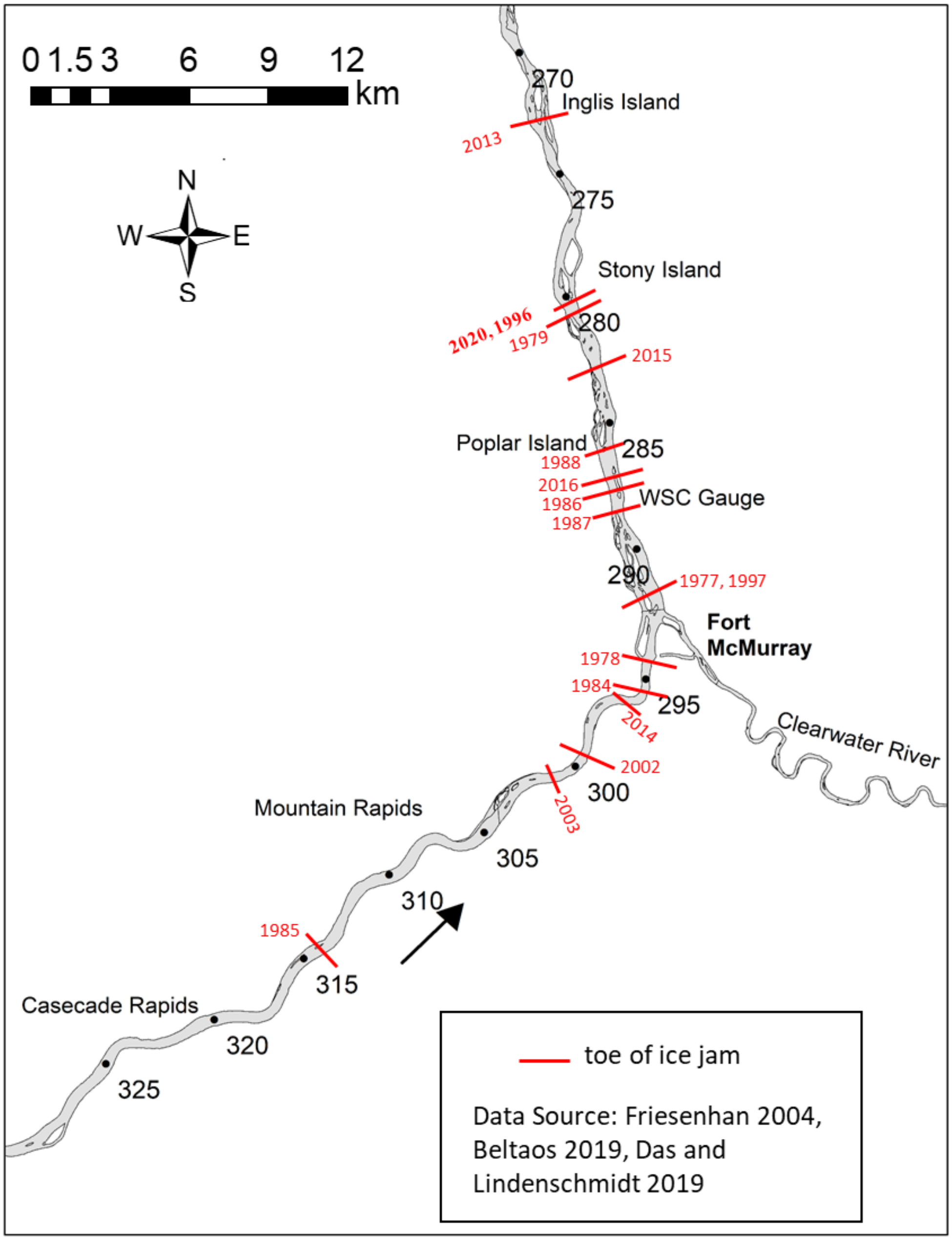
5.9 Appendices

Appendix A: Hydrological Data

Table A-1 The peak water level data at the confluence of Athabasca and Clearwater rivers.

Year	WL	Source
1972	**244.3**	Winhold and Bothe (1993)
1977	**247.9**	
1978	**242**	
1979	**246.5**	
1980	**244.4**	Turcotte et al. (2019)
1981	**244**	
1982	**242.2**	
1983	**242.2**	
1984	**241.7**	
1985	**243.4**	
1986	**244.0**	
1987	**245.1**	
1988	**244.5**	
1989	**243.1**	
1990	**243.0**	
1991	**244.6**	
1992	**241.4**	
1993	**243.5**	
1994	**244.0**	
1995	**244.3**	
1996	**246.0**	
1997	**247.08**	
1998	**243.31**	
1999	**240.4**	
2000	**240.6**	

Appendix B: Toe location of the historical ice-jam events along the Athabasca River at Fort McMurray.



Appendix C Ice-jam Stage Frequency Distributions (SFD) Under Future Climate Conditions

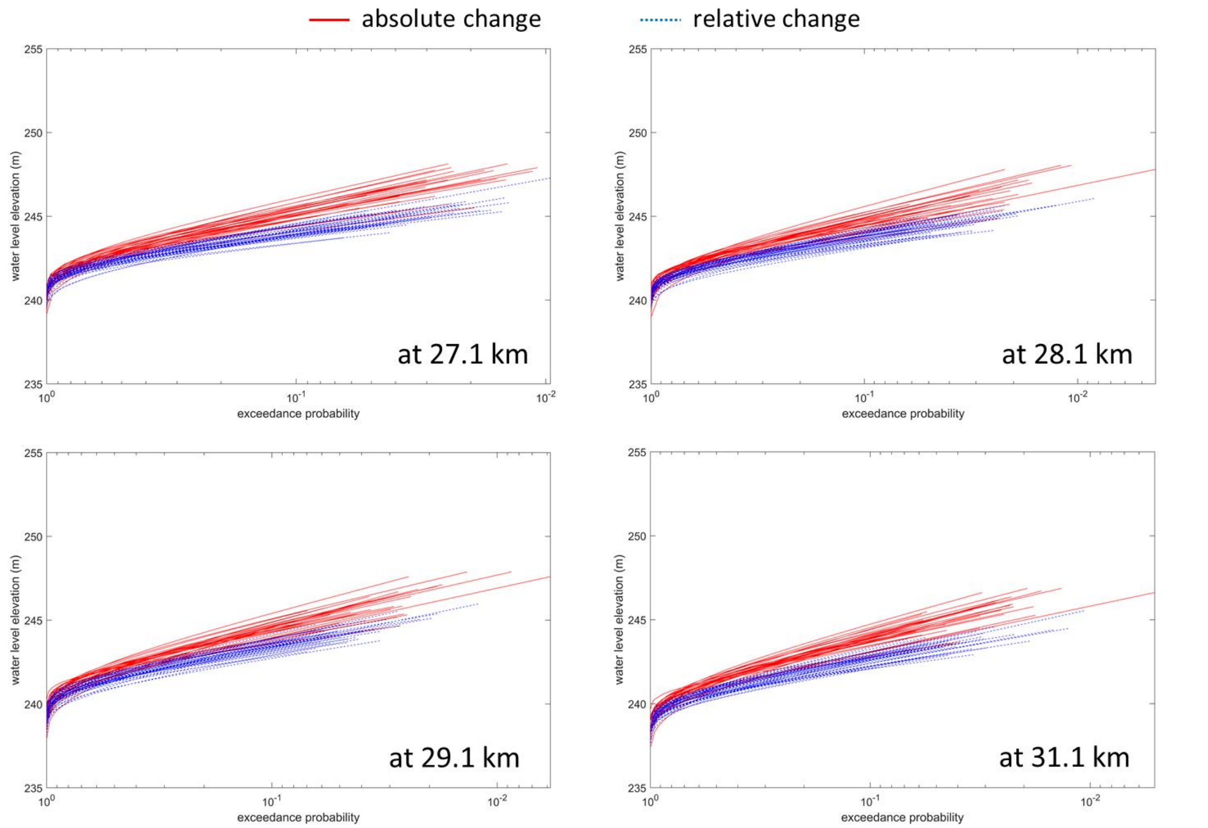


Figure C-1: The ensemble of ice jam flood-stage frequency distributions at several cross-sections along the model domain. The Athabasca and Clearwater rivers confluence and WSC gauge station are situated 26.1 30.1 kilometers, respectively.

Preface to Chapter 6

CHAPTER 6: EVALUATION OF THE FEASIBILITY OF ICE-JAM FLOOD MITIGATION MEASURES FOR REDUCING ICE-JAM FLOOD RISK

In this chapter, a framework has been developed to determine the feasibility of various ice jam flood mitigation measures. The article is accepted in the ***Journal of flood risk management***:

Das, A. & Lindenschmidt, K. E. (2020). Ice-jam flood risk assessment and hazard mapping under future climate conditions. ***Journal of flood risk management.***

Contribution of Authors: Apurba Das carried out all the simulations and data analyses and wrote the manuscript. Karl-Erich Lindenschmidt helped to develop the paper and reviewed the manuscript throughout the process.

CHAPTER 6

EVALUATION OF THE FEASIBILITY OF ICE-JAM FLOOD MITIGATION MEASURES FOR REDUCING ICE-JAM FLOOD RISK

Abstract

Ice-jam flood risk management requires new approaches in order to reduce flood damages. Although many structural and non-structural measures have been implemented to reduce the impacts of ice-jam flooding, there are still many challenges in identifying appropriate strategies to reduce the ice-jam flood risk along northern rivers. The main purpose of this study is to provide a novel methodological framework to assess the feasibility of various ice-jam flood mitigation measures based on risk analysis. A total of three ice-jam flood mitigation measures (artificial breakup, sediment dredging and dike installation) were examined using a stochastic modelling framework for potential to reduce the ice-jam flood risk along the Athabasca River at Fort McMurray. An ensemble of hundreds of breakwater level profiles was used to construct ice-jam flood hazard maps to estimate expected annual damages, using depth-damage curves for structural and content damages, within the downtown area of Fort McMurray. The results show that, while sediment dredging may be able to reduce a certain level of expected annual damages in the town, a dike with a crest elevation of 250 m a.s.l. and artificial breakup can be the effective measures to reduce the amount of expected annual damages.

6.1 Introduction

The identification of appropriate mitigation measures can be one of the main challenges in implementing an ice-jam flood management program. There are two types of measures usually applied to reduce flood damages - structural and non-structural measures. Structural measures often termed as flood control structures which include dams, reservoirs, dikes and levees, weirs and piers. Non-structural measures are usually implemented to avoid flood hazard which involves various regulation measures (e.g., zoning, subdivision controls), warnings and floodplain developments. Examples of non-structural measures include early flood forecasting and warning systems, land use regulations, and financial penalties and disincentives for development on flood-prone areas (Burrell et al. 2015). Additionally, artificial breakup prior to the ice breakup period in spring, using an ice breaker or Amphibex, can be implemented to reduce the severity of ice-jam occurrences. Sediment dredging can also be an effective mitigation measure, as it enhances ice-discharge capacity at a known ice-jam site. Moreover, blasting and mechanical removal (Morris et al. 2017) are additional mitigation measures that are often used, not pre-emptively but in emergency situations. Non-structural measures are usually less expensive and may have minimal impact (except blasting) on the surrounding aquatic and terrestrial ecology, as compared to structural measures.

In a large river, structural measures, such as dams and reservoirs, can be an effective means of mitigating ice-jam floods (Jasek et al. 2007); however, the construction and operational costs of these measures are very high. Additionally, they have some adverse impacts on river ecology, such as flow (Prabin et al. 2019) and stream temperature modulations (Carr et al. 2019), which could lead to the drying of wetlands in deltas (Prowse and Conly, 1998). In small rivers, more eco-friendly and low-cost control structures such as in-stream piers have been implemented in recent years (Burrell et al., 2015). The primary function of these structures is to arrest incoming ice floes upstream from ice-jam prone areas while still allowing water to pass through. In-stream piers have been built in many rivers, such as the Credit River in Canada and the Lamoille and Salmon rivers in the USA.

