

**IMPACTS OF CLIMATE AND REGULATION ON ICE-JAM
FLOODING OF NORTHERN RIVERS AND THEIR
INLAND DELTAS**

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By

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ABSTRACT

In cold region environments, ice-jam floods (IJFs) are important hydrological and hydraulic events that play an important role in floodplain ecology but also pose a major concern for citizens, authorities, insurance companies and government agencies, primarily because they can result in high water depths in rivers that can exceed levees leading to devastating floods. In the past 35 years, there have been significant advances in river ice hydrology. However, understanding on several aspects of IJFs still remains limited. Little work has been carried out on investigating how the frequency and severity of IJFs have been changing or might change in the future. Similarly, IJF delineation remains a significant challenge even for streams and small rivers. There is also still substantial progress to be made in quantifying the effects of climate variability and regulation on IJFs. This dissertation addresses some of these existing knowledge gaps. First, it reviews the recent advances in IJF research and identifies existing gaps, challenges and opportunities. With a changing environment, there are implications for river ice processes and this dissertation work investigates some of the potential implications particularly how the timing and magnitude of breakup flows that lead to IJFs are changing at local and regional levels. Literature review shows IJF research has been highly site specific but this dissertation also offers regional and global perspectives.

Climate and anthropogenic factors are likely to have unequal localized effects. Some regions might be more resilient and others, such as high latitude northern regions, might be more vulnerable. Thus, local implications for river ice processes and current and future probabilities of IJFs are assessed for two river basins in western Canada. The findings from the Athabasca River at the town of Fort McMurray show that the probability of ice-jam flooding in the future will be lower but extreme IJF events are still probable. The results from the town of the Peace River in western Canada suggest that regulation can have larger role in increasing IJF risks as water levels during ice-jam staging at the town were found to be higher due to regulation compared to naturalized conditions. However, regulation also offers a possibility of reducing IJF risks and promoting sustainability in regulated rivers. It is demonstrated that with appropriate reservoir operation scheme, it is feasible to minimize flood risk at upstream communities and maximize flood potential at downstream deltaic ecosystem, where it is essential.

As ice-jam flooding, both at present and in the future, remains a major concern in northern IJF prone communities, a probability curve of overbank flow based on breakup discharge is presented. Using a stochastic approach to evaluate the impacts of different magnitudes of discharge on IJF is a novel approach, and serves as an important benchmark for future IJF studies, especially for estimating future IJF probabilities. One other important methodological contribution is the introduction of a probability-based extension of the hydro-technical modelling approach that couples physically-based hydrologic and hydraulic models to assess the relative impacts of climate and regulation within a stochastic framework. Thus, the findings of this work have advanced our understanding of impacts of climate and regulation on ice-jam flooding of northern rivers and their inland deltas. As the first step in reducing flood risks, identifying, understanding and quantifying flood hazard will improve our ability to reduce risks and increase resiliency.

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LIST OF ABBREVIATIONS

ARIMA	Autoregressive Integrated Moving Average
CCSM	Community Climate System Model
CDA	Canadian Dam Association
CDB	Canadian Disaster Database
CDDM	Cumulative degree days of melting
CGCM3	Third Generation Coupled Climate Model
CLASS	Canadian Land Surface Scheme
CRCM	Canadian Regional Climate Model
CRREL	Cold Regions Research and Engineering Laboratory
DDS	Dynamically Dimensioned Search
GRU	Group Response Unit
IBIS	Integrated BIOSphere Simulator
IJF	Ice-jam flood
JTF	Joint Task Force on Peace River Ice
MESH	Modélisation Environnementale–Surface et Hydrologie
MK	Mann-Kendall
MOCA	Monte Carlo
MODIS	Moderate-Resolution Imaging Spectroradiometer
NARCCAP	North American Regional Climate Change Assessment Program

NSE	Nash and Sutcliffe efficiency
NRBS	Northern River Basins Study
PAD	Peace-Athabasca Delta
PAD-TS	Peace-Athabasca Delta Technical Studies
PDF	Probability Distribution Function
PEST	Model-Independent Parameter Estimation
PSC	Public Safety Canada
SFD	Stage Frequency Distributions
TPR	Town of Peace River
TFM	Town of Fort McMurray
USD	United States Dollar
VIC	Variable Infiltration Capacity
WCD	World Commission on Dams

CHAPTER 1

INTRODUCTION

1.1 Background

Almost 60% of the rivers in the northern hemisphere experience significant seasonal effects of river ice Prowse et al. (2007). Rivers freeze at the start of winter when the water temperature drops below 0 degree Celsius. From an energy-balance perspective, the initial ice development and subsequent freeze-up process is determined by the ‘summer heat budget of the river and rate of autumn water-to-atmosphere cooling’ (Prowse, 1995) and their ice covers break up in the spring when increasing air temperatures disintegrate the ice cover or an increased flow dislodges it (Beltaos, 1997). Whether stationary or moving, river ice interacts with river flow in many different ways resulting in diverse implications on northern communities, economies and ecosystems (Beltaos, 2000). A stable ice cover can cause additional resistance and reduce flow velocities (Beltaos & Prowse, 2009). In some channel systems, groundwater flow can be blocked if ice freezes to the bed (Beltaos & Burrell, 2003) whereas, increased (decreased) winter flows may result in thicker (thinner) ice covers in rivers (Beltaos et al., 2006b).

Ice jams are formed in rivers when the movement of ice floes is impeded by stationary ice covers, obstacles such as bridges and islands or constrictions in river width. Ice floes accumulate and pile up at these locations to form a jam which can stay intact for a few minutes or many days before it releases and can be a few meters to many kilometers long (Beltaos & Prowse, 2009). Ice jams usually result in significant backwater stages in rivers due to increased thickness and roughness (Beltaos, 1983). Figure 1-1 provides a schematic view of a river ice jam with an associated backwater level profile. Ice jams can occur during both freeze-up and breakup periods. Occasionally they occur during mid-winter breakups (Beltaos, 2002). However, ice jamming and subsequent flooding during the spring breakup period is of greater concern since they are more common (Beltaos & Prowse, 2009).

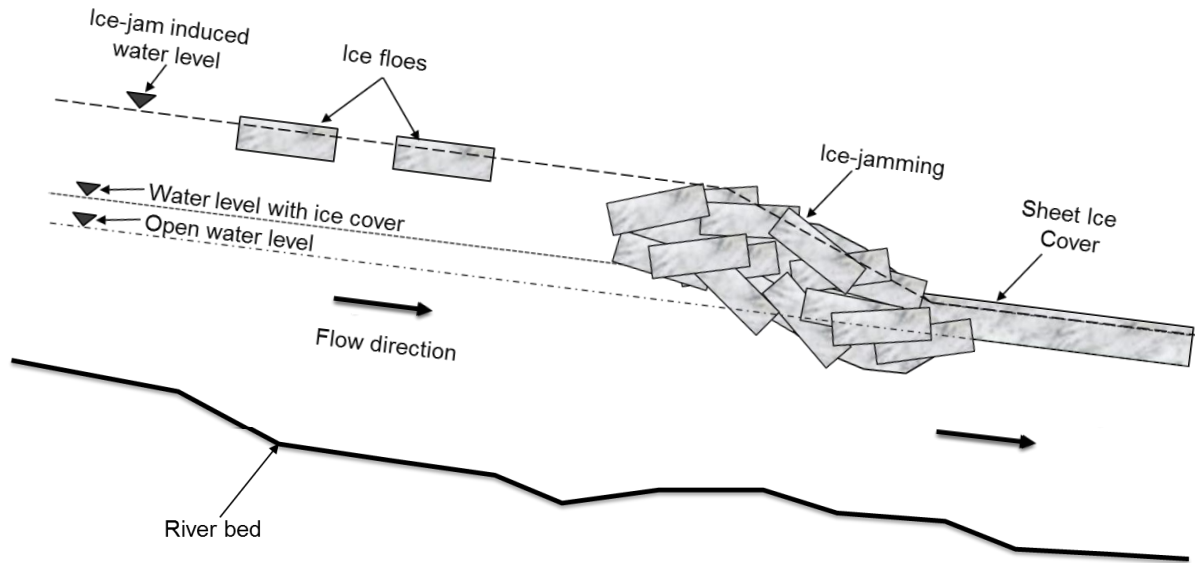


Figure 1-1. Schematic view of river ice jams and associated water levels

The ice cover breakup event can either be mechanical or thermal, depending on the hydro-meteorological conditions. Mechanical breakup occurs when there is sufficient runoff ‘to lift and dislodge the ice cover while it retains a sizeable portion of its mechanical strength’ (Beltaos, 2003b). Mechanical breakup can result in large-scale ice-jam flooding due to the severity of the event, while thermal events lead to comparatively smaller staging. During thermal events, the ice slowly deteriorates in place and eventually disintegrates under a modest current. Thermal events are associated with low runoff due to the gradual snow melt and absence of rain (Beltaos, 2003a, 2014; Beltaos & Carter, 2009). In recent years, with increasing air temperatures, mid-winter breakup events have also been reported in temperate and maritime regions of North America, and typically occur during January and February (Prowse et al., 2002a). They are triggered by winter temperatures rising above freezing and/or by rain-on-snow events (Beltaos, 2003b).

Ice-jam floods (IJFs), floods that occur primarily due to ice jamming, are important hydrological and hydraulic events in cold-region environments. Though they have been found to be beneficial for some northern inland deltaic ecosystems, such as the Peace-Athabasca Delta (PAD; Peters et al., 2006; Prowse et al., 2002b) and the Mackenzie River Delta (Goulding et al., 2009a; Goulding et al., 2009b) in Canada and the Yukon Flats in the United States (Chen et al., 2014; Jepsen et al., 2016), they also result in devastating losses to human life and economies of northern communities (Lindenschmidt et al., 2016; She, 2008). Additionally, compared to open-water flood events, IJFs

can be more severe as previous research has found since, under the same or lower discharge, they can result in two to three times higher water depths than open-water floods (Beltaos & Prowse, 2001). The feature that makes them more dangerous is their unpredictability of occurrence. IJFs are often sudden and difficult to anticipate which allow little time for the implementation of mitigation measures or even the evacuation of people (Mahabir et al., 2006; Massie et al., 2002).

IJFs during spring breakup period are more common (Beltaos & Prowse, 2009). However, they also occasionally occur during mid-winter breakup and freeze-up periods. Mid-winter breakup events have been reported in Michigan (White et al., 2006), Maine (Huntington et al., 2003), Wisconsin (Carr & Vuyovich, 2014) and Alaska (Newton et al., 2017) among others in the United States and in New Brunswick (Beltaos, 2002), Quebec (Turcotte & Morse, 2011), British Columbia (Beltaos, 2014) and Yukon (Newton et al., 2017) in Canada. IJFs in the freeze-up period are more common in hydropower based regulated rivers. Larger flows are released during winter months when energy demands are higher, which can result in a higher freeze-up stage in a river (Huokuna et al., 2017). Further, depending upon hydro-meteorological conditions, the initial ice cover may go through consolidation events, i.e. collapse and thickening of a newly formed ice cover, that might result in significantly higher water levels posing serious flood risks to riverine communities (Andres et al., 2003; Huokuna et al., 2017). An example includes basement flooding events in the Town of Peace River in Alberta, Canada in 1982, 1992, 2005 and 2008 due to high water levels in the Peace River contributing to increased groundwater flow since the regulation in headwaters of the Peace River in 1972 (Jasek et al., 2017).

Climate influences river flow, ice thickness, freeze-up conditions and stream morphology which govern river ice processes in general and particularly ice jams and breakups events (Beltaos & Burrell, 2003). Climate change could shift temperature zones, change precipitation patterns and alter local hydrological regimes (Beltaos & Burrell, 2003). Ginzburg (1992) and Soldatova (1992) have found a high correlation ($r^2=0.6-0.7$) between mean air temperature and ice cover duration in Russian rivers. In a warming world, a snowfall event might transform into a rainfall event (Krasting et al., 2013) and increased air temperature could result in higher rates of evapotranspiration (Yip et al., 2012). Owing to changes in precipitation and temperature, volume and timing of runoff in a river can change (Barnett et al., 2005). Climate change can also affect

the magnitude and frequency of extreme weather and hydrological events around the world (Dadson et al., 2013), including IJFs (Beltaos & Prowse, 2001; Prowse & Beltaos, 2002).

With changing climate and continued economic growth, the risk of flooding is predicted to increase globally (Milly et al., 2002). Without any preventative or mitigative measures, flood damages are estimated to increase up to 20 times by the end of the century (Winsemius et al., 2016). However, an increase in global exposure to floods would depend on the degree of warming (Hirabayashi et al., 2013). As high latitude northern regions are more prone to climate warming (Schindler & Smol, 2006), the implications of air temperature rises on IJFs might be larger than for open water floods (Prowse & Beltaos, 2002). The size of the snowpack and the rate of spring melt controls the severity and magnitude of IJFs in cold regions (Romolo et al., 2006a; Romolo et al., 2006b). In a warmer world, more precipitation is expected to fall as rain in snow-dominated regions (Krasting et al., 2013) and the melting of winter snow is to occur earlier in the spring (Beltaos & Burrell, 2003) resulting in a shift in the timing and magnitude of peak spring runoff.

While global climate models differ in changes in future precipitation, they all agree on increased temperatures (Barnett et al., 2005). IJFs which occur mainly during the ice-cover breakup period are very sensitive to temperature (Beltaos & Burrell, 2003). A warming world, thus, can change the ice cover breakup patterns and result in shifts in the timing of IJFs (Beltaos & Prowse, 2001). Less ice production is expected in a warmer world which could potentially reduce the persistence and potential severity of ice jams (Beltaos et al., 2006a). Strong signals of climate induced shifts in the timing of floods were already observed in continental Europe (Blöschl et al., 2017). In the northern hemisphere, climatic impacts on ice cover duration have been investigated (Duguay et al., 2006; Magnuson et al., 2000; Prowse et al., 2011) and regional trends in ice cover freeze-up and breakup have already been reported in the literature e.g. Bonsal et al. (2006); Zhang et al. (2001). However, analyses of climate change impacts on the timing and magnitude of IJFs are still limited.