Although a dike is usually used to protect against open-water floods, it can also be effective for ice-jam flood protection, if adequate design criteria for ice-jam flooding are considered for its construction. Since these structures are usually built near riverbanks, they can prevent large volumes of ice and water from inundating floodplains during ice-jam events (Beltaos, 2008b). However, extreme ice-jam backwater stages can lead to overtopping and breaching of the dikes, resulting in substantial flood damages (Lindenschmidt et al. 2016). There have been a number of events reported along the lower Platte River in Nebraska, USA, where the dike along the river was overtopped and breached due to ice jams in 1978, 1979, 1980 and 1993 (White, 1996; White et al. 2006). A breach of the dike system and associated flooding due to ice jamming have also been reported along the Vistula River, Poland and Thames River, Canada (Dick, 2019; Cyberski et al. 2006). Since dikes are associated with extensive construction, operational, and environmental mitigation costs, their utilization can be relatively expensive.

Various types of mechanical equipment can be utilized for artificial breakup and ice-jam mitigation. The artificial ice breaking options usually include an amphibious excavator (Amphibex), conventional ice breakers, barge-mounted excavators and hovercraft (McShea et al. 2008). Most of this equipment is used to pre-break ice and promote downstream ice movement to avoid ice-jam formation at a specific location. Over the years, ice breaking techniques have been used along many rivers in Canada, such as the Red River (Dangerfield, 2017), St. Lawrence River (Beltaos and Burrel, 2015) and Grasse River (McShea et al. 2008). For example, a conventional barge-mounted excavator was used to assess the effectiveness of ice breaking as a potential mitigation measure along the Grasse River in spring 2007 (McShea et al. 2008). Although the deployment of the equipment was successful in clearing the ice from most of the selected locations, it was not further used due to community safety concerns and some other unmanageable factors. The Amphibex is a hydraulically operated floating vehicle used to break ice covers before a natural breakup occurs and to dislodge threatening ice jams during breakup (Beltaos, 2008a). This technique is applied to reduce the severity of ice-jam flooding by increasing the channel conveyance capacity or moving the location of the ice jam further downstream, where impacts of flooding on property and assets are minimal. The Amphibex has been extensively deployed along many rivers in Canada, such as the Red and Whitemud rivers in Manitoba (Topping et al. 2008), the Moira and Kaministiquia rivers in Ontario (Beltaos et al. 2007a, 2007b) and the Sainte-Anne River in Quebec (Simard-Robitaille et al. 2015). The studies have reported that the Amphibex can be a suitable and effective tool for preventing and reducing severe ice-jam conditions along rivers. However, the Amphibex may not be able to perform under all conditions. For example, the Amphibex has been found to be less effective and consistent in breaking ice covers when the ice is thicker than 0.6 m (Topping et al., 2008). Moreover, the operation of the Amphibex is slow and can be dangerous under severe ice-jam conditions. In order to deal with these limitations, an improvement was initiated by the Province of Manitoba, incorporating a redesign to create a more robust and efficient Amphibex machine. As a result, the average operational costs could be reduced and the overall operation is more efficient and cost-effective (Topping et al., 2008).

Sediment dredging is the operation of excavating sediment from the riverbed to enhance channel water flow and ice discharge capacity during an ice-cover breakup. The dredging is used to avoid an extensive amount of ice accumulation and congestion and can be useful to reduce the severity of ice jamming and subsequent flooding (Burrell et al. 2015). The effectiveness of dredging to reduce the severity of ice jamming and subsequent flooding has already been examined along the Red (Lindenschmidt, 2012) and Athabasca rivers (Lindenschmidt, 2020) using hydraulic modelling. These studies found that dredging has the potential to reduce ice-jam backwater staging, as well as subsequent flooding. Dredging was also implemented along the Torne River in northern Sweden and Finland to reduce the severity of ice jamming adjacent to the city of Tornio (Lindenschmidt et al. 2018). Dredging the river increased the ice discharge capacity and shifted the potential ice-jam location further downstream of the city. There has also been an ongoing debate regarding proposals to implement sediment dredging to prevent ice-jam flooding along the Churchill River in Labrador and the Red River in Manitoba (Jacob, 2019, CBC-News, 2011). Community members from these areas advised that dredging could be a potential mitigation measure against ice-jam flooding. However, there are some adverse impacts of dredging. Sometimes, excessive deepening of the riverbed can reduce flow velocities so much as to cause additional ice accumulations to form, leading to hanging ice dam formation at the dredging site. Environmental impacts are also a necessary consideration when dredging is implemented (e.g. destruction of fish habitat and changes in water quality) (Darby and Thome, 1995). Moreover, the dredging needs to be carried out regularly, often every 10 years according to the Department of Fisheries and Oceans Canada (www.dfo-mpo.gc.ca), making it relatively expensive.

The adaptation of an ice-jam mitigation measure for a particular site depends on various factors, such as ice-jam characteristics, climatic variability, and cost consideration. At a specific site, the severity of ice-jam flooding is often controlled by the morphology of the ice jam (e.g. the volume of ice constituting the jam and the length of the ice jam), the fluvial geomorphology of the river (e.g. river slope and width-to-depth ratio), and the hydraulic regime characteristics (e.g. flow velocities and discharge). Therefore, detailed hydro-technical flood hazard and vulnerability assessments should be carried out to determine the potential severity of ice-jam flooding. This can be accomplished using a flood risk analysis. Risk analysis integrates flood hazard and vulnerability for a particular flood event. In the risk analysis, flood hazard includes the intensity and probability of certain flooding and the vulnerability incorporates the exposure and susceptibility of the flood-prone area (Forster et al., 2008; Lindenschmidt et al., 2006). Therefore, this analysis provides information to justify the expense of such a measure versus flood damage costs. However, risk-based cost-benefit analyses in an ice-jam flood context, for the purpose of selecting appropriate measures, are sparse. To date, most of the cost-benefit studies related to flooding have been limited to only the hazard side of the analysis and estimating the costs of the implemented mitigation measure. The main purpose of this study is to provide a novel methodological framework to assess the feasibility of various flood mitigation measures, based on flood risk analyses specifically for ice-jam flooding. To date, the authors are aware of only one attempt made to estimate ice-jam flood risk, which was done along the Peace River at the Town of Peace River (Lindenschmidt et al. 2016), where exceedance probabilities were estimated from the gauge data levels and extrapolated into the floodplain. However, this current study incorporates an extension and improvement of that work by calculating the flood risk from each ice-jam simulation map. An advantage of the stochastic approach is to deal with the uncertainties involved in modelling parameter selection for naturally complex flood occurrences due to ice jams in the river (Altonen and Huokuna,2017); the stochastic modelling processes deal with a vast range of parameters in capturing all the individual parameters effecting ice jam flooding. The specific objectives are to (i) develop a stochastic modelling framework to assess the feasibility of various ice-jam mitigation measures; (ii) assess the expected annual damages (EAD) from various mitigation measures; and (iii) provide a current ice-jam flood risk map of Fort McMurray along the Athabasca River.

6.2 Methodology

6.2.1 Study site

The framework for assessing the feasibility of various mitigation measures was tested along the Athabasca River at Fort McMurray, Alberta (Figure 6.1). The study domain of the river extends for a length of 51 km from the Cascade Rapids to Inglis Island. The town of Fort McMurray, at the confluence of the Athabasca and Clearwater rivers, is situated within an ice-jam prone area due to the various hydro-climatic and geomorphological features of the river. There are a series of rapids (e.g. Cascade Rapids, Mountain Rapids and Moberly Rapids), islands (e.g. McDonald, Poplar and Inglis islands), sand bars and relatively sinuous and low velocity reaches along the river. The slope of the reach varies from relatively steep (0.001) to much flatter (0.0003) and the width of the reach varies from relatively narrow (300 m) to much wider (700 m) (Lindenschmidt, 2017a). These features have a significant influence on the regime of spring ice-cover breakup. Most often the spring ice-cover breakup involves a number of ice-jam formation and release events. Ice runs from upstream ice-jam release events can become impeded in the vicinity of the town, forming a new jam and triggering associated flooding. Additionally, the Clearwater River also plays an important role in ice-jam flooding in the vicinity of the town. The ice-jam backwater often extends along the Clearwater River channel to flood the downtown site of Fort McMurray.

The town of Fort McMurray has a long history of ice-jam flooding. Some of the most extreme ice-jam floods occurred in 1835, 1875, 1977, 1978, 1979 and 1997 (IBI and Golder Associates, 2014) and 2020 (CU, 2020). Since downtown Fort McMurray can be periodically flooded due to ice-jam formation in the Athabasca River, there are many old and new residential, commercial, industrial, and institutional properties at extremely high risk for flood damages. In 2014, a flood damage assessment study indicated that the average annual damages from flooding were approximately $10,450,000, which included both direct and indirect damages (IBI and Golder Associates, 2014). Some mitigation measures are already in place for the town of Fort McMurray to reduce the impact of ice-jam floods, including floodplain management, regular spring breakup monitoring and flood forecasting and warning. In terms of structural measures, the town is only protected by the dike along the Snye Channel. A dike alongside the Clearwater River is under construction to protect from a 1:100-year flood water level elevation (250 m a.s.l.).

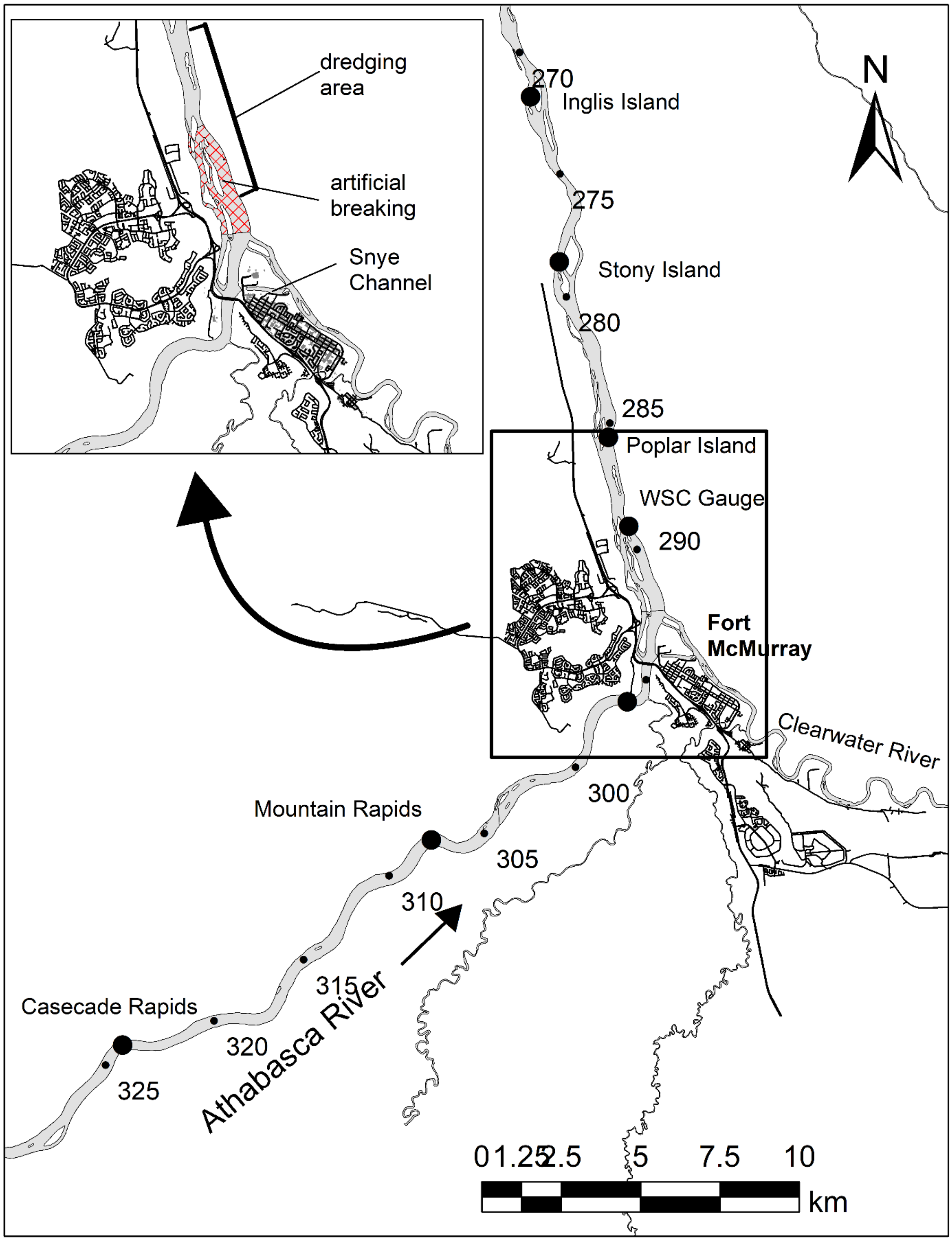


Figure 6.1 Study site of the Lower Athabasca River. The km values indicate the distances upstream of the mouth of the Athabasca River.

6.2.2 Model setup and Monte-Carlo framework

A stochastic hydraulic modelling framework, which incorporates a Monte-Carlo Analysis (MOCA) to simulate hundreds of ice-jam scenarios was used to assess ice-jam flood risk along the river in downtown Fort McMurray. A river ice model RIVICE was set up to simulate ice-jam water level profiles along the study domain. RIVICE is a one-dimensional fully dynamic river ice model. The basic hydraulics in the model are solved by the Saint Venant equations using an implicit finite difference scheme (EC, 2013). The RIVICE model uses a set of river ice and hydraulic parameters and boundary conditions to simulate various river ice processes, such as frazil ice generation, transport, juxtaposition and progression, hanging dam formation, shoving and ice cover melting and ablation (Lindenschmidt, 2017b). Once the model is set up for a scenario, the MOCA is easily performed using the Parameter Estimation Software (PEST).

In addition to river cross-sections, the RIVICE ice-jam model requires input data for the boundary conditions and parameter values. Boundary conditions include upstream discharge (Q), downstream water level elevation (W), location of the ice jam toe (x), and volume of inflowing ice (V_{ice}). Key parameters include porosity and thickness of rubble pans (*PS* & *ST*, respectively), porosity and thickness of the ice cover at the front (*PC* & *FT*, respectively), thickness of the intact ice cover (h) downstream from the ice jam, depositional and erosional velocity thresholds (v_d & v_e, respectively), ice and river bed roughness (n_{8m} & n_{bed}, respectively), and lateral to longitudinal and longitudinal to vertical stresses distributions within the ice-jam cover (*K1TAN* & *K2*, respectively). In this study, RIVICE was embedded in the Parameter Estimation Software (PEST) to set up the MOCA simulations, allowing hundreds of ice-jam water level scenarios to be generated using a range of river ice parameter and boundary condition sets. The random values extracted from the parameter and boundary condition probability distributions for MOCA inputs were obtained from previous studies and historical information relating to the study site. Details regarding the parameter and boundary condition values used in MOCA simulations are given in section 4.2.2.

In order to reduce potential ice-jam flood risk, three ice-jam flood mitigation measures were examined: dredging, artificial ice-cover breakup and dike construction. Each scenario was compared with a base scenario to assess the feasibility of the mitigation measures. The base scenario was established without implementing any mitigation measures. The following Table 6.1 shows the total number of ice jam simulations that were carried out for each scenario in the MOCA framework.

Table 6-1 Summary of the number of ice jam simulation used in analyses.

Mitigation option	Scenario	Number of simulations
base run	without mitigation	378
artificial breakup	moving the toe location	394
	0.5 m	357
sediment dredging	1 m	357
	2 m	357
	3 m	357
	4 m	357
dike scenario	dike height - 248 m	378
	dike height - 250 m	378

6.2.3 Artificial breakup scenario

Artificial pre-breakup of the ice cover prior to natural ice-cover breakup is one means to reduce the risk of ice-jam flooding along the rivers. The main goal of this operation would be to transfer the potential ice-jam toe location further downstream from the downtown area of Fort McMurray. Therefore, if ice jams form far away from the town/confluence, backwater effects from the

Athabasca River along the Clearwater River could be reduced, hence flood risk can also be lessened. An earlier, preliminary study on the impacts of artificial breakup only investigated the flood hazard aspects at locations along the Athabasca River, not Clearwater River (Lindenschmidt, 2017). In this study, the approach has been further extended by assessing the ice-jam backwater effects at the Fort McMurray and analyzing expected annual damages in the town. The proposed artificial ice-cover breakup location is indicated in Figure 6.1. The rubble ice broken apart from the ice cover can be accumulated immediately downstream of Fort McMurray. The modelling of the ice jam was carried out by selecting the toes of ice jams from km 290 to km 280. The simulated backwater level profiles were then used to produce the ensemble of ice-jam flood hazard maps and finally to calculate the flood risk at Fort McMurray.

There are some options to carry out the artificial breakup/cutting using ditch witch, circular saw and router blade (Topping et al., 2008). Ice cover can be pre-cut or broken using these machines during the pre-breakup time when the ice cover thermally deteriorates. The artificial breakup has been carried out along the Red River to avoid ice jam flooding at the city of Selkirk and the rural municipalities of St. Andrews and St. Clements since 2006. Approximately 25 km from Selkirk to Lake Winnipeg is artificially broken every year before the spring breakup. The artificial breakup operation is carried out for 4 - 6 weeks using four Amphibex machines in both day and night shifts. Long-term experiences show that this is an appropriate approach to prevent ice jams and flooding along the Red River communities (Topping et al., 2008).

6.2.4 Sediment dredging scenario

The feasibility of potential dredging to reduce the risk of ice-jam flooding along the Athabasca River at Fort McMurray was examined using the stochastic framework. Dredging is most effective when close to and immediately downstream of the area of flood risk (Lindenschmidt, 2017). The dredging area was mimicked by lowering the corresponding cross-sections of the river along with the model domain (Figure 6.1). Five scenarios were examined for sediment dredging by deepening the river section by 0.5, 1, 2, 3, and 4 m. For each scenario, hundreds of water-level profiles were simulated to produce an ensemble of flood hazard maps used to estimate the ice-jam flood risk. The flood risk information was then applied to assess the feasibility of sediment dredging to reduce the flood risk.

6.2.5 Dike scenario

The feasibility of a dike system to protect from ice-jam flooding was also carried out by estimating ice-jam flood risk. Two different dike heights (248 and 250 m) were simulated to assess the level of risk that may be reduced by the dike. Although the current proposed dike height is to protect against slightly above the 1:100-year ice-jam flood elevation (IBI and Golder Associates, 2014), not all risks can be eliminated due to potential overtopping of the dike. The ensemble of ice-jam water level profiles was assessed to determine the impact of overtopping using flood hazard maps. Finally, expected annual damages of the different dike heights were calculated.

IBI and Golder Associates (2014) provided some assessments about various alternatives, including dike protection systems. They evaluated the feasibility of five dike protection options for complete flood protection at the town. These are dike along the Lower Townsite, Saline Creek Parkway, Ptarmigan Trailer Park, McDonald Island, Hanging Stone.

6.2.6 Flood risk estimation

Flood risk is described as the probability of the adverse consequences of a flood event exceeding a particular level (hazard) and resulting in certain damages such as financial damages, business losses, ecological impacts occurring (vulnerability) (Merz and Thieken, 2004). Overall, flood risk analysis incorporates hazard and vulnerability (Equation 6.1). Hazard indicates the probability of occurrences and intensity of the flood (e.g. water level elevation), while vulnerability is associated with exposure (e.g. which assets are found within the flood extents) and susceptibility (e.g. the value of the asset impacted by the flooding) (Figure 6.2).

$$Flood\ risk = Hazard \times Vulnerability \ldots\ldots\ldots\ldots\ldots\ldots\ldots. (6.1)$$

The hazard of a flood event is often associated with property and infrastructure damage, injuries and casualties, agricultural and business losses, and adverse impacts on the aquatic environment (e.g. physical disturbance and loss of aquatic habitats). Ice-jam flooding requires the incorporation of some additional factors, such as the presence of ice and freezing conditions. Therefore, a hazard analysis usually incorporates information about locations and affected areas, magnitude and severity, and probability/frequency of flooding. Vulnerability usually depends on various physical and non-physical characteristics of the location, including land-use type, people (e.g. age & health), and warning and emergency flood protection systems. All these potential damages can be then incorporated with flood depths to estimate the susceptibility (depth-damage curves). The damages can be classified into two categories – tangible and intangible damages. Tangible damages are the damages that can be determined in the form of monetary value (e.g. infrastructure and property losses), while intangible damages are the damages that cannot be determined in the form of monetary value (e.g. environmental damages & loss of human life). However, incorporating all of these factors is out of the scope of the current study. This study is only considering the tangible damages (structural and contents damages of buildings) to estimate the flood risk. The steps carried out to estimate ice-jam flood risk for various mitigation measures at Fort McMurray on the Athabasca River are as follows:

Flood hazard: Flood hazard maps for the downtown of Fort McMurray were produced based on simulated ice-jam water levels at the confluence of the Athabasca and Clearwater rivers. All the simulated water levels were extracted and applied to produce flood hazard maps using ArcGIS. The LiDAR digital elevation model (DEM) with 1×1 m resolution was used to calculate the flood depth and extent. The methodology by Lindenschmidt et al. (2016) was followed to produce the flood hazard maps, in which the ice-jam water level was subtracted from the ground level DEM to estimate the intensity of the flood (depth and extent).

In order to calculate the probability of flood inundation, the number of times of each grid cell could be flooded from the ensemble of flood hazard maps were estimated using Equation 6.2. Since the probability of flood inundation incorporates all the simulated ice jam water level profiles, the probability map would reflect the probability of flood depths from low to extreme events.

$$Probability\ of\ flood\ inundation\ = \frac{number\ of\ times\ the\ cell\ floods}{total\ number\ of\ simulations} \quad \ldots\ldots\ldots\ldots\ldots (6.2)$$

Vulnerability: Exposure and expected damages from the flooding were estimated based on the different land-use types and flood depths. The land-use data distinguished between different types of buildings since the flood damage estimations depend on building usage (residential and non-residential) and construction materials. The type of building was derived from Google Maps using ArcGIS. The street view option of the Google map was used to classify the building types. The classification and relative damage curves of the buildings were adopted from the IBI and Golder Associates (2015) report. A total of ten types of buildings were identified based on their area, size, construction material and design. The residential buildings were categorized into six classes: large dwelling unit, small dwelling unit, starter and older inner-city houses, large and small apartments, and temporary houses. The non-residential and commercial buildings were classified as office and retail, industrial and warehouse, hotel and motel, or institutional.

The damage curves were divided into two classes, content and structural damages. Content damages usually refer to damage to movable items in the buildings such as furniture and clothes, while structural damages refer to damage to the building's structure and fixed components, such as walls, furnaces and heaters (IBI and Golder Associates, 2015). The damage curves used in this study were adopted from Lindenschmidt et al. (2016). More details on the damage curves and building classification can be found in IBI and Golder Associates (2015).

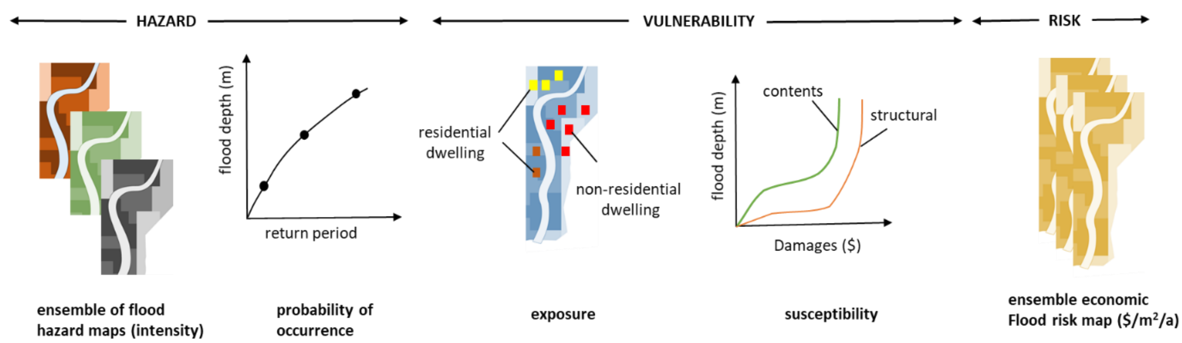


Figure 6.2 Conceptual diagram for ice-jam flood risk estimation (modified from Merz and Thieken, 2004).