On the other hand, the new hydrological reality is that half of the world's rivers have dams that have significantly modified river flow regimes (WCD, 2000). In Canada alone, there are 15,000 dams, of which 933 are categorized as 'large' dams (CDA, 2017) under the definition of the International Commission on Large Dams. In regulated rivers, changes in river flow regimes will also affect river ice processes (Beltaos, 2014). Regulation can affect the nature of freeze-up and

breakup, ice growth, severity of ice jams, duration of ice cover (Beltaos & Prowse, 2009) as well as frequency and magnitude of IJFs depending upon the flow operation of the reservoir (Beltaos, 2014; Prowse et al., 2006). However, the severity of change will be spatially distributed along the river. For instance, Conly and Prowse (1998) analyzed the historical ice conditions in the Peace River in western Canada, and found that the regulation largely altered the ice-on and ice-off times and duration of ice cover with virtually the non-existence of an ice cover near the dam but less severe effects at the downstream delta.

Despite significant advances in river ice hydrology, our understanding of several aspects of IJFs remains limited. Very little work has been carried out on changes to the breakup regime of rivers and consequences to the frequency and severity of IJFs (Beltaos & Prowse, 2001). Although the importance of river ice in causing hydrologic extremes, such as low flows and floods, has been documented for a small number of site-specific cases, no regional assessments of its large-scale implications have been conducted (Prowse & Beltaos, 2002). Similarly, IJF delineation still remains a significant challenge (Kovachis et al., 2017), even for streams and small rivers (Turcotte et al., 2017). IJFs are controlled by meteorological conditions and are thus sensitive to changes in prevailing climates (Prowse & Beltaos, 2002). Projected future decreases in south to north air-temperature gradients suggest that the severity of ice-jam flooding may be reduced, but this could be offset by changes in the magnitude of spring snowmelt (Prowse et al., 2011). However, despite recent advancements, there is still progress to be made in quantifying the effects of a changing climate on the ice regime and IJFs of northern rivers (Beltaos & Burrell, 2015).

1.2 Research objectives

The main objective of this research is to investigate the impacts of climate variability and regulation on spring ice-jam flooding of northern rivers and inland deltas. I organized my research into five sections – the five research chapters presented in this thesis – each of which sought to address one outstanding question with regards to ice-jam flooding in northern rivers and inland deltas.

The specific research questions are as follows:

- a. What are the impacts of climate on river ice processes in present and potentially in future?
- b. What is the relative contribution of climate and reservoir regulation on ice-jam flooding?

- c. How can we promote IJFs in a downstream deltaic ecosystem, where it is essential, without necessarily increasing flood risk in upstream communities?

I begin with a comprehensive review of IJF research reviewing all the journal articles published up to October 2017 to assess the nature and scope of scholarly research on IJF, and to suggest an agenda for research that better integrates IJF challenges with research opportunities (Chapter 2). In Chapter 3, I investigate the implications of a changing climate on ice-jam flooding in an unregulated river presenting a case study of the Athabasca River at Fort McMurray. In Chapter 4, I assess relative effects of climate change and regulation on ice-jam flood frequency and magnitude in a regulated river (the Peace River). As IJFs are known to have adverse effects in upstream communities, but beneficial impacts in some downstream deltas, I explore how IJFs can be promoted and prevented at desired locations in Chapter 5.

1.3 Thesis outline

Chapter 2 presents a review of IJF research. There have been significant advances in river ice hydrology for the past 35 years (Beltaos & Burrell, 2015; Beltaos, 2000). Different river ice processes such as ice formation, breakup, jamming, as well as linkages between the ice regime with water quality and sediment transport have been reviewed (Beltaos, 2000, 2008; Morse & Hicks, 2005). Similarly, there has been extensive research on understanding hydro-climatic drivers and controls of ice-jam flooding, as well as some research to assess future climatic effects on river ice hydrology (Beltaos & Prowse, 2009; Prowse & Beltaos, 2002). Beltaos (2010) assessed the methodology and limitation of IJF risk and a recent review by Kovachis et al. (2017) summarizes the current challenges and research needs in delineating IJFs. However, a comprehensive review on IJF literature has not yet been presented. In this chapter, I reviewed all the peer-reviewed publications on IJFs analyzing the data available from the Web of Science. The main motivation of this study is the notion that the state-of-the-art of IJF research should be reflected from the scholarly literature which can provide insights on current progress and gaps as well as identify future opportunities. The study was submitted in February 2018 for potential publication in *Natural Hazards* and is currently under minor revision. [Rokaya, P., Budhathoki, S., Lindenschmidt, K-E. (2018), Ice-jam flood research: a scoping review, *Natural Hazards*, minor revision].

In Chapter 3, I focus on understanding the implications of hydro-climatic variability on ice-jam flooding, presenting the Athabasca River at Fort McMurray in western Canada as a case study. Some ice-jam breakup events in the Athabasca River basin have already been studied, especially those occurring at the Town of Fort McMurray (TFM) (Andres & Doyle, 1984; Hutchison & Hicks, 2007; Kowalczyk & Hicks, 2003; She et al., 2009). However, the potential impacts of reduced streamflows and other hydro-climatic variability on river ice processes have not been fully investigated. Although future climate change impacts on hydrology (Kerkhoven & Gan, 2008, 2011; Prowse et al., 2006) and water availability (Leong & Donner, 2015) have been assessed, potential implications on river ice processes, especially on the IJFs, have not been examined. Thus, the objectives of this study were to: (a) assess the impacts of hydro-climatic trends on river ice processes and (b) estimate the probabilities of IJFs at the TFM in the future. A non-parametric Mann-Kendall (MK) trend test (Mann, 1945) was used to analyze trends in river ice cover formation and breakup. RIVICE, a one-dimensional hydrodynamic model (Lindenschmidt, 2017) was then applied to assess probabilities of overbank flow based on breakup discharge using a stochastic method. And finally, MESH, a land-surface hydrology model (Pietroniro et al., 2007), was implemented to examine probability of IJFs in future (2041-2070 period) using meteorological inputs from the Canadian Regional Climate Model driven by two global circulation models. This study is under review for potential publication. [Rokaya, P., Morales, L., Bonsal, B., Wheeler, H., Lindenschmidt, K-E. (2018), Implications of hydro-climatic variability on ice-jam flooding along the Athabasca River in Fort McMurray, *Hydrological Sciences Journal*, under-review].

Chapter 4 discusses the effects of regulation and climate on the frequency and magnitude of IJFs, presenting the Town of Peace River (TPR) in Alberta, Canada as a case study. In this chapter, I investigate how IJF frequency and magnitude can change under regulation and climate. I generated and compared naturalized flows with regulated flows to quantify the influences of regulation. I also compared different time periods in naturalized and regulated years to identify climatic effects. IJF risks were assessed within an integrated approach involving a physically-distributed hydrological model and river ice hydraulic model. This study was submitted in February 2018 for potential publication in *Water Resources Research*. [Rokaya, P., Wheeler, H., Lindenschmidt, K-E. (2018), Effects of regulation and climate change in ice-jam flooding, *Water Resources Research*, under-review].

In Chapter 5, I aim to address the conundrum of promoting IJFs in the downstream deltaic ecosystem, where they are essential, without necessarily increasing flood risks in upstream communities in the Peace River in western Canada. This study reviews previous approaches, and explores possible reservoir operation schemes with an integrated hydrologic and hydraulic river ice modelling approach to minimize flood risk and maximize flood potential at desired locations. The initial results from hydrological modelling work were presented and published in the conference proceedings of the Canadian Geophysical Union Hydrology Section's Committee on River Ice Processes and the Environment (19th Workshop on the Hydraulics of Ice Covered Rivers, July 9-12, 2017, available at <http://cripe.ca/docs/proceedings/19/Rokaya-et-al-2017.pdf>). The full paper was submitted in December 2017 for potential publication in *Journal of Water Resources Planning and Management* and has been accepted. [Rokaya, P., Wheeler, H., Lindenschmidt, K-E. (2017), Promoting sustainability of a drying deltaic ecosystem in a regulated river, *Journal of Water Resources Planning and Management*, accepted].

This thesis adopts a 'dissertation by manuscript' style. Following this introductory chapter, Chapters 2, 3, 4 and 5 are based on four manuscripts. Finally, Chapter 6 sets out the conclusions of my research, discusses linkages between the five manuscript chapters, and suggests avenues for future research.

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CHAPTER 2

ICE-JAM FLOOD RESEARCH: A SCOPING REVIEW

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2.1 Abstract

Almost 60% of the rivers in the northern hemisphere experience significant seasonal effects of river ice. In many of these northern rivers, ice-jam floods (IJFs) pose serious threats to riverine communities. Since the water depths associated with ice-jam events can be exceptionally higher than open-water floods for the same or even lower discharges, IJFs can be more disastrous to local communities and economies, especially as their occurrence is often very sudden and difficult to anticipate. However, in the last several decades there have been many important advances in river ice hydrology which has improved our knowledge and capacity in dealing with IJFs. In this context, this study assesses the current state of science on IJF research. We reviewed all the published journal articles on IJF available from the Web of Science till October 2017 to report the nature and scope of scholarly research on IJF, and to suggest an agenda for research that better integrates IJF challenges with research and mitigation opportunities.

2.2 Introduction

Ice-jam floods (IJFs) are important hydrological and hydraulic events occurring across the northern regions of the world. Though they have been found to be beneficial for some northern inland deltaic ecosystems such as the Peace-Athabasca Delta (Peters et al., 2006a; Prowse et al., 2002) and the Mackenzie River Delta (Goulding et al., 2009a; Goulding et al., 2009b) in Canada, and the Yukon Flats in the United States (Chen et al., 2014; Jepsen et al., 2016), they also result

in devastating losses to human lives and economies of northern communities (Lindenschmidt et al., 2016; She, 2008). Additionally, compared to open-water flood events, IJFs can be more severe as previous research has found since, under the same or lower discharge, they can result in two to three times higher water depths than open-water floods (Beltaos & Prowse, 2001). The feature that makes them more dangerous is their unpredictability of occurrence. IJFs are often sudden and difficult to anticipate which allows little time for the implementation of contingency measures, especially evacuation (Mahabir et al., 2006; Massie et al., 2002).

IJFs during spring breakup period are more common but they also occasionally occur during mid-winter breakup and freeze-up periods. Mid-winter breakup events have been reported in Michigan (White et al., 2006), Maine (Huntington et al., 2003), Wisconsin (Carr & Vuyovich, 2014) and Alaska (Newton et al., 2017) among others in the United States and in New Brunswick (Beltaos, 2002), Quebec (Turcotte & Morse, 2011), British Columbia (Beltaos, 2014a) and Yukon (Janowicz, 2010; Newton et al., 2017) among others in Canada. IJFs in freeze-up period is more common in hydropower based regulated rivers. Larger flows are released during winter months when energy demands are higher, which can result in a higher freeze-up stage in a river. Further, depending upon hydro-meteorological conditions, the initial ice cover may go through consolidation events, i.e. collapse and thickening of a newly formed ice cover, that might result in significantly higher water levels posing serious flood risks to riverine communities (Andres et al., 2003; Huokuna et al., 2017). An example includes basement flooding events in the Town of Peace River in Alberta, Canada in 1982, 1992, 2005 and 2008 since regulation in headwaters of the Peace River in 1972 (Jasek et al., 2017).

Financial costs of IJFs are estimated to be USD 250 million per year (2006 value) for North America (Eamer et al., 2007). However, as Beltaos and Prowse (2009) note, a full economic valuation of river-ice damages is yet to be conducted. The current estimates account only for tangible monetary costs and do not reflect other serious implications such as residents' relocation and even loss of life (Beltaos, 2000). Prowse et al. (2007) also suggest that existing estimates could be seriously underestimated considering that just a single IJF event has been known to result in substantial financial damages. For instance, an IJF event in 2013 at the interior Alaskan village of Galena was estimated to have resulted in USD 80 million in damages (Kontar et al., 2015) whereas the cost of another single IJF event in the Irkutsk Region of Russia in 2001 alone has been

appraised to have been as high as USD 200 million in damages (Zaitsev et al., 2006). The potential risks of ice-jamming in rivers in Russia are so high that often the most advanced fighter jets of the Russian arsenal, such as the Su-34, are extensively employed to bomb and release jams to avoid any IJFs (Sridharan, 2016).

In the literature, an increasing number of journal articles, as well as conference proceedings such as the river ice workshops of the Committee on River Ice Processes and the Environment (CRIPE) of the Canadian Geophysical Union (CGU), Hydrology Section and the ice symposia of the Ice Research and Engineering Committee of the International Association for Hydro-Environment Engineering and Research (IAHR), have contributed in advancing river ice hydrology for the past 35 years (Beltaos & Burrell, 2015; Beltaos, 2000). Different river ice processes such as ice formation, breakup, jamming as well as linkages between the ice regime with water quality and sediment transport have been reviewed (Beltaos, 2000, 2008a; Morse & Hicks, 2005). Similarly, there has been extensive research on understanding hydro-climatic drivers and controls of ice-jam flooding as well as some research to assess future climatic effects on river ice hydrology (Beltaos & Prowse, 2009; Prowse & Beltaos, 2002). Beltaos (2010a) assessed the methodology and limitation of IJF risk and a recent review paper by Kovachis et al. (2017) summarizes the current challenges and research needs in delineating IJFs. However, a comprehensive review on IJF literature has not yet been presented.