Once the probability of flood inundation (hazard) and damages for each flood inundation map (vulnerability) are estimated, the total flood risk (EAD) for each mitigation scenario was estimated using the following equation 6.3.

$$Total\ flood\ risk = P \times \sum_{i=1}^{n=N} D \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 6.3$$

where P is the probability of the flood events, N is the number of times the cell is flooded, and D are the damages for the corresponding flood depth. Exceeding probability of each water level, P is calculated using the formula, $(m - 3/8)/(N+1/4)$ provided by Gerard and Karpuk (1979), where m is the rank of the water level of each simulation and N is the number of simulations.

6.3 Results and Discussion

6.3.1 The 1977 ice-jam flood damage estimation

The accuracy of potential flood damage estimation was assessed using the results of the 1977 ice-jam flood event along the Athabasca River at Fort McMurray. In this event, an ice-jam formed immediately downstream of the confluence of the Athabasca and Clearwater rivers, which backed up water into the Clearwater River and inundated the Lower Townsite area of downtown Fort McMurray (Figure 6.3). The flood elevation at the confluence of the Athabasca and Clearwater rivers was approximately 247.9 m a.s.l. About 1500 people were evacuated and the damage was initially estimated to be between 3 and 4 million Canadian dollars (FMFE, 1977).

Figure 6.3 The 1977 ice-jam flood event in Fort McMurray's downtown area (source: the Fort McMurray Heritage Society, used with permission).

Figure 6.4 shows the flood extent and depth and associated damages in the Fort McMurray downtown area due to the 1977 ice-jam flood event. The results indicate that many buildings in the Lower Townsite area were flooded and the damage to these buildings was mostly estimated between \$250 and \$500 per m^2. Although very few buildings were inundated along the Snye channel, the damage was estimated to be higher, from \$1000 to \$2000 per m^2, due to the high value of the assets in those areas. Moreover, many buildings were inundated in the southeastern part of the town; the damage for most of those buildings was estimated between \$500 and \$1000 per m^2. The total estimated damage using the 2014 values of the damage curves amounted to \$12.6 million, which, when inflation is considered, corresponds to \$3.47 million in 1977. This value lies within the \$3-\$5 million initially estimated (FMFE, 1977). The 2020 ice-jam flood which caused estimated damages of about \$ 0.5 billion (Antoneshyn, 2020)– the significant difference from the 1977 damages likely reflects a substantial urban development and changes in the cost (inflation rate) since that time.

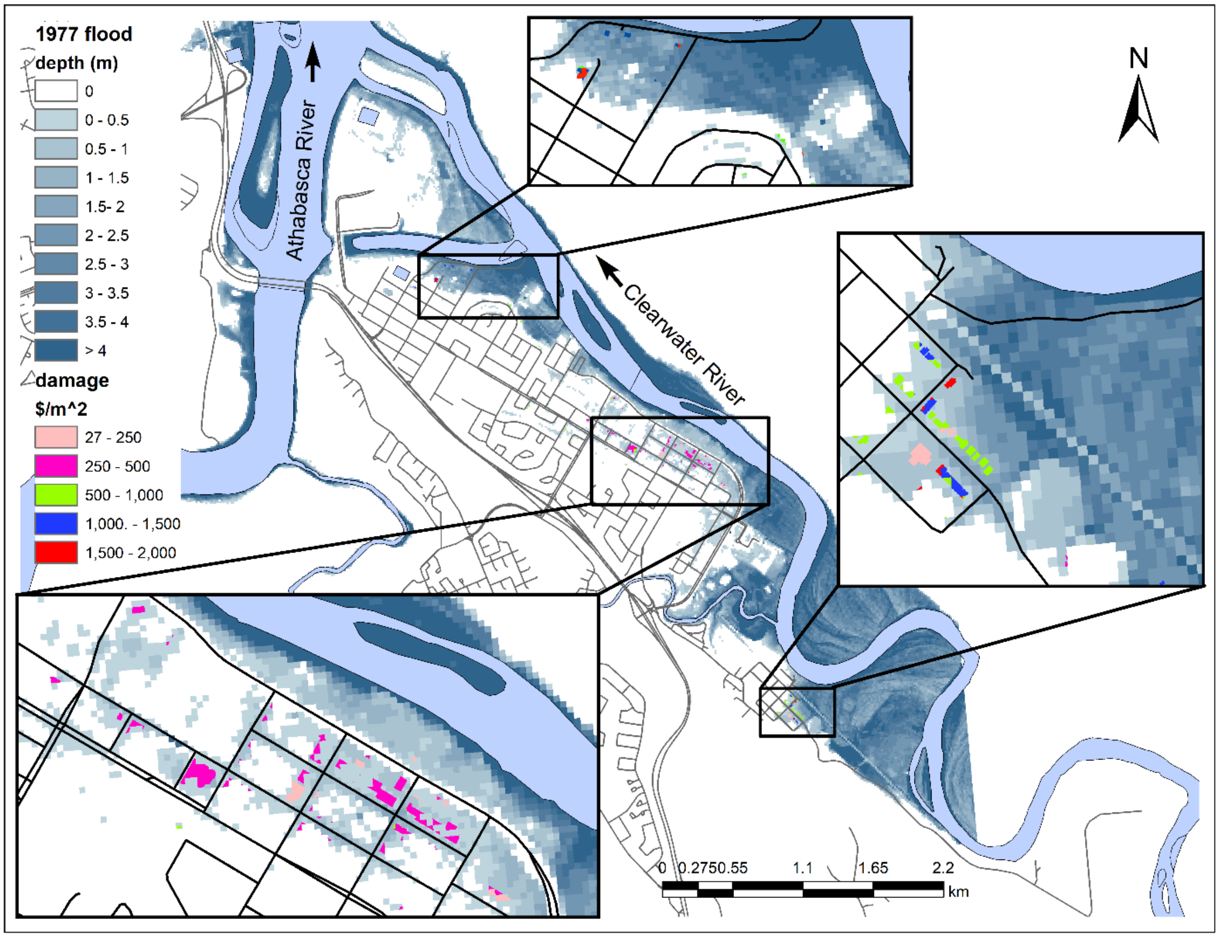


Figure 6.4 The 1977 ice-jam flood damages (structures and contents) along the Athabasca River at Fort McMurray.

6.3.2 Flood Hazard mapping

Figure 6.5 illustrates the average flood intensities and probabilities of flooding for the implementation of the various mitigation measures to protect downtown Fort McMurray from future floods. Flood intensity indicates the average flood depths and extents, while probabilities provide the frequencies of flooding in the town for each mitigation scenario. Overall, the average flood depths do not vary much at most of the locations in the town, however differences in the flood depths can be more discerned in the areas alongside the Clearwater River and Snye Channels. The results show that the intensity of ice-jam flooding is much higher, and flood events is more frequent in the base scenario, where no mitigation measures are carried out. In this scenario, the average flood extent in the downtown area of Fort McMurray is maximum and the probability of flooding in most of the town is higher, between 1% and 10%.

Artificial breakup significantly reduces the average flood intensity and flooding probability in the town. It is important to note that the main goal of artificial breakup is to relocate the toe of the ice-jam formation further downstream along the Athabasca River, away from the town. In this manner, the flood extent and depths of ice-jam flooding could be reduced substantially. The probability of flooding is low compared to the base scenario, with a probability generally between 0.25% and 0.5%.

The average flood hazard intensity can also be reduced by sediment dredging; however, the probability of flooding is still high for the 0.5 m dredging scenario, mostly between 1% and 10%. The probability of flooding is further reduced in the 1 and 3 m dredging scenarios (between 0.25% and 0.5%), while it slightly increases for 4 m dredging (mostly between 0.5% and 1%.). This excessive drop in riverbed elevation at this particular location substantially reduces the flow velocities underneath the ice cover, increasing the potential for the formation of a hanging dam, hence increasing the water-level elevation. Overall, flood extents are for the most part similar for all the sediment dredging scenarios. A few examples of the reduction of ice jam water level depths along the model domain is presented in Figure 6.6.

The flood extents are more extreme in the diked system due to the potential of overtopping of the dike during extreme events. However, the probability of flooding in this scenario is low, with only a few ensemble events overtopping the dike to flood the town. Therefore, average flood depths may not be as severe as the flood extent for this scenario. The probability of flooding is mostly between 0.25% and 10% for the 248 m a.s.l. crest-elevation dike and 0.25% for the 250 m a.s.l.

crest-elevation dike. Overall, the town is more vulnerable to ice-jam flooding along the Snye channel and the south-east corner, where the flood intensity and probability are relatively higher.

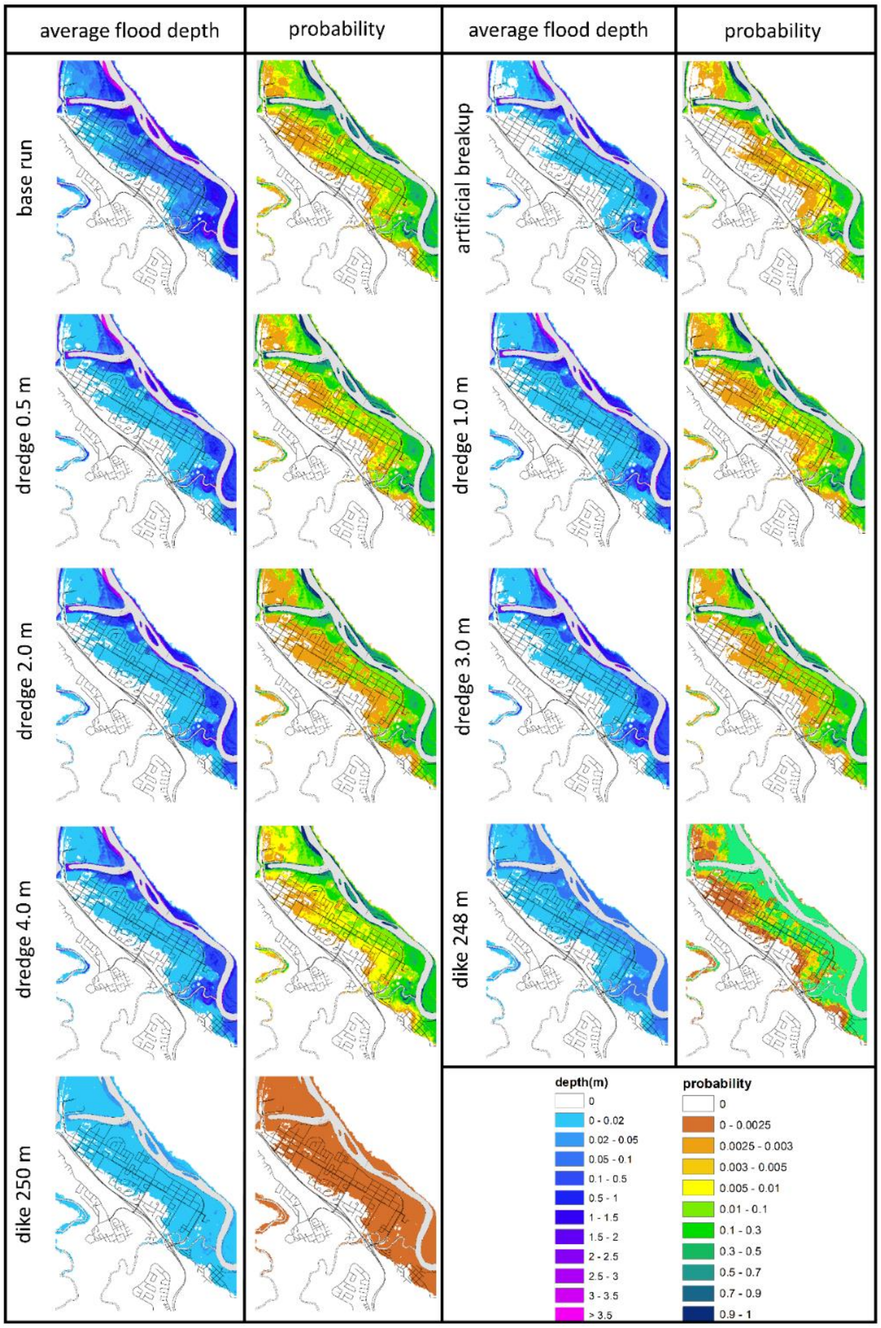


Figure 6.5 Flood hazard maps for different scenarios along the Athabasca River at Fort McMurray.

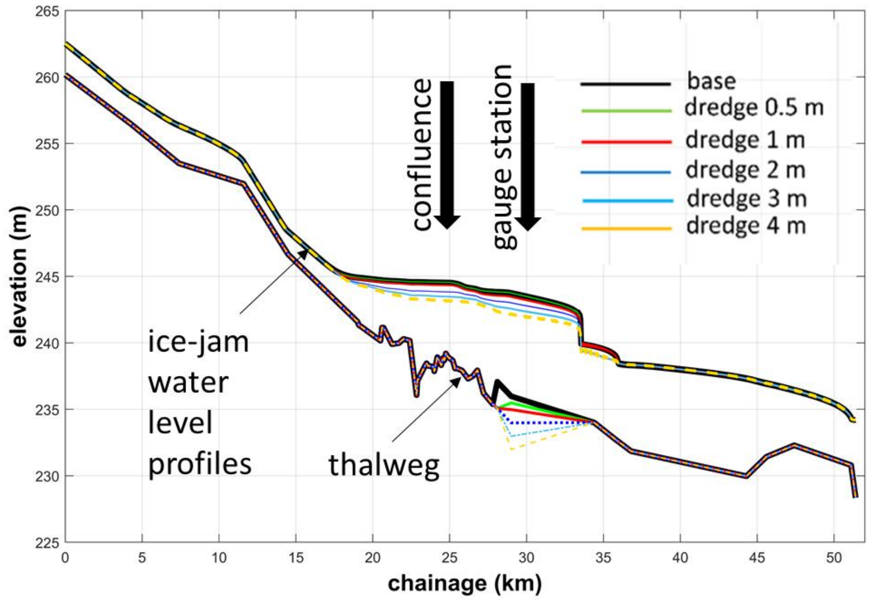


Figure 6.6 Examples of the ice jam water level elevations reduction due to dredging along the Athabasca River at Fort McMurray.

6.3.3 Flood risk analysis

The flood risk maps for the different mitigation measures are illustrated in Figure 6.7. The results show that the maximum number of buildings are under a certain level of flood risk in both base and dike scenarios. However, the dike systems could reduce a significant level of risk. Moreover, artificial breakup could also reduce the substaintial level of flood risk for most of the buildings in the town. The results illustrate that the flood risk in the base scenario can be greater than \$10 meter square/annual (m^{-2}/a) for many of the buildings adjacent to the Snye Channel while it could be reduced to \$5 m^{-2}/a for most of the buildings through the artificial breakup and dike with crest elevation of 250 m a.s.l.

The average flood risk of most buildings is still estimated to be between \$5 and \$10 m^{-2}/a for the base scenario. In this case, the flood risk varies in the downtown area of Fort McMurray, depending on the type and location of the building and the intensity of the flooding. For example, the flood risk of many buildings along the Lower Townsite areas are estimated to be between \$10 and \$30 m^{-2}/a. Risk is estimated to be between \$30 and \$50 m^{-2}/a for some of the buildings along the southern reach of the Clearwater River. Relatively high risk is attributed to buildings due to the high flood depths and the high value of the assets in those areas.

Although, the number of buildings with high flood risk have been reduced in the dredging scenarios, most of the buildings along the Lower Townsite, Snye channel and southern reach of the Clearwater River are still under a certain level of flood risk. The maximum risk for many of the buildings along these areas is between \$10 and \$30 m^{-2}/a. Overall, in the dredging scenario, the flood risk for most of the buildings is similar to other mitigation scenarios, below 10 m^{-2}/a.

In summary, overtopping of the dike would only occur during extreme flood events and the overall number of the buildings having flood risk is relatively high for the different dike crest elevation scenarios. Artificial breakup could reduce the maximum number of buildings that are vulnerable to risk and reduce the overall flood risk along the Lower Townsite area. However, in the artificial breakup scenario, the flood risk for many buildings along the Snye channel is still relatively high, compared to the 250 m a.s.l. dike crest elevation scenarios. Overall, sediment dredging could reduce the number of buildings that are vulnerable to certain flood risk, however, they are not as effective as other mitigation measures to reduce the flood risk.

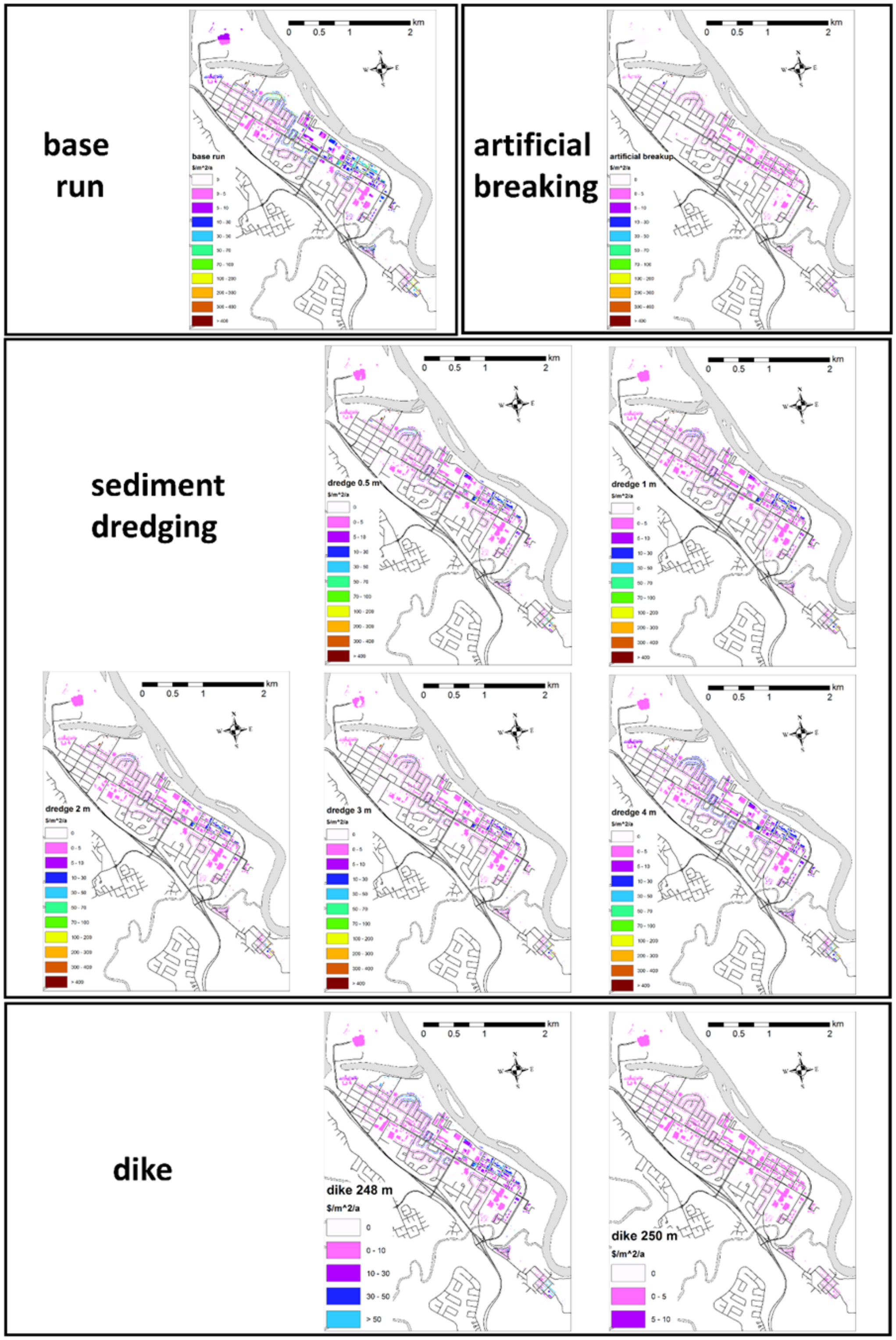


Figure 6.5 Flood risk maps for different mitigation scenarios along the Athabasca River at Fort McMurray.

The expected annual damages (EAD) of different mitigation scenarios are demonstrated in Figure 6.8. The results show that artificial breakup can reduce the most ice-jam flood risk among all the mitigation scenarios. While the base scenario has the maximum EAD, about $11.2 million, artificial breakup has an EAD of about $1.7 million. The 250 m a.s.l dike crest elevation also has a great potential to reduce the flood risk, which could reduce the EAD to $0.95 million. Although the sediment dredging scenarios could reduce the EAD to a certain level, they are less effective compared to the other two mitigation measures, 250 m a.s.l. crest-elevation dike and artificial breakup. Moreover, in sediment dredging scenarios, the best possible result was found to be for 3 m dredging in which the EAD was reduced to about $5.8 million. Further studies, by changing the dredging location, can be applied to identify the potential of sediment dredging to reduce flood risk.

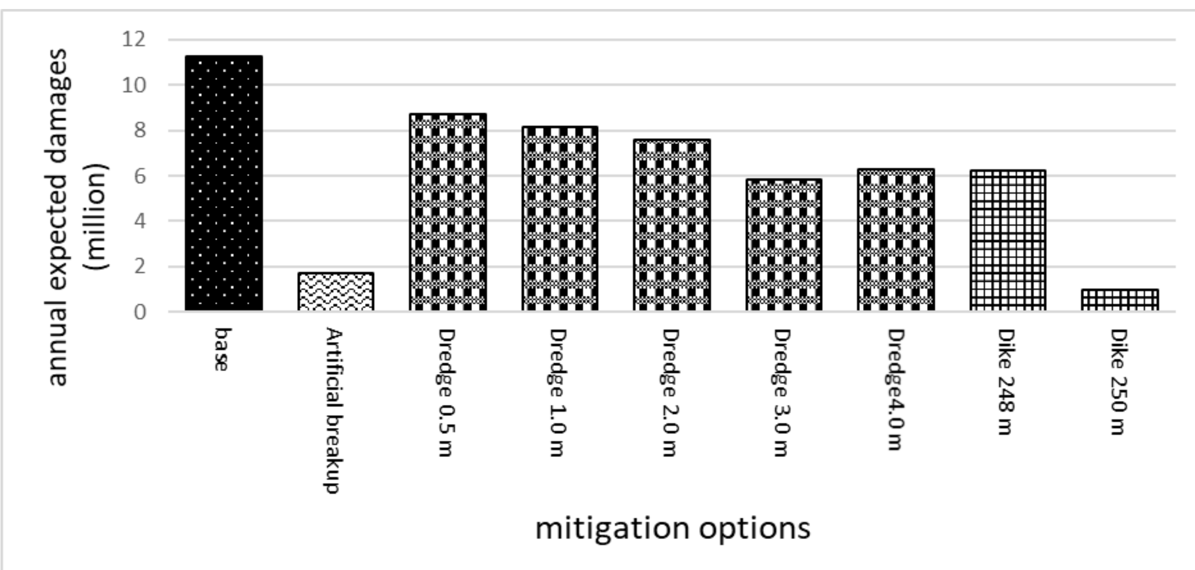


Figure 6.6 The expected annual damages from the ensemble of flood risk maps for different mitigation scenarios at Fort McMurray.

The EADs and cost estimates of implementing all the mitigation options have been used to perform a conservative benefit-cost ratio (BCR) analysis. The analyses are based on the information available in the literature/reports cited in Table 6.2. The BCR can be defined as the ratio of net annual benefits (average annual damage from base run - average annual damages from the alternative) to the annual average operation/construction/maintenance costs of each alternative. The BCR represents the economic efficiency of each option. When the benefits are greater than the costs BCR would be greater than one (economically efficient), and when the benefits are less than the costs BCR would be less than one (economically inefficient).