The main motivation of this study is the notion that the state-of-the-art of IJF research should be reflected from the scholarly literature which can provide insights on current progress and gaps as well as identify future opportunities. In this paper, we reviewed all the peer-reviewed publications on IJFs analyzing the data available from the Web of Science (published by October 2017). Title, abstract and key words and, when required, full articles were reviewed as part of this assessment. The purpose of this paper is thus to assess the nature and scope of scholarly research on IJF, and to suggest an agenda for research that better integrates IJF challenges with research opportunities. As Morrison et al. (2017) state, “understanding how scholarly community communicates advances and challenges in research will help in identifying and prioritizing research needs”.

2.3 Materials and Methods

We analyzed data from the Web of Science (Clarivate Analytics) and journal articles published up to October 2017, with no earlier date limit. The data were accessed on October 25, 2017 and hence, the results reflect the content of the Web of Science database at this point in time. The search string (TITLE-ABS-KEY (ice jam* flood*)) resulted in 326 papers which, when constrained by ‘Document type: Article’, resulted in 226 articles. As the Web of Science database is continually updated, the total number of publications may differ if data are obtained at a future date. Further reading of the abstract of all 226 articles revealed that only 188 articles were related to ice-jam flooding and thus were reviewed for further analyses.

The selected 188 articles were at first grouped into six major themes based on the focus of the articles (see Table 2-1) These major themes include articles reporting on (a) model applications, (b) field work, (c) new theories, methods and tools, (d) interdisciplinary approaches, (e) risk reduction and (f) general and review papers. This was an iterative process and required reading of abstracts several times and in some cases, the entire manuscript more than once. While the majority of the papers were categorized under a single theme, the scope of some papers spanned over several themes and were categorized accordingly. In a second step, the articles within a theme were further grouped into several topics. The abstracts were again reviewed several times to ensure that topics adequately captured the content of the papers.

Table 2-1: Different themes identified under IJF research. As the scope of some articles span over several themes, the total percentage is more than 100%.

SN	Themes	Number of articles	Percentage of articles
1	Field measurements	19	10
2	Theories, methods and tools	15	8
3	Model applications	64	35
4	Interdisciplinary approaches	30	16
5	Flood risk-reduction	24	13
6	General and review	61	33

It is also important to acknowledge the scope and limitations of this study. This review is explicitly focussed on IJF; thus, our analysis represents only those papers which self-identify and relate to IJF based on the title, abstract, and author-defined key words. Literature reporting on the findings from field measurements, laboratory works or model simulations on other aspects of river ice hydrology were not included. For instance, while articles on climate change impacts on IJF or model simulations of IJF events are of a focus, climate change impacts on ice cover duration or laboratory experiments or numerical simulations of ice properties are not within the scope of this review. Similarly, as the focus is on peer-reviewed articles, proceeding papers from conferences including CRIPE’s river ice workshops and IAHR’s ice symposiums are not included in this assessment.

2.4 Results and Discussion

2.4.1 Trends and patterns on IJF research

Publication history

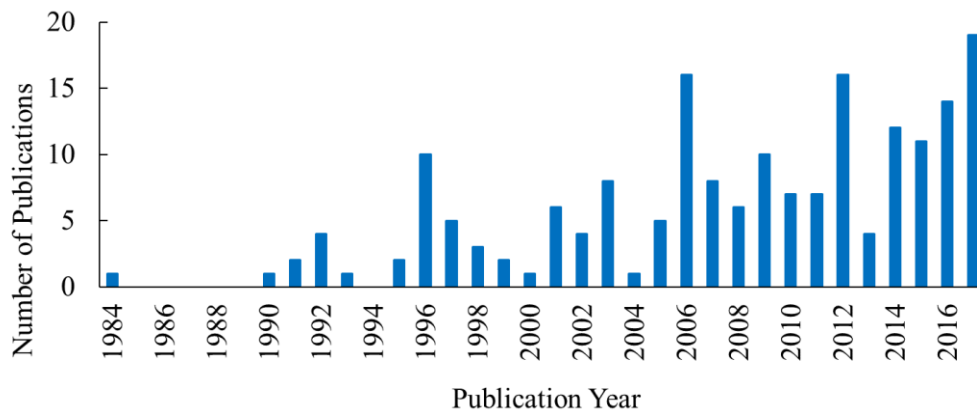


Figure 2-1: Publication trend in IJF research

A total of 188 journal articles were identified that addressed some components of IJF. The first article appeared in 1984 by Vogel and Stedinger (1984) which addressed flood-plain delineation in ice-jam prone regions. After that six years had passed before another IJF article appeared in the peer-reviewed literature. The momentum in publications began to increase towards the beginning of the 21st century, as more than 80% of articles were published between 2001-2017 (see Figure 2-1). Recent years have seen a rapid growth with almost 45% articles published in the last 7 years

which suggests increased recognition of IJF research. However, other aspects of river ice hydrology have been published for longer durations. We expect that a much larger pool of relevant IJF research exists – research that is published outside of the academic press or does not self-identify as being focused on IJF. There are also several conference proceeding papers and research reports that are outside the scope of this assessment.

Contributing disciplines

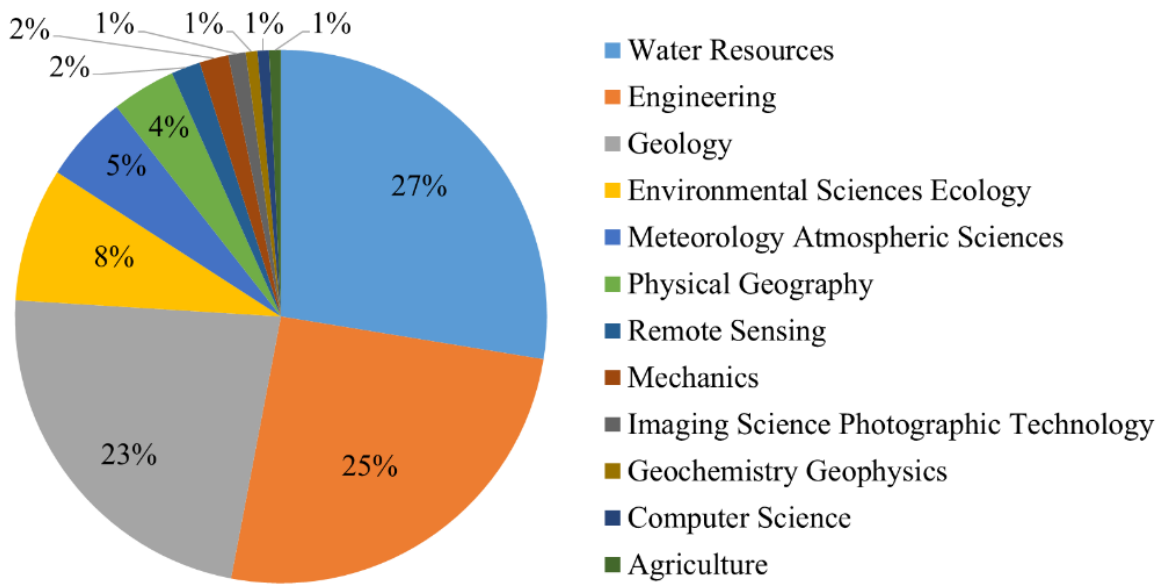


Figure 2-2: Contributing field of study in IJF research

Figure 2-2 shows the contributing field of study in IJF research as obtained by data analysis from Web of Science. It demonstrates that IJF research is a multidisciplinary issue with publications originating from several research fields. Though Water Resources (27%), Engineering (25%) and Geology (23%) are found to be major contributing fields of study, there are also significant and growing contributions from other research fields such as Ecology, Atmospheric Sciences, Physical Geography and Remote Sensing. The reason for the diversity and interest is that, in the northern hemisphere, river ice is one of the major components of the cryosphere, and ice covers are observed along one third of the total river length (with seasonal ice effects pronounced on about 60%) (Prowse et al., 2007). Additionally, stationary or moving river ice interacts with river flow in many different ways resulting in diverse implications to communities, economies and ecosystems (Beltaos, 2000). Nevertheless, increased contributions from other academic fields and applications

of interdisciplinary approaches has provided new insights as well as additional data. For instance, remote sensing has been useful in documenting and monitoring river ice processes and paleohydrology studies have provided long-term historical insights in hydrology and climate.

IJF case studies

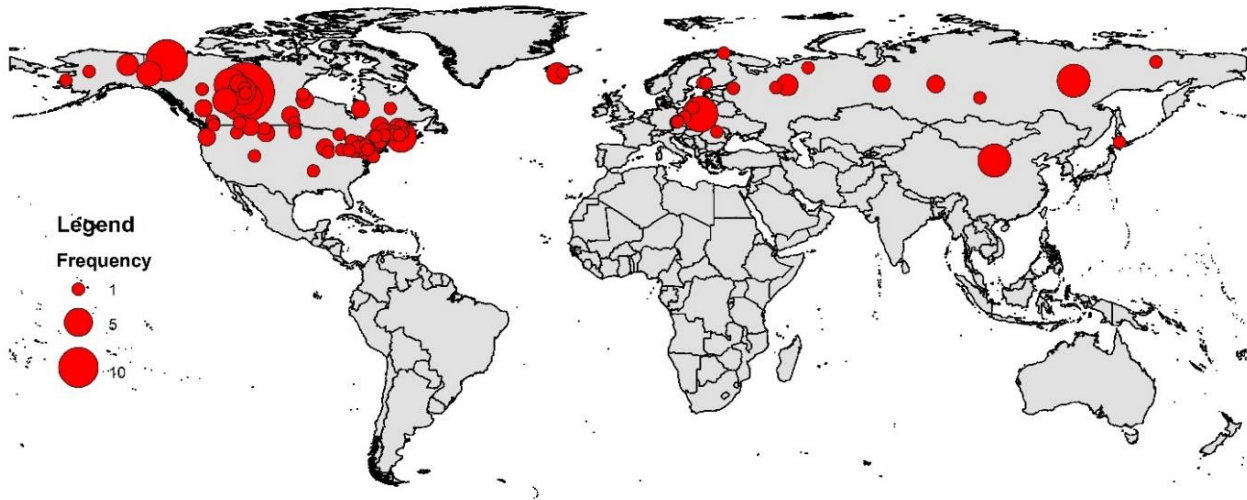


Figure 2-3: Geographic distribution and frequency of case studies on IJF. The size of the circle is proportional to the frequency of case studies reported in the literature.

A total of 94 case studies of IJF have been addressed in the 188 papers. 21 articles out of the 188 were either review papers or papers postulating new concepts or theories on ice-jam flooding and hence, did not consist of specific study sites. Similarly, some articles focused on more than one location whereas some case study sites were repetitive in several publications. Figure 2-3 shows the spatial distribution and frequency of published case studies which highlight the focus of current literature in North America, and particularly in Canada. However, the figure is not reflective of the frequency of IJF events in themselves. For instance, 22 papers were reported on the Peace-Athabasca Delta (PAD), an important Ramsar site and one of UNESCO's World Heritage sites in western Canada where ice-jam flood events have become infrequent. This is of great concern as previous research has shown that only IJF events can recharge the high-elevation 'perched' basins of the PAD (Peters et al., 2006a; Prowse et al., 2002). The figure also shows no cases of IJFs reported from Norway and Sweden though IJFs are observed in these countries. This reveals the gap in reporting in journal articles (reporting in conference papers and research reports, see Beltaos

and Prowse (2001) and Prowse and Beltaos (2002) for examples) but not the absence of IJFs in other areas.

2.4.2 Advances in IJF research

Theme 1: Lesson learnt from fieldwork

Around 10% of the all articles were categorized under the theme of ‘field measurement’ which reported on studies that carry out field experiments/measurements on major river ice processes that are important in IJF research. Based on the content of the articles, three research topics were identified under this theme which included papers on ‘ice cover formation’ (16%), ‘jamming and breakup’ (63%) and ‘the role of structures on river ice processes’ (16%). The first topic of ‘ice cover formation’ includes articles related to quantifying frazil ice production, transport and deposition (Vergeynst et al., 2017), quantifying freeze-up process in steep channels (Turcotte et al., 2013) and ice cover formation processes along river reaches (Beltaos, 2008b). These methods provide a framework for quantifying and evaluating freeze-up processes as well as understanding major dominant processes that determine the nature and severity of river freeze-up.

A larger portion of the articles from the theme 2, ‘field measurements’ were under the second topic of ‘ice jamming and breakup’ which included observations of ice jamming process (Beltaos et al., 1996; Michel, 1992; Stanley & Gerard, 1992) as well as waves induced by ice jam release events (Hutchison & Hicks, 2007; Jasek, 2003). These field measurements of ice jamming and breakup processes have contributed in developing new theories such as limit equilibrium of ice-jams as well as calibrating and validating continually improving river ice models (Hicks, 2009).

Similarly, there are also articles that discuss different methods of removing and artificially releasing ice jams (Doyle, 1991), and river flow under ice-covered conditions (Majewski, 2007) that are useful in IJF mitigation work.

. Finally, the third topic ‘the role of structures on river ice processes’ includes articles that address the impacts of infrastructure on river ice processes (Wang et al., 2015), evaluate the performance of ice control structures on mitigating ice jams (Lever & Gooch, 2007) or introduce new ice control structures (Lever et al., 1997). These studies show how infrastructures such as bridge and piers

influence ice jam processes. Articles on ice control structures suggest design recommendation that are low cost and well suited to control breakup ice jams.