The benefit-cost ratio shows, artificial breakup can be more economically efficient compared to all other mitigation measures, as the overall operation of the Amphibex machine is less expensive. In artificial breakup, it is estimated that the indicated area (Figure 6.1) would take approximately 12 days to break up the designated ice-cover area. This estimation has been derived by comparing and studying the Amphibex operations along the Red River. Since 2006, the Amphibex machines break up approximately 30 km of river ice to reduce the probability of ice jams along that river. The information of the Amphibex operation and related costs are deduced from Topping et al. (2008) and several newspaper articles (Hoye 2019, Dangerfield 2017). The cost of operation of the Amphibex is approximately $450/hour, which includes fuel, wages, and maintenance of the machine (Topping et al. 2008).

Although the Amphibex operation can be an economically efficient tool for flood risk reduction along the Athabasca River at Fort McMurray, it cannot perform well in all conditions, such as for ice thicknesses greater than 0.6 m. Therefore, it is necessary to examine, in the field, the potential of implementing the Amphibex to reduce ice jam flood risk along the Athabasca River.

Since, the 250 m a.s.l dike height could substantially reduce the amount of EAD for the town, it can also be a cost effective mitigation measure for the downtown of Fort McMurray. The cost estimates of the dike to protect against a 1:100-year flood water level and all necessary information have been retrieved from IBI and Golder Associates (2014). Table 6.1 shows that BCR is less than in the case of artificial breakup, therefore it is a second economically feasible option. The sediment dredging is relatively expensive and required every 10 years. The average cost per cubic yard of sediment removal is approximately $6 (Dredging Specialist, 2020). Based on the BCR estimate, they are the lowest economically beneficial options among all the mitigation scenarios.

Table 6-2 A cost-benefit analyses for all the considered mitigation options.

Mitigation Option	**Description**	**Base Expected Annual Damage**	**Annual Damage**	**Net Benefit (Base Damage - Annual Damage)**	**Annual Operation, Construction and Maintenance Costs**	Benefit-Cost Ratio
Artificial breakup	From confluence of Athabasca-Clearwater rivers to WSC gauge, 3 km	11277846.9	1693170.8	9584676.1	1536000	6.2
Sediment dredging, 0.5 m	971565 m^3	11277846.9	8717655.1	2560191.7	7659554.2	0.3
Sediment dredging, 1 m	1522482.5 m^3	1 1277846.9	8149093.5	3128753.3	11982991.5	0.3
Sediment dredging, 2 m	2625455 m^3	11277846.9	7574361.3	3703485.5	20638792.9	0.2
Sediment dredging, 3 m	3727115 m^3	11277846.9	5834137.6	5443709.2	29284294.2	0.2

Sediment dredging, 4 m	4830227.5 m^3	11277846.9	6260785.2	5017061.7	37941194.3	0.1
Diking	Complete dike protection with 1.0 m Freeboard to Dike System - above 1:100-year Ice Jam Level (250.5 m)	11277846.9	951015.02	10326832	1705420	6.1
Assumption						
Artificial breakup	Approximately 12 days may require breaking the indicated area in Figure 6.1. This is an approximate estimation that has been calculated by comparing the artificial breakup operation along the Red River. For example, approximately 30 km in length with an average width of operation 225/2 m (approximately) (total area = 112.5 × 30000 m^2) stretch along the Red River requires approximately 30 days to artificially break up the ice each year using four Amphibex machines. Based on this information, 3 km in length with an average width of 850/2 m along the Athabasca River may require approximately 11.33 (12 days) to break up the ice using the same number of Amphibex machines. However, local ice is typically thicker than 0.6 m, so the actual number of days may be higher than 12. The average cost of the Amphibex operation is approximately $450/hour (source: Topping et al. 2008). Moreover, each Amphibex machine costs $1.2 m illion and the project/machine life for the machines was assumed to be 10 years (this number can vary, depending on type and maintenance quality, if the project/machine life increases or decreases, BCR would also increase or decrease). To estimate a consistent financial assessment, a general discount rate of 4% was used.					
Sediment Dredging	It is assumed that dredging is required every 10 years. Again, this is an approximate estimation and may require detail hydrotechnical assessment to estimate the accurate costs of the operation. The average cost is approximately $6 per cubic yard and mobilization and de-mobilization cost is $35,000 (source: Dredging Specalist, 2020, Dredging 101. https://www.dredgingspecialists.com/Dredging101.htm). To estimate a consistent financial assessment, a general discount rate of 4% was used.					
Diking	Project life is 50 years, total cost $85, 271, 000 (source: IBI and Golder Associates, 2015).					

6.4 Discussion and Concluding Remarks

The feasibility of various mitigation measures based on flood damage potential was examined using a novel flood risk estimation approach. An ensemble of hundreds of ice-jam flood hazard maps was used to determine the flood risk for the downtown of Fort McMurray. The ice-jam flood damage potential was evaluated by estimating EAD for the town of Fort McMurray. The results of the base scenario indicate that usually, Fort McMurray has a high flood risk i.e. high EAD. Based on the examination of the different mitigation measures, the results show that artificial breakup has a major potential to reduce the EAD, as the frequency of flood events significantly reduce in the artificial-breakup scenario of an ice cover section. This scenario has a high potential to reduce the number of buildings exposed to flood risk and lower the EAD for downtown Fort McMurray. Lindenschmidt (2017) indicates that backwater staging may become more severe from artificial breakup for less hazardous flood events with return periods less extreme than 1:15 years. For more extreme flooding, flood hazard decreases (see Figure 12 in Lindenschmidt, 2017) which is in line with the results presented here. The preliminary study also recommends that "a subsequent study is also required to determine the impact of the backwater staging on the flood hazard of Fort McMurray alongside Clearwater River" (Lindenschmidt, 2017), which was fulfilled here. This analysis even went further by considering, not only flood hazard but also flood risk and it is shown that complementing flood hazard with vulnerabilities can provide a more encompassing and thorough flood risk analysis. One aspect that still needs research is the duration of a flood event, since freezing water or persistence of floodwaters in the floodplain may cause extra damages to houses, properties and buildings.

It was also found that the 250 m a.s.l. crest-elevation dike has a great potential to reduce the EAD. However, overtopping of the dike in extreme events may increase the number of buildings susceptible to flood risk because an extreme ice-jam flood event (> 250 m a.s.l) can flood a substantial area of the town. Although certain dredging depths could reduce the EAD, further investigations are necessary to fully understand their potential to reduce the flood risk.

Ensembles of hundreds of ice-jam flood events along the river near downtown Fort McMurray were evaluated for each mitigation option to identify alternatives based on flood risk information.

However, a certain level of uncertainty is still inherent in the stochastic approach applied in this study. For example, a disproportionate number of extreme high or low parameter values could lead to inconsistent results that could create a complex situation of implementing any flood mitigation measure. Therefore, the required number of simulations should be selected carefully, as many as possible by assessing the time constraint and computational capacity to minimize the disproportionate number of extreme high or low parameter values.

The uncertainties can also be associated with parameter and boundary condition selections and model setup. For example, a boundary condition, the toe location of ice jams, may not always be uniformly distributed; there might be some locations along the river that are more prone to ice jams than others. Moreover, some of the model cross-sections were collected in the 1980s, which may have altered due to sedimentation and other geomorphological changes over the years. Similarly, the ice volume, herein treated as an independent calibration parameter, may depend on discharge, according to known ice breakup mechanics.

Overall, the study results could provide an effective design process for implementing ice-jam flood mitigation measures along the river, including both structural and non-structural measures. The methodology of this study could also be further applied to designing and implementing a comprehensive flood protection system in any ice-jam prone location. The interactive maps of flood hazard and associated risk can help with the development of effective flood risk management strategies.

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6.6 Appendices

Appendix A Model setup Monte-Carlo framework

Figure A-1: The ensemble of simulated ice jam water level profiles for various mitigation scenarios along the Athabasca River.