Theme 2: New theories, methods and tools

The second theme, ‘new theories, methods and tools’ on IJF research constitute about 8% of the publications. This theme introduces new concepts, methods and tools in IJF research which was further classified into three major topics based on the content of the articles. These topics include ‘*theories and concept*’ (43%), ‘*methods*’ (43%) and ‘*tools*’ (14%). New ‘*theories or concepts*’ includes articles proposing new theories such as ice-jam release waves or javes for short (Beltaos, 2013a, 2013b) as well as self-sustaining waves (Beltaos, 2017). Concepts such as limit equilibrium of ice jams (Michel, 1992), and internal strength properties of ice jams (Beltaos, 2010b) as well as thresholds between mechanical and thermal breakup of ice covers (Beltaos, 2003) have been proposed. These theories and concepts have been important in advancing IJF research in general. Javes and self-sustaining waves have explained extreme breakup processes that are rapid and result in ice cover breakup over long river stretches that can result in devastating events but also can be beneficial for replenishing delta habitats with water, sediment and nutrients. Thresholds in mechanical and thermal breakup have served as a benchmark in assessing the severity of possible breakup events.

Similarly, new ‘*methods*’ have been introduced in IJF research which include methods for quantifying transported frazil ice (Vergeynst et al., 2017), to predict the potential frazil ice may have on flooding (Gholamreza-Kashi, 2016) as well as estimating winter peak stages along a river reach (Tuthill et al., 1996). Methodologies to compare the impacts of climate and regulation on IJF (Beltaos, 2014a) and a synthetic method to quantify and assess IJF risks (Beltaos, 2012a) have also been proposed. These methods help in quantifying relative impacts of climate and regulation on IJFs.

New advances on model calibration and sensitivity analysis include the use of stage frequency distribution as an objective function for model calibration (Lindenschmidt, 2017b) and local and global sensitivity analyses of river ice processes (Sheikholeslami et al., 2017). Using stage frequency distributions in place of single values or time series such as water levels or flows allows the stochastic nature of the input parameters in hydraulic models to be characterise which is an

important feature of some hydraulic processes such as ice jam formation. Similarly, study on sensitivity analyses offer insights into how the internal model parameters and boundary conditions affect model behavior.

The third topic, '*tools*' comprises applications of new technologies such as remote sensing for ice volume calibration (Zhang et al., 2017) as well as social media to analyse virtual relief networks and communication channels during IJF (Taylor et al., 2016). Using new scientific advances such as remote sensing in estimating ice volume is a novel approach and can assist in river ice modelling studies including IJF forecasting as ice volume is one of the most important boundary conditions in river ice models. Similarly, use of social media and other new communication platforms can greatly assist in collecting data, disseminating timely forecasts and warnings, and executing emergency response.

Theme 3: Advances in model application

The theme 'model applications' includes papers that introduce new numerical or hydrodynamic models or use existing varieties of physically-based or numerical models in IJF research for various applications. A total of 64 articles (35%) were identified to have some modelling component in the research. Most of the papers are related to examining different river ice processes or forecasting IJF events. The papers under this theme were further sub-divided into five major research topics to assess the scope, nature and purpose of model applications. The analyses show that most of the articles emphasized in '*simulating river ice processes or understanding particular river ice phenomenon*' that are critical to IJF. Forty five percent of the articles on 'model applications' fall under this topic which include studies on ice cover formation (Lindenschmidt & Chun, 2014; Lindenschmidt et al., 2012), jamming (Beltaos et al., 1996; Healy & Hicks, 2007; She et al., 2009; Shen & Liu, 2003) and breakup (Nzokou et al., 2009; Wang et al., 2013) including the river waves caused by ice-jam release (Beltaos, 2013b, 2014b; She & Hicks, 2006).

Articles on IJF '*forecasting*' constitute another major fraction (22%) of model applications. Fuzzy logic (Mahabir et al., 2008; Zhao et al., 2015) or artificial neural networks (Wang et al., 2010; Zhao et al., 2012) or a combination of both methods (Mahabir et al., 2006; Mahabir et al., 2007) have been widely documented in IJF forecasting literature. Similarly, several hydrodynamic models have also been used for forecasting purposes such as those reported by Beltaos et al.

(2012); Blackburn and Hicks (2003); Brayall and Hicks (2012) and Fu et al. (2014). Though river ice processes are complex phenomena, development of reliable forecasting tools can contribute in operational water management and considerable advances have been made in the last decade as documented by Morse and Hicks (2005). However, there are still several challenges in IJF forecasting such as insufficient data and models' capabilities to simulate ice jam release surge. A general coupled hydrological-river ice model is yet to be developed (Beltaos & Prowse, 2009). Models have also been applied for '*risk assessment or hazard mapping*' such as Lindenschmidt et al. (2016) and Magritsky et al. (2017). About 17% of publications under the model applications theme were found to address risk assessment and hazard mapping.

The evaluation of '*impacts of climate change and regulation on IJF*' (Andrishak & Hicks, 2008; Beltaos et al., 2006a; Leconte et al., 2006; Prowse et al., 2006; e.g. Prowse & Conly, 2002) constitute 11% of the articles under this theme. These studies focus on quantifying relative impacts of climate and regulation on IJFs. Some of the articles also assess future climatic impacts using downscaled projected climate scenarios. About 9% of model applications were found to introduce 'new approaches or models' in IJF research such as using stage-frequency distributions for model calibration (Lindenschmidt, 2017b) and introducing a non-proprietary, open source, one-dimensional river-ice model (Lindenschmidt, 2017a).

Theme 4: Interdisciplinary approaches

Traditionally, field measurements, laboratory experiments and modelling tools have dominated IJF research. However, recent decades have observed increased applications of other disciplines such as 'remote sensing', 'paleohydrology' and 'dendrochronology' making up to 16% of the total publications in IJF literature. Articles under this theme were further identified into three major topics based on their disciplinary background. The results show that half of the publications on this theme (53%) are on applications of '*remote sensing*' whereas '*paleohydrology*' and '*dendrochronology*' studies contribute to the remaining 37% and 10%, respectively. Since many northern rivers and deltas are vast in size but poorly gauged, accessing reliable data in real-time has been a significant hindrance. This could partly explain the significant number of articles using remote sensing and geographic information system based tools as space-borne technologies offer new possibilities for IJF research. Thus, to classify river ice (Mermoz et al., 2009) or monitor ice breakup (Lindenschmidt & Das, 2015; Pavelsky & Smith, 2004); or ice-jam flooding (Temimi et

al., 2005) or to map IJF inundation (Pagneux et al., 2010; Pagneux & Snorrason, 2012), remote sensing technologies are increasingly used. Laser scanning (Lotsari et al., 2015) and unmanned aerial vehicles (Lin et al., 2012) have also been used in IJF research. On the other hand, floodplain stratigraphy (Hugenholtz et al., 2009; Livingston et al., 2009), paleolimnology (Wolfe et al., 2006; Wolfe et al., 2005) and isotope tracer methods (Wolfe et al., 2008; Yi et al., 2008) have been used to reconstruct long-term IJF history, identify relative impacts of climate change and regulation on ice-jam flooding and characterize sources of water inputs to floodplain deltas and lakes, respectively. Ice scar chronology has also been widely used to reconstruct historical IJF events and study IJF frequencies (Boucher et al., 2009a, 2009b; Lagadec et al., 2015). Advances in the river ice research field in general have been long hindered by inadequate data. From developing relationships based on historical data to model validation, inadequate data have remained a significant challenge. Thus, applications of these new fields in river ice research can offer additional long-term data and insights.

Theme 5: Progress in risk reduction

Theme 5 on IJF risk reduction includes those papers that discuss IJF risk assessment, hazard mapping, preparedness as well as mitigation measures. A relatively small portion of the total articles, i.e. 12% fall under this theme. This theme was further sub-divided into three major topics: ‘*risk assessment*’, ‘*preparedness*’ and ‘*mitigation*’. The IJF *risk assessment* topic includes about 36% of the total publications under this theme which addresses issues such as hazard mapping (e.g. Agafonova et al., 2017; Frolova et al., 2017; Lindenschmidt et al., 2016; Magritsky et al., 2017) and floodplain delineation (e.g. Barnes-Svarney & Montz, 1985; Pagneux & Snorrason, 2012; Vogel & Stedinger, 1984). On the *preparedness* side, monitoring of ice-jamming processes (Banshchikova, 2008), introduction of new forecasting and prediction models (Buzin & D’yachenko, 2011; Gholamreza-Kashi, 2016) and reviewing of flood management options (Burrel et al., 2007; Verta & Triipponen, 2011) are the major subjects which make up to 27% of the total articles under Theme 5. Similarly, about half of the articles (45%) on this theme are on the topic, IJF *risk mitigation* which mainly discusses different ice control structures and their applications, performance and benefits (e.g. Calkins, 1991; Carr et al., 2016; Lever & Gooch, 2001; Lever & Gooch, 2007; Lever et al., 1997; Morse et al., 2006).

Theme 6: General and Review Papers

The final theme, Theme 6, consists of articles that are either review articles or articles with a specific focus that did not fit in the aforementioned five themes but were too few to be divided into separate themes. About 30% of the total papers were grouped under this theme which had a large scope with articles focussing on diverse issues. This theme was broadly sub-divided into five major topics, i.e. *review articles*, *case studies*, *hydro-climatic studies*, *morphological and ecological studies* and *descriptive* articles based on the content of the articles. About 12% of the papers are *review articles* which include articles on advances in river ice hydrology (Beltaos, 2000; Morse & Hicks, 2005), river ice science and engineering (Beltaos & Burrell, 2015), ice-jam management (Beltaos, 2008c), IJF delineation (Kovachis et al., 2017) as well as ecological perspectives on flooding (Peters et al., 2016). These reviews summarize progresses and challenges, and suggest future directions in IJF research.

A large number of the articles (30%) are on specific *case studies* such as particular flood events such as the 2001 flood in Gdansk, Poland (Majewski, 2006, 2016) or the 2009 flood along the Red River, Canada (Wazney & Clark, 2016) or a particular phenomenon at a certain location such as recharging of ‘perched’ basins of the Peace-Athabasca Delta in western Canada (Peters & Prowse, 2006; Peters et al., 2006a; Peters et al., 2006b). Though case studies are narrow in scope and highly site specific in nature, they also provide important insights in understanding river ice processes.

Another major topic (21%) in Theme 6 is *hydro-climatic studies*. These studies investigate the impacts of climate, teleconnections and human influences on IJF. Prowse and Conly (1998), Romolo et al. (2006), Kil'myaninov (2012), Beltaos (2013a), Buzin et al. (2014) and Carr and Vuyovich (2014) are some of the papers addressing this topic. IJF research is multifaceted, and climate and human influences have many direct and indirect implications. Changes in climatic variables such as precipitation and temperature as well as flow modification for human needs can result in diverse implications in river ice processes. Hence, the above mentioned studies provide valuable insights in understanding some of these intricate relationships and implications.

The fourth topic in this theme is related to IJF effects on river *morphology and ecology* comprising about 16% of the articles. Impacts of IJF on vegetation growth and distribution (e.g. Mann & Plug, 1999; Rood et al., 1998; Smith & Pearce, 2000), sediment transport (e.g. Milburn & Prowse, 1996; Moore & Landrigan, 1999) and channel morphology (e.g. Moody & Meade, 2014; Smith & Pearce, 2002) are some of the articles in this topic.

The final topic in this theme consists of 23% of the articles that are *descriptive* in nature such as aspects of flood history (Cyberski et al., 2006; Nachlik & Kundzewicz, 2016), or discussions on ice regimes and breakup patterns (Beltaos, 1997; Beltaos, 2007, 2012b; Beltaos et al., 2006b; Janowicz, 2010; Jasek, 2003) as well as the introduction of a new ice-jam database (White, 1996).

2.4.3 Gaps, Challenges and opportunities on IJF research

Gaps and Challenges

The geographic distribution and number of case studies (see Figure 4) show that the IJFs are observed in most of the countries in the Northern Hemisphere. However, in publications, the analysis from the Web of Science shows that more than 60% of the total articles originate from Canada, followed by the United States (20%). A large dominance of publications from a specific geographic location may reduce the diversity of issues in IJF research literature. For instance, Heggen and Alfredsen (2013) argue that the current river ice knowledge is largely based on large rivers such as those of Canada and Russia compared to relatively small and fairly steep rivers such as those of Norway. Timalsina et al. (2013) also suggest that most of the current ice modelling research is focussed on large and low-gradient rivers, and examples of applications of river ice models in shallow and fast-flowing rivers with more complex dynamic ice processes are rarely reported. Thus, the progress and challenges in IJF research across those least represented countries may not be reflected in current literature, a key knowledge base for academics and practitioners.

During this scoping review, only one article was found that addresses social aspects of IJF. The research from Pagneux et al. (2011) presents a case study on the public perception of flood hazard and flood risk in an Icelandic town prone to ice-jam floods. This limited research on social aspects of IJF shows that, unlike open-water flood, IJF research is still in its infancy in incorporating the human dimension. However, research has shown that resilience can be improved by integrating social perception in risk management (Bodoque et al., 2016). While the significance of interdisciplinary and transdisciplinary approaches in open-water flood research has been widely acknowledged, including the integration of social science knowledge (e.g. Brown & Damery, 2002; Fratini et al., 2012; Herk et al., 2011; Lane et al., 2011), this review shows that sole engineering or technical approaches are still largely employed in IJF research.

Similarly, despite the severity of IJFs, we noticed that very few research studies are dedicated to IJF resilience. About 13% of the total articles addressed some component of IJF risk reduction. Most of the papers on risk reduction were either on mitigation measures such as ice control structures or hazard assessment and floodplain delineation. Only about 3% of the total publications reported on preparedness against IJF risks. Additionally, about 7% of the total articles addressed IJF forecasting using different models, however, the focus was largely on research rather than operational usages. Thus, research reporting on operational flood forecasting including early warning systems and risk communications that are acknowledged as essential tools for enhancing resilience (e.g. Cools et al., 2016; De Roo et al., 2003; Fakhruddin et al., 2015) are largely absent.

Opportunities

The application of new interdisciplinary tools and methods offer additional avenues for collaborative IJF research. Where inadequate data have been an issue, new remote sensing tools can provide important historical and real-time data (Hicks, 2009). There is now opportunity to monitor river ice processes in remote locations, and document even dynamic events such as ice cover breakups which can be dangerous for manual observation (Mermoz et al., 2009). Remote sensing can also offer prospects to calibrate models and assist in IJF forecasting.

With one third of the current publications reporting on different model applications in IJF research, this assessment shows that the major focus of research has been on technical/engineering approaches with limited incorporation of social aspects of IJF. On the positive note, it suggests untapped opportunities to integrate knowledge, methods and tools from social science research in enhancing IJF risk resiliency.

Similarly, this review also shows that the changing environment poses new challenges for IJF research. One particular issue frequently mentioned in the literature is the increased severity and frequency of mid-winter breakup events. Newton et al. (2017) identified 52 mid-winter breakup occurrences in western Canada (1950-2008) and Alaska (1950-2014). As mid-winter breakups are sudden and difficult to anticipate, they can be more destructive than spring breakup events. With a changing environment, spatial shifts in breakup events including mid-winter are likely to occur (Beltaos, 2002). Further research is required in coupling river ice models with climatic (such as

Global and Regional Climate Models) and hydrologic models for detailed quantitative predictions of climate change impacts in IJFs (Beltaos & Prowse, 2009).

2.5 Conclusion

This study assesses the current state-of-the-art of IJF research highlighting the progresses, gaps and opportunities. The review finds there have been important advances in IJF research in recent years. Field measurements have assisted in quantifying some of the river ice processes which are critical in IJF research. Similarly, new concepts and theories have provided new directions for research, and improvements in modelling capability have enhanced our process understanding. Similarly, integration of knowledge, methods and tools from other disciplines such as remote sensing, paleohydrology and dendrochronology has helped in advancing IJF research and opening new avenues for collaborative research. However, this assessment also found that the major focus of journal articles has been on technical/engineering approaches with one third of the current publications reporting on different model applications in IJF research. Most of these studies have also originated from a limited number of countries, reducing potentially diversity of issues faced in other regions. Similarly, cross-disciplinary collaborations are limited and there is poor integration of social sciences in IJF research. Likewise, the major focus is on research with few articles on practice as there were limited papers on preparedness, operational forecasting and early warning systems. Nevertheless, these gaps also suggest that there are untapped opportunities in IJF research from integrating interdisciplinary methods to applying new tools to predicting future implications.

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2.7 Author contributions

PR conceived the rationale for the study and discussed with KEL. PR and SB carried out the data analysis. PR wrote the paper. KEL and SJ commented on the manuscript and contributed to the text in later iterations.

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CHAPTER 3

IMPLICATIONS OF HYDRO-CLIMATIC VARIABILITY ON SPRING ICE-JAM FLOODING ALONG THE ATHABASCA RIVER IN FORT MCMURRAY

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3.1 Abstract

In northern rivers, ice cover formation and breakup are important cold region hydrological processes. However, as in other cold regions across the globe, the interior of western Canada is observing rapid warming which has significant impacts in terms of hydrological and landscape change. Since any alteration in hydro-climatic regime can have profound impacts on river ice processes, there is a growing interest to understand and assess the impacts of current and future hydro-climatic trends on river ice processes, especially on ice-jam flooding. This paper studies the implications of hydro-climatic trends and variability on river ice processes, particularly on the freeze-up and ice-cover breakup along the Athabasca River in Fort McMurray which is very prone to ice-jam flooding. Using a stochastic approach in a 1D hydrodynamic river ice model, a relationship between overbank flow and breakup discharge was established. Furthermore, the likelihood of ice-jam flooding in the future (2041–2070 period) was assessed by forcing a hydrological model with meteorological inputs from Canadian Regional Climate Model driven by two global climate models. Our results show that the probability of ice-jam flooding in the future will be lower but extreme IJF events are still probable.

3.2 Introduction

In cold region hydrology, river ice plays a major role in the hydrological regime, which in turn influences physical, chemical and biological processes. For instance, a stable ice cover can cause additional resistance and reduce flow velocities (Beltaos & Prowse, 2009) whereas in some shallow channel systems, groundwater flows can be blocked if ice freezes to the bed (Beltaos & Burrell, 2003). Thus, ice cover formation and breakups are important cold region processes in northern rivers. However, ice-jamming and breakup events can also be disastrous to riverine communities depending upon hydro-meteorological conditions and river ice properties (Lindenschmidt et al., 2016). Ice-jam floods (IJFs) can be particularly dangerous since they can occur very rapidly, and are often associated with water levels higher than those attained during open-water flooding conditions (Kowalczyk & Hicks, 2003). The water depths have been reported to be as high as 2.5–3 times the regular open-water level at same discharge during such ice-jamming conditions, (Beltaos & Prowse, 2001).

However, as in other cold regions across the globe, the interior of western Canada is observing rapid warming which has significant impacts in terms of hydrological and landscape change (DeBeer et al., 2016). Though major river systems, such as Mackenzie and Nelson rivers, have shown no noticeable long-term trends at their mouths (Déry et al., 2011; Déry & Wood, 2005; Woo & Thorne, 2003), some smaller systems nested within these, such as the Athabasca River and other rivers draining from the Rocky Mountains to the south, have shown statistically significant declines in annual flow since late 1950s (Bawden et al., 2014; Peters et al., 2013; Schindler & Donahue, 2006).

Peters et al. (2013) performed a multi-scale hydro-climatic analysis of runoff in the Athabasca River basin (ARB) and found a decreasing trend since 1958 in the lower reaches. Similar results were reported earlier by Schindler and Donahue (2006) who calculated a 30% decline in summer flows in the lower reaches since 1970. Bawden et al. (2014) also determined decreasing trends in mean annual flow, mean summer flow and annual maximum flow whereas Monk et al. (2012) reported decreasing trends in ecologically relevant hydrological variables since 1958. But the findings of a century-long record from Rood et al. (2015) showed statistically significant decreasing trends only in headwaters. Though they did not find statistically significant decreasing trends in the lower basin, they also acknowledge significant declines in flows since 1970. Since

any alteration in hydrological regime can have profound impacts on the composition, thickness, severity and timing of river ice processes (Prowse et al., 2007), there is a growing interest to understand and assess the implications of current and future hydro-climatic trends on river ice processes in the ARB and particularly for the town of Fort McMurray (TFM). This is a key motivation for this research and has been missing in above mentioned hydro-climatic studies.

Frequent and severe ice jams during the breakup period have been observed in the past along different reaches of the Athabasca River (Andres & Doyle, 1984). Historical records show that there has been about one IJF every five years over the period 1875–2012 along the Athabasca River (see Table A1 for the list of the events). Although IJFs have occurred along different reaches of the Athabasca River, they are more prominent near the TFM (see Figure 3-1) due to the river reach's flat river bed slope and the presence of numerous islands and bars (Andrishak & Hicks, 2011; She, 2008). Since the gauging station was installed at the TFM in late 1957, 15 ice-jam floods have been recorded along the Athabasca River, the majority (60%) of which occurred at the TFM resulting in loss of millions of dollars in direct and indirect damages. The 1977 ice-jam flooding of the TFM caused 2.6 millions dollars of damage whereas 1997 event is estimated to have resulted in several millions dollars of damage (Mahabir et al., 2006).

Some ice-jam breakup events in the ARB have been studied in recent years, especially those occurring at the TFM. These include ice-jam events in the years 1977–1979 (Andres & Doyle, 1984), 2001–2003 (Hutchison & Hicks, 2007; Kowalczyk & Hicks, 2003) and 2006–2007 (She et al., 2009). However, the potential impacts of reduced streamflows and variations in temperature and precipitation in recent decades on river ice processes (such as ice formation, breakup and jamming) have not been fully investigated. Future climate change impacts on streamflow (Kerkhoven & Gan, 2008, 2011; Prowse et al., 2006), hydrological indicators (Eum et al., 2017) and water availability (Dibike et al., 2016; Leong & Donner, 2015) have been assessed, but potential implications on river ice processes, especially on the ice-jam floods, have not been examined. Thus, the objectives of this study are: (a) to assess the impacts of hydro-climatic trends on river ice processes and (b) to estimate the probabilities of future ice-jam flooding in the TFM.

A non-parametric Mann-Kendall (MK) trend test (Mann, 1945) was used to analyse trends in river ice cover formation and breakups after removing first order autocorrelation. RIVICE, a one-dimensional hydrodynamic model (Lindenschmidt, 2017b) was then applied to assess

probabilities of overbank flow based on breakup discharge under ice-jam conditions using a stochastic method. Finally, MESH, a land-surface and hydrology modelling system (Pietroniro et al., 2007) was implemented to examine the potential future discharges at freeze-up and breakup periods as well as to infer the probability of ice-jam flooding in future (2041–2070 period).

3.3 Study area

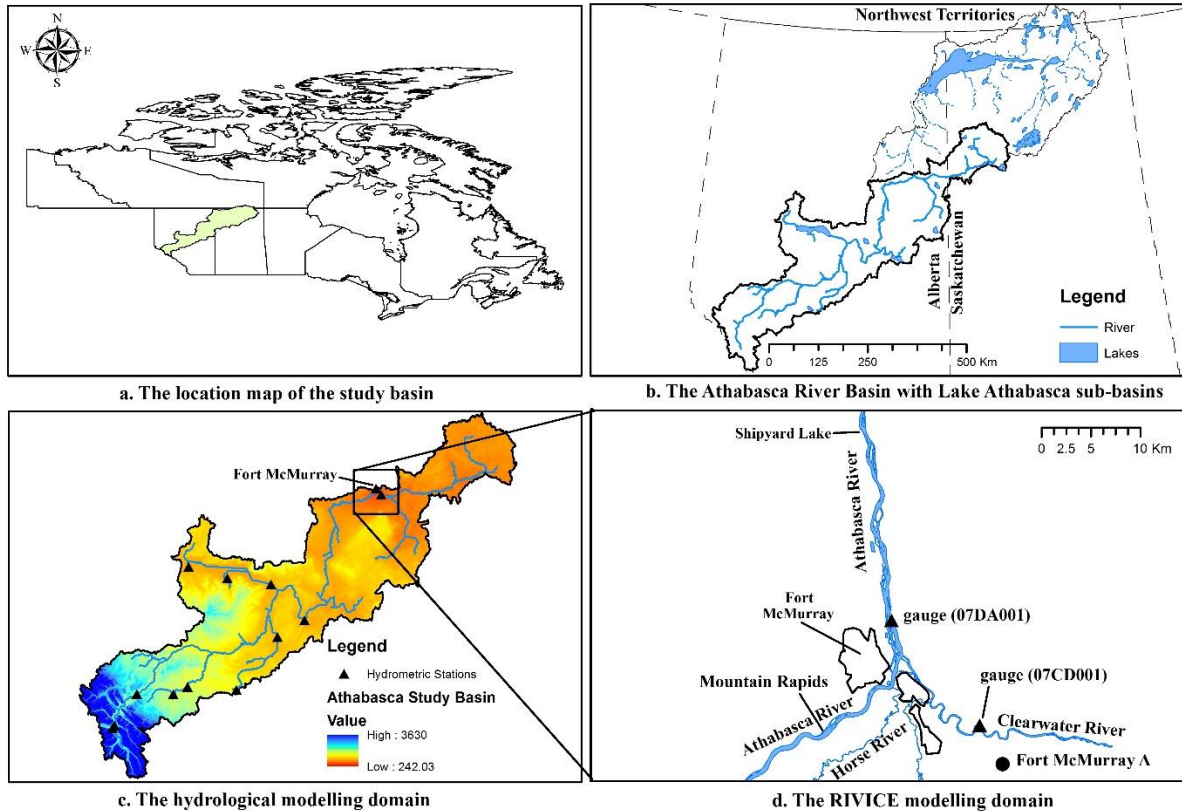


Figure 3-1: The study area: (a) study basin, (b) the Athabasca River basin with Lake Athabasca sub-basins, (c) hydrological modelling domain and (d) RIVICE modelling domain

The Athabasca River originates in the Rocky Mountains of central Alberta (see Figure 3-1) and spans across the provinces of Alberta and north-west Saskatchewan to drain over 150,000 km² of land area. The river initially flows through the mountainous and forested landscape of Jasper National Park and onwards through Brule Lake and Jasper Lake, into rolling foothills and onwards to Lake Athabasca (Peters et al., 2013). From Lake Athabasca, water flows northward via the Slave River to Great Slave Lake, the Mackenzie River, and the Arctic Ocean (NRBS, 2002). The river

is 1538 km long and the elevation ranges from 3747m at its origin at Mount Columbia to 187m at its terminal point at Lake Athabasca (Peters & Prowse, 2006).

The study area has a continental climate with significant seasonal variations. From 1981–2010, the meteorological station “Fort McMurray A” has a daily mean temperature that drops below freezing from the middle of October to early April, with an average January temperature of -17.4°C . The average temperature in July is 17.1°C . Annual precipitation for the same period averages around 400 mm of which roughly 75% occurred as rain. The hydrological regime of the ARB is characterized by low flows in the winter months and a rising hydrograph starting in late April and May and peaking, generally, in June. The flow gradually declines to winter flow conditions in December (Burn et al., 2004).

The town of Fort McMurray (TFM) lies at the confluence of the Athabasca and Clearwater rivers (see Figure 3-1). As the Athabasca river flows north past the town, the changes in river morphology at the TFM makes the river more conducive to ice jam flooding (Lindenschmidt, 2017c). At the TFM, the bed slope of the river reach decreases from approximately 0.0010 to 0.0003. In addition, the river width widens (from approximately 300 to 700 m) and numerous islands and bars are present which provide obstacles to ice floes (Andrishak & Hicks, 2011; She, 2008). The presence of several tributaries including Clearwater, Horse and Hangingstone rivers in this reach provide additional sources of water and ice which can exacerbate an already hazardous ice flood situation along the Athabasca River (Das et al., 2017).