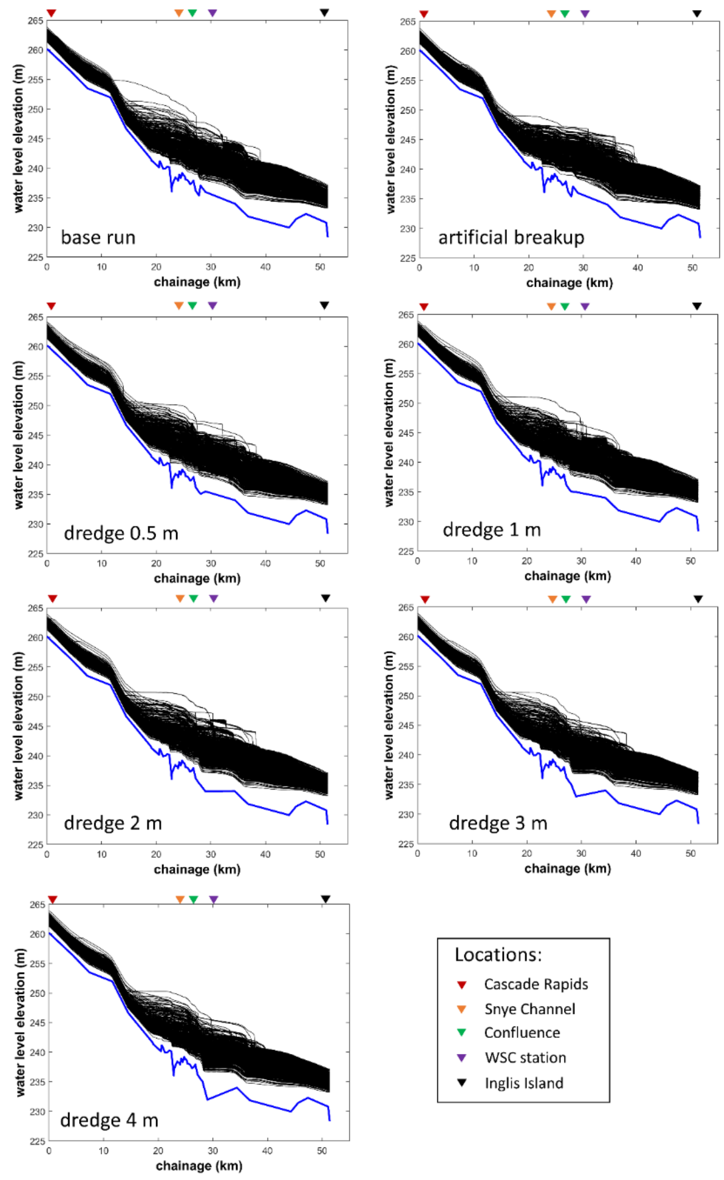

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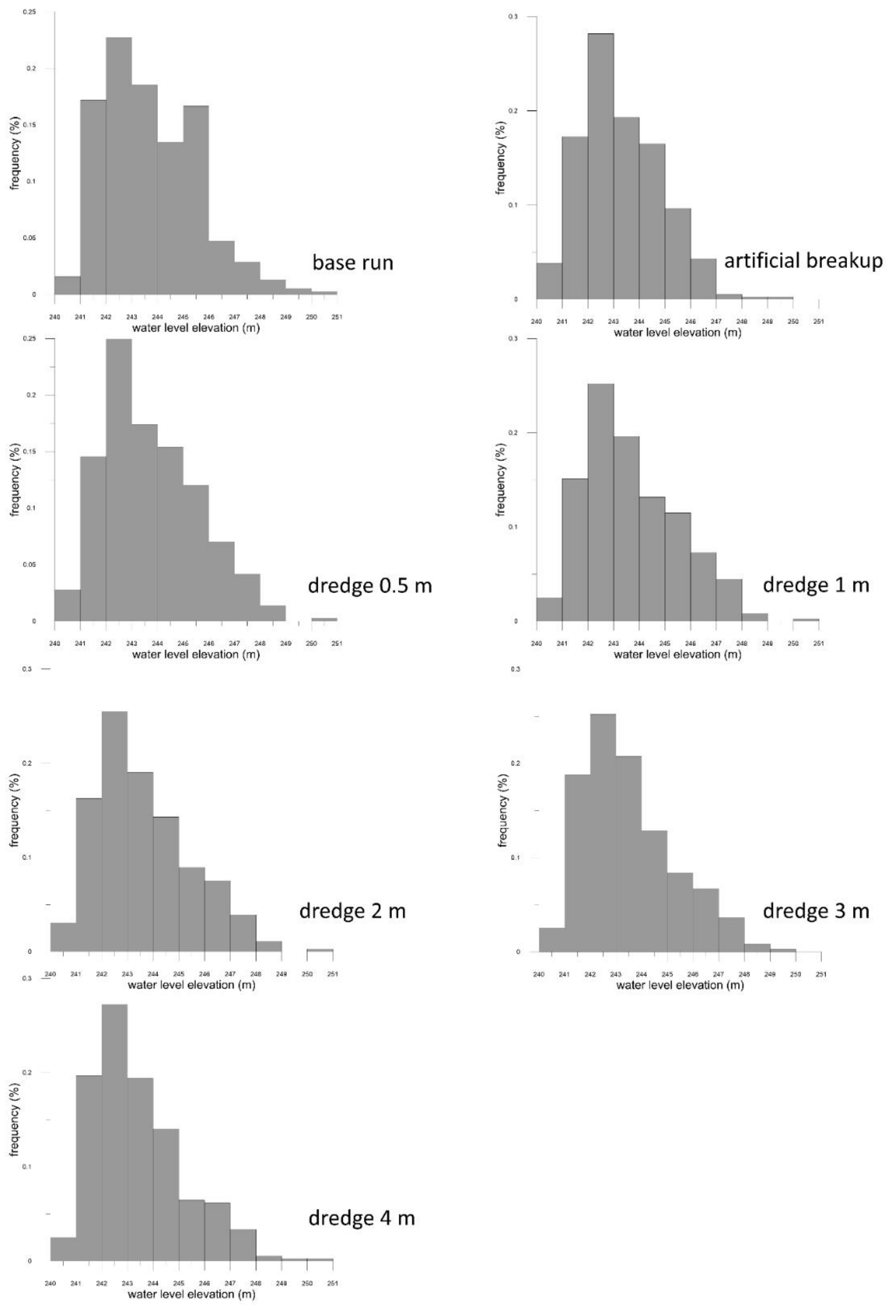
Figure A-2: The relative frequencies of simulated ice jam water level elevations at the Fort McMurray along the Athabasca River.



CHAPTER 7

SYNOPSIS AND DISCUSSION

7.1 Introduction

Ice-jam flood risk delineations are required to determine the severity of flooding, execute emergency measures, and design and develop water resources management strategies along many rivers in cold regions. This delineation involves ice-induced water level estimation, flood hazard mapping and vulnerability identification. Ice-induced water level elevations are essential for the development of stage-frequency curves, which is one of the pre-requisites for designing many hydraulic structures (e.g. bridges, dikes and levees), and estimating flood risk. The stage-frequency curve usually informs exceedance probabilities of different river stages that allow us to determine flood hazard. Flood hazard can be combined with stage-damage curves to estimate flood risk.

The development of ice-induced stage-frequency curves for a location is very challenging because, most often, historical or observed ice-related peak stages are not readily available or the data is not adequate. Although some indirect methods exist to develop stage-frequency curves, they are still limited to winter sheet-ice cover or equilibrium ice jam options. These methods pose difficulties in estimating the upper end of the ice-affected stage-frequency curve. To solve these challenges, a comprehensive study of physical and hydraulic processes of ice jam formation is required. In this study, some progress has been made towards reducing the uncertainties related to ice-jam flood level estimations for flood risk analysis. Through a stochastic modelling framework, an ensemble of hundreds of ice-jam backwater level elevations can be simulated to estimate exceedance probabilities of floodwater levels. Hundreds of ice-jam scenarios allow assessment of the variability in the results. Less variability in the results can help to identify confidence and prediction bands for exceedance probabilities of the floodwater levels. Moreover, this approach is able to incorporate a whole range of parameters involved in the physical and hydraulic processes of ice jamming.

7.2 Analytical Discussion

Since the ensemble of ice-jam backwater level elevations is applied to flood hazard mapping for risk analysis, it is necessary to understand the role and impacts of different input parameters, boundary conditions and components of flood hazard delineation. This need has been addressed in this study through global sensitivity analysis (GSA), which provides diagnostic insights into the hydraulic model parameters, boundary conditions and Digital Elevation Models (DEMs) for flood hazard studies. This study identified that ice jam flood hazard is highly sensitive to the model boundary conditions (stream discharge, the volume of ice and toe of ice jam location) and DEM. The results could help in resource allocation for data collection and further ice-jam flood modelling studies, especially in quantifying the effects of climate change on ice-jam flooding. For example, non-influential parameters can be assumed as unchanging and influential parameters should be selected carefully to model climate change impacts on ice jamming.

Many sophisticated general circulation models are well established for predicting future climatic conditions, and quantitative prediction of the severity of ice jamming can be carried out using these climatic models. However, studies related to climate change impacts on river ice are sparse. To fill this gap, a novel methodological framework has been developed to quantify the severity of ice-jam flooding under future climatic conditions using a stochastic modelling approach. Results indicate that flood hazard is highly sensitive to model boundary conditions and effort has been made to estimate these boundary conditions, especially upstream discharge. This boundary condition values were estimated as a function of future climatic inputs. The upstream discharge was derived from a physically based hydrological model using the Canadian Regional Climate

Model (CRCM) driven by an atmospheric-ocean General Circulation Climate Models (GCM) under future climatic conditions. Using the delta method, mean weekly absolute and relative changes over a 30 year period were applied to develop maximum flow frequency curves to run the stochastic simulation under future climatic conditions. Finally, prediction bands of stage-frequency curves were developed using a stochastic modelling framework for the study site. The average and maximum probability of 1:100 year ice-jam flood water levels were extracted from the prediction bands to analyze flood hazard under future climatic conditions.

Once flood hazard under future climatic conditions has been estimated, the studies can be further extended to determine future flood risk. The flood risk is usually estimated as a function of the channel water level exceedance probabilities, floodplain flood water depth and an inundation depth-damage relationship. Figure 7.1 illustrates the flood risk maps for the maximum 1:100-year flood hazards of historical and future periods. The flood hazards for future periods have been delineated from the results estimated using the absolute and delta change approach. The results show that the maximum flood risk is expected to be increased under future climatic conditions compare to the historical period. Moreover, the number of buildings with ice jam flood risk has substantially increased under future climatic conditions developed using the absolute change method, while the number of buildings with ice jam flood risk is more or less the same under future climatic condition developed using the relative change approach.

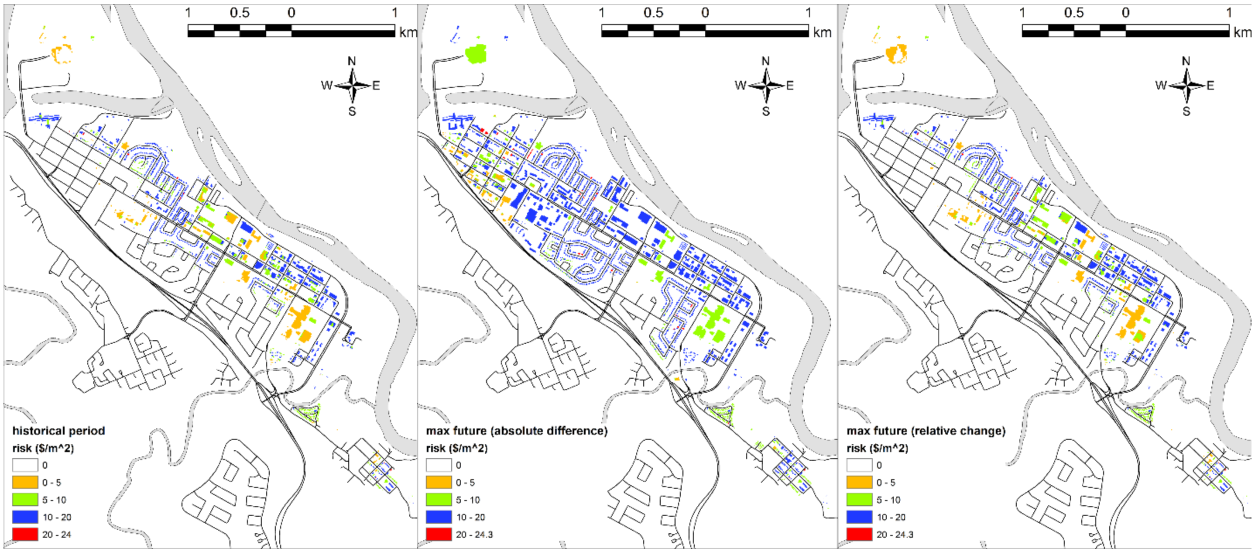
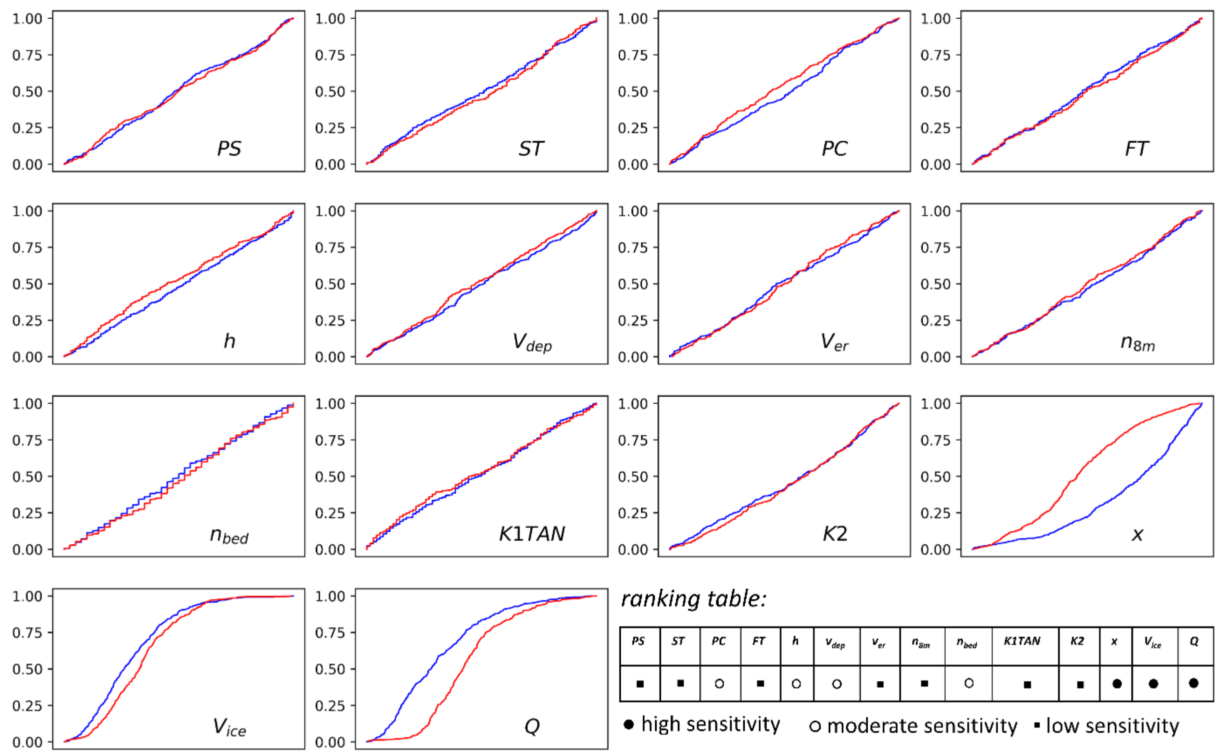


Figure 7.1 Flood risk maps for historical and future climatic conditions along the Athabasca River at downtown Fort McMurray.