3.4 Data and Methods

3.4.1 Flow and water level data

The discharge data were retrieved from the Water Survey of Canada (WSC) through Environment and Climate Change Canada’s Hydat database (<https://ec.gc.ca/rhc-wsc/default.asp?lang=En&n=9018B5EC-1>). The data are available at a daily time-step. The water level data were available from the WSC regional office in Alberta. While the data for ice covers breakup are available from 1958, the data for freeze-up is available only from 1961 due to some missing values. Some breakup water levels were obtained from Sun and Trevor (2018).

3.4.2 Freeze-up and breakup dates

Freeze-up is conceptually defined as ‘the time at which a continuous and immobile ice cover forms’ (IPCC, 2007). Breakups occur in spring when increasing temperature disintegrates the ice cover or increased flow dislodges it (Beltaos, 1997). WSC provides a ‘B’ flags along with hydrometric data which indicates ice induced ‘backwater’ effect due to the presence of ice at or immediately downstream of the gauge in the river. Thus, the discharge with the first ‘B’ flag indicates the beginning of the freeze-up of the river whereas the last ‘B’ flag is indicative of the end of the ice cover season. In our study, the freeze-up date is considered as the day with the highest water level within ± 3 days of the first ‘B’ flag and the breakup was assumed to be the date of the greatest water depth in which there was an increase prior, and decrease after, within a few days of the last instance of “B” flag being present (Lindenschmidt, 2017a). The ‘B’ flag was further assessed to ensure that backwater conditions resulted from known ice timing effects and not from log-jam or beaver-dam effects (Monk et al., 2012; Peters et al., 2014).

3.4.3 Trend analysis

A non-parametric Mann-Kendall (MK) trend test (Mann, 1945) was used to detect trends in historical records of discharge, precipitation and temperature at multiple stations. The MK test is a widely-used methodology and can be more robust than other methods for skewed environmental data. However, autocorrelations of time series can inflate the statistical significance (i.e. p-value) of the MK test and its parametric counterparts (Von Storch, 1999; Yue et al., 2002). Usually, the first order autocorrelation (AR(1)) is removed (Yue et al., 2002). The assessment of serial autocorrelations in the datasets showed only freeze-up stage and freeze-up flow, have a significant first order autocorrelation (see Figure C-1). Nevertheless, for the consistency in data processing and analyses, first order autocorrelation was removed for all hydro-climatic datasets using method suggested by Zhang et al. (2000) from the time series prior to the trend analysis. In this analysis, the null hypothesis (H_0) was assumed as no trend (p-value > 0.05), which was tested against the alternative hypothesis H_1 of increasing or decreasing trends. However, caution should be taken in applying prewhitening in time series analysis. Prewhitening can distort or remove the structure of variability across time scales (Razavi & Vogel, 2018) leading to potentially inaccurate assessments of the significance of a trend (Yue et al., 2002) and reducing the likelihood of accepting the null hypothesis when it may be false (Yue & Wang, 2002).

3.4.4 River Ice Modelling

RIVICE

RIVICE is a one-dimensional hydrodynamic model developed by Environment and Climate Change Canada (ECCC, 2013; Lindenschmidt, 2017b), which uses an implicit finite-difference numerical method to simulate river ice processes and phenomena such as ice generation, ice transport, ice cover formation, hanging dam development and ice jam progression along the river (Lindenschmidt et al., 2015). It simulates ice-jams by coupling ice dynamics with river hydraulics as outputs from meteorological and river bathymetrical input parameters (Lindenschmidt & Chun, 2013). The fundamental premise of the model structure is the loose coupling between the hydraulic and river ice computations, in which data are exchanged frequently, after every time step, to retain model accuracy without increasing the computational burden. Under conditions of very rapid ice cover formation, the time-step varies from seconds to a few minutes to best capture these rapidly changing events (Lindenschmidt et al., 2016). Further details on model structure, setup and calibration can be found in the literature for various Canadian rivers: the Peace River in Alberta (Lindenschmidt et al., 2015; Lindenschmidt et al., 2016), the Qu'Appelle River in Saskatchewan (Lindenschmidt & Davies, 2014; Lindenschmidt & Sereda, 2014), the Red River in Manitoba (Lindenschmidt et al., 2012b) and the Dauphin River in Manitoba (Lindenschmidt et al., 2012a).

RIVICE Calibration

Fort McMurray sustained extreme ice-jam flooding in the late 1970s with consecutive flooding in 1977, 1978 and 1979. These events have been well documented and reported (see Andres and Doyle (1984); Doyle (1977)) and thus, were used for model calibration and validation. First, the model was calibrated for open-water and ice cover formation for the 1979 ice-jam flood event. It was then validated against the 1977 event. The ice-jam events were chosen based on the availability of water level and other hydrometric data (see Lindenschmidt (2017a, 2017b, 2017c)) and thus were used for model calibration and validation.

The initial calibration was performed using a trial-and-error approach to provide direction in selecting the optimum ranges of parameter values for the Monte Carlo (MOCA) simulations. Based on previous studies such as Lindenschmidt et al. (2015); Lindenschmidt and Sereda (2014); Lindenschmidt et al. (2016) and recent global sensitivity analysis of RIVICE parameters by

Sheikholeslami et al. (2017), 13 parameters were calibrated, which included slush ice and ice cover characteristics, hydraulic roughness, ice strength properties and boundary conditions (see Table B-1 for full list of parameters and their ranges).

One thousand random model parameter sets were sampled from uniform and Gumbel (Thompson, 1999) probability distributions for further MOCA based river ice analyses. When data were available to construct their probability distribution functions (pdfs) such as discharge and water level, the Gumbel function was used but when *a priori* knowledge on pdf shape was not available, a uniform pdf was used. This method is discussed in detail in Lindenschmidt (2017a, 2017b, 2017c).

3.4.5 Hydrological Modelling

MESH

MESH (Modélisation Environnementale–Surface et Hydrologie) is a semi-distributed physically based land surface-hydrological modeling system developed by Environment and Climate Change Canada for hydrological applications (Pietroniro et al., 2007). It uses the Canadian Land Surface Scheme (CLASS) for vertical exchanges and generation of lateral fluxes of energy and water balance for vegetation, soil and snow, and the WATFLOOD for flow routing (Haghnegahdar et al., 2014). It also uses the Group Response Unit (GRU) approach, i.e. combining areas of similar hydrological behavior, to address the complexity and heterogeneity in the drainage basin for computational efficiency (Kouwen et al., 1993). This is a more suitable approach for large scale drainage basins due to its operational simplicity while retaining the basic physics and behavior of a distributed model (Pietroniro & Soulis, 2003).

Input data and model setup

A hydrological model using MESH was set up for the ARB, with the outlet of the basin delineated at the streamflow station ‘Athabasca River below McMurray’ (07DA001, see Figure 1). The drainage database was prepared using GreenKenue, an advanced data preparation, analysis, and visualization tool (http://www.nrc-cnrc.gc.ca/eng/solutions/advisory/green_kenue_index.html). The digital elevation model (at spatial resolution of 30m) was downloaded from Geogratis (<http://geogratis.gc.ca/>), land use data from GeoBase

(<http://www.geobase.ca/geobase/en/data/landcover/index.html>) and soil data from Agriculture and Agri-Food Canada (<http://sis.agr.gc.ca/cansis/nsdb/slc/v3.2/index.html>).

Meteorological forcing data

The meteorological forcing input data for hydrological simulations were retrieved from the North American Regional Climate Change Assessment Program (NARCCAP) (Mearns et al., 2012; Mearns et al., 2009). NARCCAP consists of simulations from six Regional Climate Models over consistent periods (1971-2000 and 2041-2070) and spatial domains of equal resolution (~50 km) (Weller et al., 2013). It uses the A2 emission scenario, since it was one of the ‘marker’ scenarios developed by the Intergovernmental Panel on Climate Change (Nakicenovic et al., 2000). This 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).

NARCCAP data were selected due to their higher temporal resolution (3-hourly), which is essential for MESH as it runs at 30 minutes’ time steps. Unlike many hydrological models, MESH performs both water and energy balances and requires seven forcing files (i.e. precipitation, humidity, wind, pressure, temperature, incoming longwave radiation and shortwave radiation) which are all available from the NARCCAP. NARCCAP has different suites of Regional Climate Models (RCMs), each driven by two different Atmosphere-Ocean General Circulation Models and one reanalysis, NCEP/DOE AMIP-II Reanalysis (NCEP), a retrospective model of the atmosphere based on observed data. Among six available RCMs, the Canadian Regional Climate Model (CRCM) (Caya & Laprise, 1999), driven by the Community Climate System Model (CCSM) and the Third Generation Coupled Climate Model (CGCM3) was chosen for this study to simulate future conditions which Mearns et al. (2012) found to perform reasonably well compared to other RCMs. Figure 3-3 shows average daily air temperature comparison between different RCMs+GCMs for 2041-2070 period for Fort McMurray. It shows that CRCM+CCSM and CRCM+CGCM3 to be comparatively closer to the median of all models.

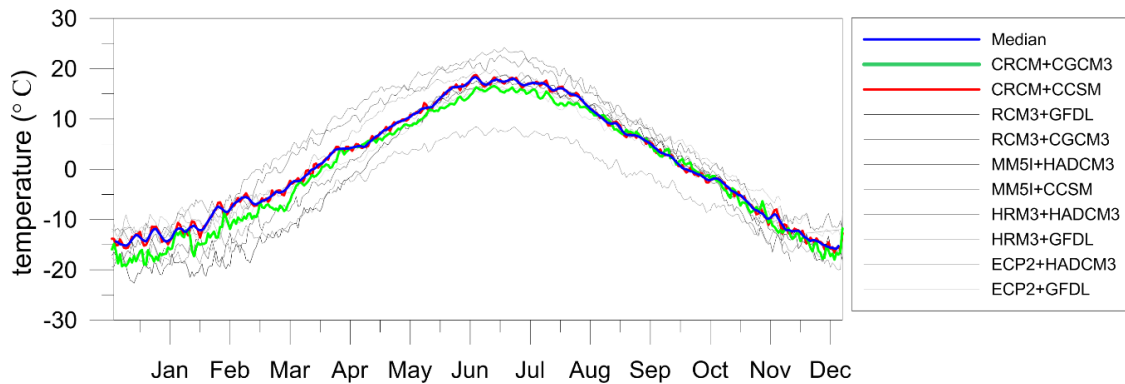


Figure 3-2: Average daily temperature for 2041-2070 period among different RCMs+GCMs compared at Fort McMurray

MESH Calibration

Calibration was carried out using the parallel version of the Dynamically Dimensioned Search (DDS) algorithm (Tolson & Shoemaker, 2007) using a multi-algorithm auto-calibration program, OSTRICH (Matott, 2005). DDS has the advantage over other widely used optimization algorithms (e.g. SCE) in hydrology of not requiring internal parameter tuning, and the search strategy is scaled per the specified maximum number of model iterations. It is referred to as a ‘greedy algorithm’, since it does not update the best solution achieved unless a better objective function is obtained from another solution (Tolson & Shoemaker, 2007). The log of Nash and Sutcliffe efficiency ($\log(NS)$) was used as an objective function. Initial conditions were randomly perturbed for each model run within the range specified for the individual variables. This prevents the model from becoming trapped in local minima and enables objective function optimization using the entire search space.

The meteorological forcing data, CRCM+NCEP from 1983 to 2000 were used in model calibration and validation. The model was first calibrated from 1992–2000 and then validated from 1983–1991. Shrestha et al. (2016) suggested calibrating hydrological models for more recent years due to comparatively higher uncertainty in observed data in early decades. Six parameters from each four major GRUs (forest, grass, wetland and cropland), representing exchange of energy and water balance between land surface and atmosphere, and four parameters from flow routing were calibrated. Ten optimal sets of parameters were generated based on the objective function of $\log(NS)$ which ranged from 0.71 – 0.74. Then the parameter set that also performed reasonably

well in other performance metrics ($NS > 0.7$, $R^2 > 0.7$, bias $< 10\%$) was selected for the model validation. To assess the future implications of a changing climate on streamflow and river ice processes, the calibrated and validated model was run for the 2041–2070 period using the CRCM+CCSM and CRCM+CGCM3.

3.5 Results and Discussion

3.5.1 Ice Phenology in the Athabasca River

Ice-affected stages and open-water rating curve

An open-water rating curve was established for Fort McMurray from a 50-year time series (1961–2010) of daily discharge and water level data. The open-water data are well documented and available for all the studied years. However, ice-induced instantaneous maximum water levels and associated discharge data during peak ice-jam breakup periods were available for only 32 out of the 50 years. Figure 3-3 shows that ice-jam conditions can lead to significantly higher water levels compared to the open-water period despite having comparatively smaller river discharges. It can also be observed that freeze-up usually occurs below a river water level elevation of 239 m.a.s.l.