As the flood hazard studies under future climate conditions suggest that the risk is still present for riverside communities, it is necessary to develop an effective mitigation strategy that can protect properties and infrastructure as well as inhabitants of the town. Although there are many methods available to mitigate the impacts of ice-jam flooding, it is still difficult to find the most appropriate measure for a location because several factors, such as available budget and resources, and characteristics of the ice regime, must be considered. Hence, an effective method for assessing the feasibilities of different mitigation measures has been developed in this study. A stochastic modelling framework has been carried out to measure the capacity of various mitigation measures (e.g. artificial breakup, sediment dredging and diking) to reduce flood risk. Incorporating hundreds of flood hazard maps to calculate EAD is a novel and effective approach. The decision of selecting an appropriate measure can be taken from the flood risk maps and BCR analysis. The risk analysis has been extended in this approach by calculating the flood damages of each ice-jam simulation. First, the ensemble of channel flood water level elevations was transformed into an ensemble of flood hazard maps. The ensemble of flood hazard maps is then used to estimate the total flood risk of each mitigation scenario. Moreover, the probability distribution of flood hazard maps provide a great overview of the degree of flooding in the floodplain and have the potential to help in decision making for the development of mitigation measures.

Once the ensemble of flood hazard maps provides an ensemble of flood risk values, the values can be further used in global sensitivity analysis to assess the impacts of model parameters and boundary conditions on flood risk. Figure 7.2 illustrates the flood risk sensitivity to model parameters and boundary conditions. The parameters and boundary condition sets were selected based on the values of EAD - the no flood risk set has zero EADs and the flood risk set has greater than zero EADs. The results show flood risk is not very sensitive to model parameters, while it is highly sensitive to all the boundary conditions. The ranking table shows that flood risk has moderate to low sensitivity to model parameters and high sensitivity to boundary conditions. The highly influential boundary conditions, such as upstream discharge, the volume of incoming ice floes and the toe of ice jam locations, are very important for ice-jam flood risk estimations. Therefore, all of these boundary conditions have a great influence on the hydraulic and physical processes of ice-jam formation, subsequent flooding and severity of flood risk. For example, a different location of the toe of the ice jam changes the physical characteristics of an ice jam due to geomorphological variations along the river channel. Moreover, varying discharges and volumes of inflowing ice can also change the hydraulic and physical characteristics of the jam. Thus, they can change the effects of ice-jam induced backwater staging and the degree of severity of ice-jam flooding.



ranking table:

PS	ST	PC	FT	h	v_{dep}	v_{er}	n_{8m}	n_{bed}	$K1TAN$	$K2$	x	V_{ice}	Q
▪	▪	○	▪	○	○	▪	▪	○	▪	▪	●	●	●

● high sensitivity ○ moderate sensitivity ▪ low sensitivity

Figure 7.2 Cumulative distribution plots of no flood risk (blue) and flood risk (red) parameters and boundary conditions sets. Ranking table for measuring the degree of sensitivity to each parameter and boundary condition.

7.3 Novelty of the thesis

Incorporating risk analysis and mapping using a stochastic modelling approach in a variety of ice jam modelling scenarios is a novel addition to ice jam flood risk management. A global sensitivity analysis (GSA) using flood hazard extent and depth as objective functions is a new approach to evaluating model parameters, boundary conditions and, in particular, Digital Elevation Models (DEM). Although similar analyses have been used previously to understand sensitivity to model parameters and boundary conditions in various studies (Lindenschmidt 2017, Lindenschmidt and Chun, 2013), using flood inundation and flood risk variables for the objective functions and the DEM as a parameter is a novel portion of this study. In this approach, the flood hazard maps are generated from randomly chosen test DEMs (ASTER, SRTM, and CDEM), which are compared with the flood hazard maps generated from the "true" elevation DEM (LiDAR) to estimate the errors in flood extents and depths. These errors are then used to select the behavioral and non-behavioral parameter sets for GSA. This research provides guidance to the flood mapping community, such as where resources should be directed in future ice-jam flood hazard and risk mapping research.

The development of a framework to quantify the severity of ice-jam flooding under future climatic conditions is the novel contribution of this dissertation. This study provides a novel framework to assess the severity of ice jam flooding under future climatic conditions within a probabilistic context by coupling hydrological model results in a hydraulic river ice model. Most of the climatic impact studies on river ice have been limited to the assessment of future freeze-up/breakup dates and prediction of future flow and water level elevation along rivers, but this study has advanced this further by incorporating hydraulic modelling for ice-jam flood hazard mapping and risk analysis to determine total expected annual damages in the future. This study has extended the study of Rokaya et al. (2019) by developing the probable stage frequency distribution (SFD) and estimating the expected annual damages for the downtown of Fort McMurray under future climatic conditions.

Estimation of flood risk to assess the capability for flood risk reduction of different mitigation measures (artificial breakup, dredging and diking) is another novelty of this dissertation. To date, only one attempt has been made to provide flood risk maps for ice-jam events and it was carried out along the Peace River at the Town of Peace River (Lindenschmidt et al., 2016), where exceedance probabilities were estimated from gauge data levels, and the levels were then extrapolated into the floodplain. However, this study incorporates an extension and improvement of that work by calculating the flood risk using floodplain mapping from each ice-jam simulation. In this study, hundreds of flood maps were produced from an ensemble of simulated ice-jam backwater level profiles. The frequency of the inundation flood depths for each grid was determined using a GIS application. The probability of each flood map was combined with the depth-damage curve to estimate the expected damages for an ensemble of flood hazard maps. Flood risk analysis and mapping have been incorporated to assess the feasibilities of various mitigation measures along the Athabasca River at Fort McMurray. Since such risk-based feasibility studies have not been carried out before for ice-jam flooding, this is another novel contribution of this thesis. The study provides a new framework to determine ice-jam flood hazard in a probability context.

Moreover, a direct deterministic approach may be difficult for carrying out ice-jam flood risk analysis and mapping. Therefore, in this study, some progress has been made using a deterministic model in a stochastic modelling framework for ice-jam flood risk analysis, which could also guide ice-jam flood risk management studies for cold region scientific communities.

7.4 Advantages and Limitations

The stochastic modelling approach to flood risk analysis provides an opportunity to assess the variability or frequency distribution of probable ice-jam flood risks, which can guide the water resources manager in implementing both long-term and short-term measures for an ice-jam prone location. The ensemble of hundreds of simulation results using randomly chosen parameters and boundary condition sets is able to capture the stochastic nature and physical processes of ice-jam formation that cannot be captured through a deterministic model. Moreover, the approach is well suited for subsequent hazard and risk analysis in a probabilistic manner.

There are various limitations and uncertainties associated with the stochastic framework assumption and parameter selection (e.g. climatic and hydrological simulation data). They are discussed below:

- One of the important boundary conditions, the volume of inflowing ice has been calibrated and selected as an independent input parameter, though the ice volume during spring breakup may not be independent of river flow. For example, low spring flow conditions may result in thermal breakup and significant ice melt, leading to relatively small ice volumes to form ice jams. The opposite is true for the high spring flows, however in this stochastic approach the model simulation can be incorporated with high flows with low volumes to mimic under-developed ice jams. Although MOCA does not consider this ice volume dependency on discharge, for low spring discharges ice floes are simply juxtaposed and progress upstream and in high spring flows ice floes can be shoved to thicken ice-jam covers.
- The toe of the ice-jam location is not always uniformly distributed along the river and there are some preferred ice-lodgment sites. However, making a more appropriate distribution of ice-jam toe locations for the stochastic framework requires adequate historical information. For future research, a multimodal distribution could be used to randomly select an ice-lodgment location for each run to constrain the majority of the selections to a few preferred locations. A geospatial model can also be applied to develop a more appropriate distribution for ice-jam toe locations.
- There are some uncertainties in the modelling results pertaining to the various assumptions and selected climate models that were used in the framework. The use of RCMs that have been nested in the GCMs usually provide information at relatively coarse spatial

resolutions, therefore the model output was used to derive future climatic conditions associated with some inherent uncertainties. Moreover, the historical observed CDDMs have been applied to the future period to estimate the maximum breakup flow which may veer from actual conditions since the last-B day also depends on flow magnitude.

- Some anthropogenic changes, such as land-use data and depth-damage relationships, can also affect the overall flood risk results. For example, the land-use data of downtown Fort McMurray was extracted from a Google Earth image acquired in 2016 and there could have been additional development or changes in the landscape. Also, some of the developments may not have existed in 1977, which has implications for the flood risk calibration. Moreover, the depth-damage curves used in the analyses were derived using market price values from 2014.
- Overall the study considered the peak breakup water level due to ice-jam formation, however occasional maximum/peak breakup water levels could occur by large waves that are generated upon the release of ice jams formed upstream or simply by a sheet ice cover if there is no ice jam event in a given year.
- Stochastic approach requires the simulation of hundreds of model runs, which is time-consuming and requires extra computing resources.

Considering these limitations involved in this study, a thorough understanding of hydraulic, hydrologic, and ice-related processes in rivers is required for professional engineers who will be applying this stochastic framework. All of these limitations can be incorporated in future research to improve the current approach of assessing ice-jam flood hazard and risk along ice-jam prone areas for the current and future periods.

CHAPTER 8

CONCLUSION AND FUTURE RESEARCH

8.1 Conclusion

Using a stochastic modelling approach in various ice-jam flood analyses along the Athabasca River at Fort McMurray fulfils the objectives of this study. Through the research in this dissertation, progress has been made in the evaluation of ice jam flood hazard and risk analysis. Moreover, the findings of the research in this dissertation are summarized below:

- The DEM is one of the most influential components of ice jam flood hazard delineation.
- Hydraulic boundary conditions, upstream discharge, the volume of ice and the location of the toe of the ice jam have a high degree of influence on flood hazard delineation.
- The severity of ice jam flooding is likely to be reduced along the Athabasca River at the downtown area of Fort McMurray under future climatic conditions.
- The stochastic modelling approach is an effective approach to evaluate the impacts of future climatic conditions on ice jam flooding.
- The Athabasca River at the downtown area of Fort McMurray has a probability of high EAD from ice jam flooding without any mitigation measures.
- The dike systems and artificial breakup may have the significant potential to reduce the EAD from ice jam flooding along the Athabasca River at the downtown of Fort McMurray. However, overtopping of the dike in extreme events may increase the overall ice-jam flood risk for most of the buildings in the town.
- Certain dredging depths could reduce the EAD; however further investigations are necessary to fully understand its potential.

- Overall, the stochastic modelling framework can be an excellent approach to evaluate ice-jam flood risk and identifying effective mitigation measures for an ice-jam prone area.

All of these findings in this research are based on various assumptions of the model parameters and involve a certain level of uncertainty, therefore, the mitigative actions and measurements should be considered by experienced professional engineers who possess (or have access to) a thorough understanding of hydraulic, hydrologic, and ice-related processes in rivers.

8.2 Research Needs

Using a stochastic modelling approach, some progress has been made in the field of ice-jam flood hazard and risk analyses; however, there are still many opportunities to contribute to the scope of this field. One of the most important research should be carried to address and quantifying the uncertainty involved in different parameter selection for river ice modelling and simulate the ice jam scenarios.

Since a comprehensive ice-jam flood hazard study is required to include some additional factors, such as freezing characteristics, ice pieces and flow velocity, this stochastic modelling approach could be incorporated with a two-dimension model to capture those factors in an ice jam hazard analysis.

Further research could be carried out to clearly understand the role and impacts of model parameters on ice-jam flooding in different ice-jam prone locations using global sensitivity analyses. Such analyses could be implemented using similar GSA criteria and capture the site-specific influence of model components on ice-jam flooding. A different location of GSA analysis could capture the influence of various fluvial geomorphological settings on the physical and hydraulic characteristics of ice jams.

More study is needed on how to project future breakup flows and which kind of delta (absolute, relative, other) approach is optimal to assess the impacts of climate change on the severity of ice-jam flooding. Continuous monitoring of ice-jam formation and collection of related data, such as ice volumes, are important to improve the predictive capacity of the model. Since ice volume is a highly influential parameter, long term observed data could be used to calibrate and validate the stochastic modelling results for estimating ice volumes. The field data could be used to capture current climatic effects and transfer and extrapolate these trends to future climatic conditions using the stochastic modelling approach.

8.3 References

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