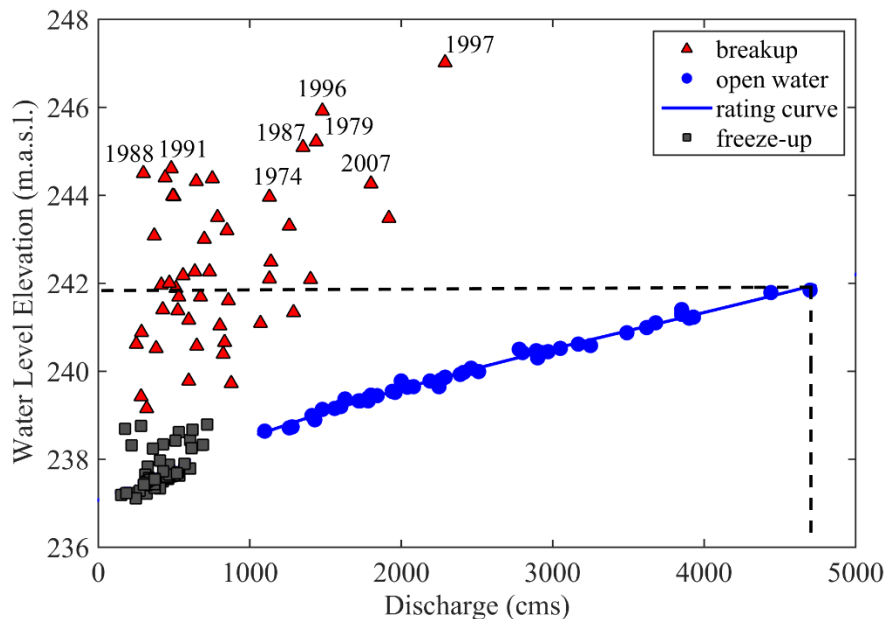


Figure 3-3: Open-water rating curve for 1961-2012 period. The red triangles denote ice-induced instantaneous maximum water level whereas blue circle represent open-water and black squares symbolise freeze-up stage.

Trends in freeze-up

The analysis of historical flow and water level data shows that there has been a shift in freeze-up timing. The results show that in earlier decades (i.e. 1960s and 1970s), freeze-up generally occurred during the first two weeks of November whereas in latter decades (1980s–2000s) an earlier shift towards the last two weeks of October has occurred (Figure 3-4b). Trends analysis showed a statistically significant decreasing rate of -0.17 day/year ($p = 0.037$). Similar results of early freeze-up in many Canadian rivers were also observed by Zhang et al. (2001). This early freeze-up might be associated with atmospheric and hydrologic conditions since, from an energy balance perspective, the rate of autumn water-to-atmosphere cooling and the summer heat budget govern initial ice development and subsequent freezing (Prowse, 1995). Ginzburg (1992) also found strong correlations ($r^2=0.6-0.7$) between freeze-up date and mean air temperature of the preceding autumn.

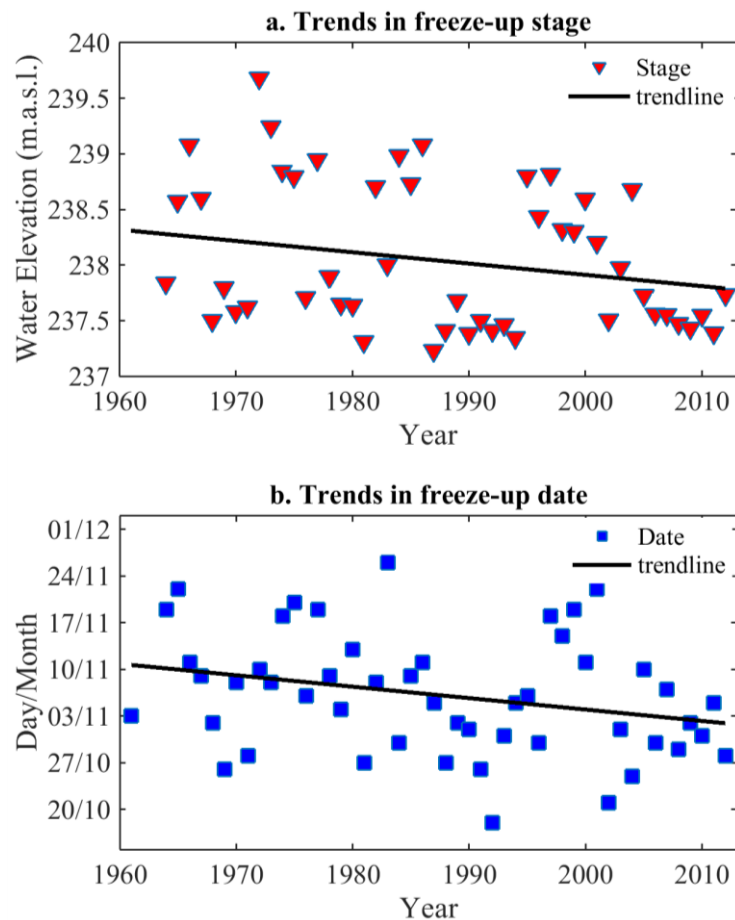


Figure 3-4: Freeze-up trends in the Athabasca River at Fort McMurray for the last five decades:
(a) trends in freeze-up stage and (b) trends in freeze-up date

Not only early freeze-up but also decreasing trend in freeze-up stage was observed at the gauging station in the TFM. A decreasing trend of -1.20 cm/year ($p = 0.10$) was determined. The 1970s was a comparatively high flows decade, which resulted in higher freeze-up levels and since then freeze-up levels have been in decline. This is also partly explained by the decreasing patterns in temperature and flows as Prowse et al. (2007) states, a colder climate and reduced flow result in earlier freeze-up whereas warmer climate and increased flow lead delayed freeze-up. The trends for average monthly temperature and average monthly flow for October for the last 52 years (1961–2012), as observed at the meteorological station, Fort McMurray A (see Figure 3-1d) and river gauge station, Athabasca River below McMurray (see Figure 3-1d) show a gradual decline in both average air temperature (at a rate of -0.038 °C/year) and streamflow (at a rate of -5.16 m³/s/year), respectively. Trend analyses showed statistically significant trend at the 5% significance level for the discharge ($p = 0.006$) but not for the temperature ($p = 0.08$). Interestingly, while the trend at an annual or a decadal interval for air temperature is increasing, air temperature during freeze-up months decreased in recent decades.

Trends in breakup

Similar to freeze-up, key climatic and hydrologic conditions influence the timing and severity of river ice breakup (Vuglinsky, 2002). The breakup event can either be mechanical or thermal, depending on the hydro-meteorological conditions. Mechanical breakup occurs when there is sufficient runoff ‘to lift and dislodge the ice cover while it retains a sizeable portion of its mechanical strength’ (Beltaos, 2003b). Mechanical breakup can result in large-scale ice-jam flooding due to the severity of the event, while thermal events lead to comparatively smaller staging. During thermal events, the ice slowly deteriorates in place and eventually disintegrates under modest current. Thermal events are associated with low runoff due to the gradual snow melt and absence of rain (Beltaos, 2003a, 2014; Beltaos & Carter, 2009).

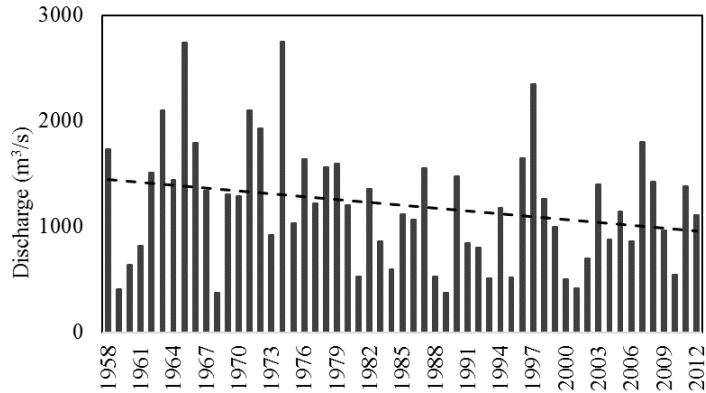


Figure 3-5: Daily maximum flow during the breakup period at the station “Athabasca River below McMurray”.

In the Athabasca River, breakup dates usually range from mid-April to mid-May, with more than 95% of breakup events occurring in this period between 1958-2012. The breakup was assumed to be the date of the greatest water depth in which there was an increase prior, and decrease after, within a few days of the last instance of “B” being present (Lindenschmidt, 2017a). The statistical analyses of breakup dates show no signs of early breakup or any change in breakup dates. However, declines in average monthly flows in April and May for the period 1958 - 2012 were observed. For instance, the average monthly flow in April and May at the gauging station, “Athabasca River below McMurray” at the TFM were at a decreasing rate of $-1.91 \text{ m}^3/\text{s}/\text{year}$ and $-6.98 \text{ m}^3/\text{s}/\text{year}$, respectively. However, at the 5% significance level, the trends were not statistically significant. Figure 3-5 shows the daily maximum flow during the breakup period at the gauging station in the TFM which is also in decreasing trend at a rate of $-3.73 \text{ m}^3/\text{s}/\text{year}$. This decreasing pattern can reduce the likelihood of dynamic breakup and ice-jam flooding event, as higher spring flows are required for dynamic breakup and subsequent flooding events (Prowse et al., 2007).

3.5.2 River Ice Modelling

Model Performance

The modelling domain extends 40 km along the Athabasca River from Mountain Rapids to near Shipyard Lake. This part of the river is characterized by the series of rapids and numerous sand bars and islands. The width of river varies between 300 and 700 m with slopes of approximately 0.0010 and 0.0003 in the upper and lower reaches, respectively. The TFM lies at the confluence

of the Athabasca and Clearwater rivers. As the model domain extends downstream from a very steep section with many rapids, a large supply of rubble ice is generated in this reach when the ice covers break up.

The model was first calibrated for the ice-jam flood event of 1979. The flow and water level boundary conditions were derived from the gauge data. The gauge reading showed 1480 m³/s but the upstream flow was estimated to range between 1300 and 1850m³/s. 1366 m³/s was used as the upstream discharge whereas the downstream water level was determined to be 235.5 m.a.s.l., based on freeze-up stage. The initial parameters values and ranges for slush ice and ice cover characteristics, hydraulic roughness and ice strength properties were estimated from the previous breakup studies at Fort McMurray (Andres & Doyle, 1984; Doyle, 1977) and elsewhere (Lindenschmidt et al., 2015; Lindenschmidt & Sereda, 2014; Lindenschmidt et al., 2012b; Lindenschmidt et al., 2016). Figure 3-6a shows good agreement between the surveyed and simulated water level profiles. The red diamond shapes show observed ice-induced water levels, which is in good agreement with the simulated ice cover.

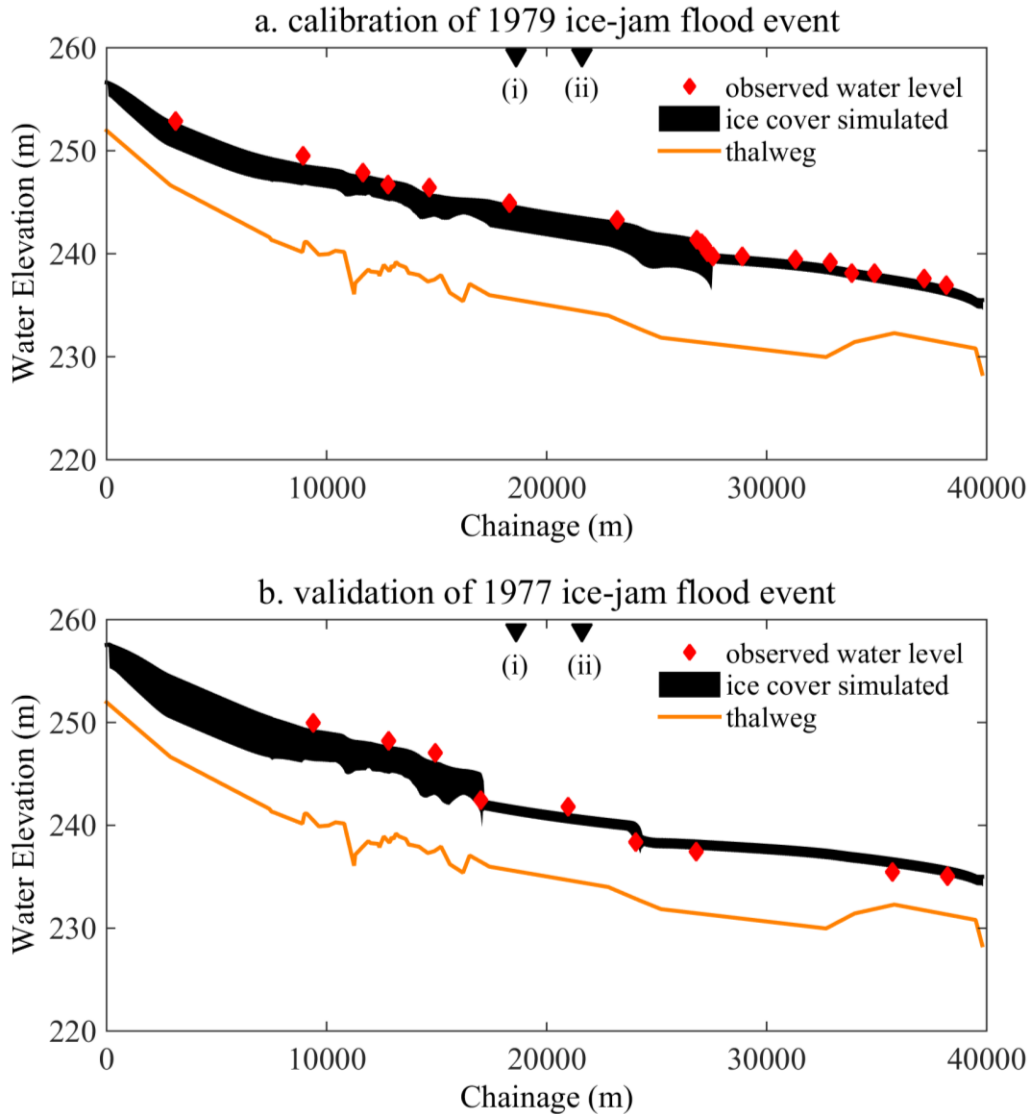


Figure 3-6: Longitudinal profiles of simulated and observed water levels along the Athabasca River from Mountain Rapids to near Shipyard Lake: (a) calibration of 1979 ice-jam flood event and (b) validation of 1977 ice-jam flood event. At the figures' top, indicated locations are: (i) Clearwater River confluence and (ii) WSC station, Athabasca River below McMurray

The model was then validated using data from the 1977 ice-jam flood event. A $934 \text{ m}^3/\text{s}$ flow was recorded at the gauge but Andres and Doyle (1984) estimated a discharge in a range of $1135\text{--}1600 \text{ m}^3/\text{s}$. For this study, a discharge of $1000 \text{ m}^3/\text{s}$ was used as an upstream boundary condition, whereas a water level elevation of 235 m.a.s.l. was used as the downstream boundary condition, based on freeze-up stage. The ice cover simulation results correspond well with the ice-induced water level observations (see Figure 3-6b).

Monte Carlo Simulations

After calibrating and validating the RIVICE model for the Athabasca River, 1000 ensembles of water level profiles were simulated within a MOCA framework embedded in Model-Independent Parameter Estimation (PEST), an industry standard software package for parameter estimation and uncertainty analysis of complex environmental and other computer models (Doherty, 1994). Besides the model parameters such as ice roughness, river bed roughness, porosity of slush, thickness of slush pans, porosity of ice cover, thickness of ice cover front, longitudinal and vertical stresses, four major boundary conditions (i.e. upstream discharge, downstream water level, incoming ice volume and the location of the toe of the ice jam) significantly influence the formation and morphology of ice jams along the Athabasca River. Thus, for MOCA simulations, appropriate probability distributions for both model parameters and boundary conditions were selected to generate random numbers from uniform or Gumbel distributions. The lower and upper bounds for the model parameters were selected from the literature and through the calibration and validation process of the RIVICE model (see Table B-1). Gumbel distributions were used to generate random values for the upstream discharges for both the Athabasca and Clearwater rivers. Uniform distributions were considered for downstream water level and the location of the toe of the ice jam as *a priori* knowledge on pdf shape was not available.

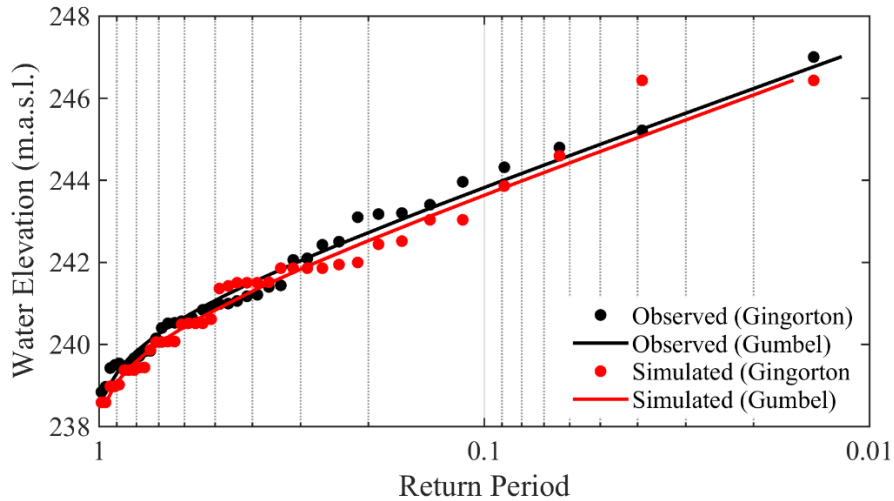


Figure 3-7: Simulated and observed ice jam stage frequency distributions (Gumbel) with plotting positions (Gringorton) for the gauge at Fort McMurray

The incoming ice volume was calibrated against the maximum instantaneous ice jam stage frequency curve within the framework of a MOCA analysis. This method of using stage-frequency distribution for calibration is discussed in detail by Lindenschmidt (2017c). Using mean and standard deviation to derive location and scale parameters, a Gumbel distribution of ice volume was generated until the resulting simulated ice jam stage frequency matched the stage frequency curve of the recorded water levels at the gauging station. Figure 3-7 shows the median of simulated stage-frequency distribution and observed stage frequency distribution.

Probability of overbank flow

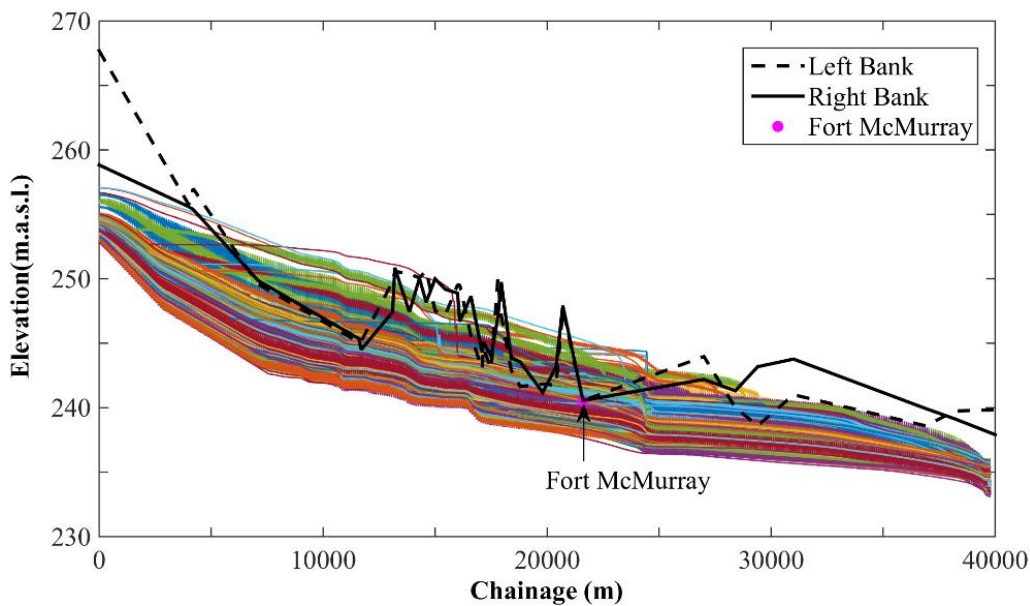


Figure 3-8: Longitudinal profiles of 1000 simulated water levels along the Athabasca River (different coloured lines show the ensemble)

Of the 1000 random ice-jam simulations, 389 cases of overbank flows were simulated when the water level profile was higher than any point along the river bank profile for Fort McMurray, as shown in Figure 3-8 (Fort McMurray is at chainage 21600). Then the distribution of the upstream discharge was analyzed to determine the magnitude of discharge required to result in overbank flow. The probability distribution (Figure 3-9) shows that at different discharge magnitudes, different probabilities of overbank flow can be expected. For a 50 percent probability of overbank flooding, the results show that a discharge of >1000 m³/s is required. As discharge increases, the probability further increases, leading to higher chances of overbank flow. However, it is to be

noted that it is not a probability of an ice jam occurring in any one year. It is the probability of backwater level elevations which can also result from under-developed ice jams or covers from remnants of fragmented ice, which also induce backwater staging.

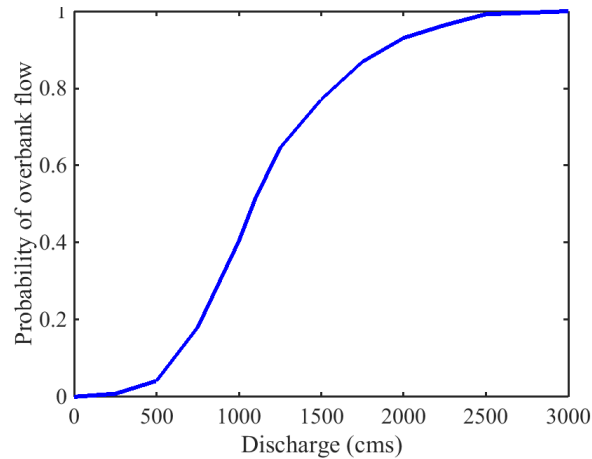


Figure 3-9: Probability of overbank flow of the river at different discharges.

A similar study was carried out for the Peace River by Beltaos (2003a), using trial and error to establish a discharge of 4000 m³/s as a minimum threshold flow for ice-jam flooding. Our method is an extension since it does not rely on a single trial and error simulation, but on an ensemble of possible ice-jam flooding scenarios from which the probabilities of potential ice-jam flooding discharge can be drawn. The finding is also in line with previous observed ice-jam flooding events in the ARB. During the 1957-2012 period, there were 14 cases of ice-jam flooding recorded and the event with the lowest daily discharge occurred in 1990, when the maximum daily discharge was 1480 m³/s. However, it is also apparent from Figure 3-5 that peak daily discharges show a decreasing trend for the spring breakup season.

3.5.3 Hydrological Modeling of the ARB

Performance of MESH Model

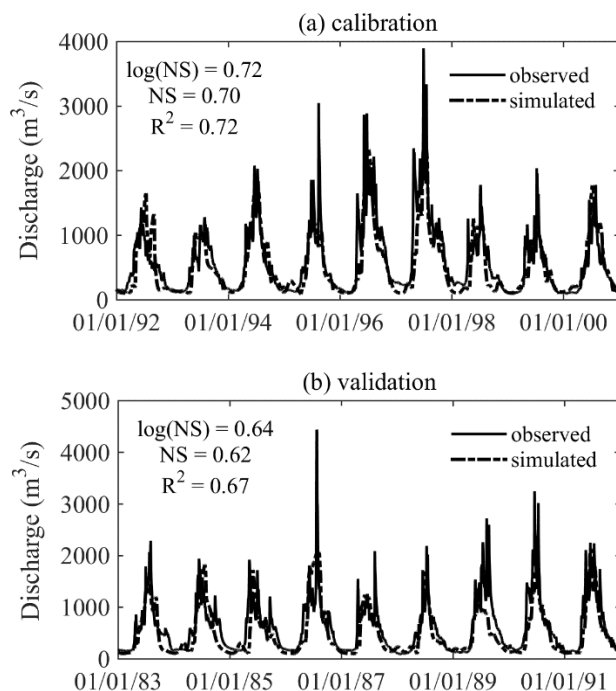


Figure 3-10: Daily observed and simulated discharge at the gauge ‘Athabasca River below McMurray’ for the calibration and the validation periods.

Figure 3-10 shows the results from the calibration and validation at daily scale. Log(NS) of 0.72, NS of 0.70 and R^2 of 0.72 were achieved for the calibration whereas log(NS) of 0.64, NS of 0.62 and R^2 of 0.67 were obtained for the validation years. The model performance was also compared for the months of October and April month when the majority of freeze-up and breakup occurs. The statistical analysis showed R^2 of 0.52 for October and 0.30 for April. The average performance of the model can be attributed to two different sources of uncertainties. The average performance of the model can be attributed to two different sources of uncertainties. Firstly, the ARB is characterized by both climatic diverseness and spatial variability in the hydrologic processes, due to its dominant physiographic heterogeneity (Eum et al., 2014a). Modelling large scale northern basins still remains a great challenge due to limited data, over-parameterization of the models, complexity of snow processes that are difficult to capture numerically and due to the intricate interactions between atmosphere and land surfaces (Paz & Collischonn, 2007; Spence, 2010). Previous studies in the ARB have also only been able to achieve satisfactory results. Leong and Donner (2015) reported a NS of 0.35 over an entire 30-year time period (1981-2010) with the best results achieved in the 1991-2000 decade (NS 0.72) and the most underestimated in the following

2001-2010 decade (NS -0.68), using the land surface process model Integrated BIOSphere Simulator (IBIS), which is similar to MESH. Eum et al. (2014a); Eum et al. (2014b) were able to achieve NS values from 0.61-0.87 (during the calibration period of 1983-1988) and 0.56-0.82 (during the validation period of 1989-2010) at a monthly scale across different stations in the ARB, using high-resolution gridded climate datasets with the distributed and process-based hydrologic model, Variable Infiltration Capacity (VIC). However, on a monthly time scale, errors are averaged out by removing spikes, which results in improved statistical performance. Similarly, good agreement (NS of 0.72) was reported by Toth et al. (2006), but only on a monthly time scale, using the distributed hydrological model WATFLOOD and station-observed meteorological data. Other studies in the ARB such as Pietroniro et al. (2006) have also presented their results using monthly averages.

Secondly, some processes and their interactions, such as land cover changes and human interventions, are not adequately represented in some physically-based models (DeBeer et al., 2016). The Alberta oil sands, the third largest crude oil reserve in the world, also uses water from the Athabasca River, which is presently allocated at 4.4% of the mean annual flow (Sauchyn et al., 2015). This study did not consider this industrial water withdrawal, which may have some consequences on river ice processes and downstream ecology. For instance, Andrishak and Hicks (2011) found that industrial water withdrawal had some impacts on winter flow affecting fish habitat in the downstream Fletcher Channel. Nevertheless, unlike previous hydrological studies in the ARB, this study simulated historical and future conditions using a physically-based land-surface hydrological model at a very high temporal resolution using 3-hourly meteorological forcing data, accounting both energy and water balances.

Likelihood of IJFs in future

Figure 10 shows that compared to the historical baseline period, winter flows are expected to be higher, especially between December to January. Flows in late spring, especially in May are projected to decrease. This is expected for two reasons. First, increase in rainfall events and decrease in snowfall events in Athabasca watershed is anticipated due to warming climate (Dibike et al., 2018a). Second, more snowmelt runoff will occur in winter depleting snow cover available on the ground to be melted in late spring months of April and May (Dibike et al., 2018b). A study by Leong and Donner (2015) in the ARB also found that, though winter flows might increase,

spring/summer flows will significantly decrease in the future. A study by Erler et al. (2015) using dynamically downscaled climate projections also suggested similar results. Spring flows are driven by snowmelt and a recently study by Dibike et al. (2018b) reported that snow water equivalent might decrease up to 50% in March and April by the end of the century.

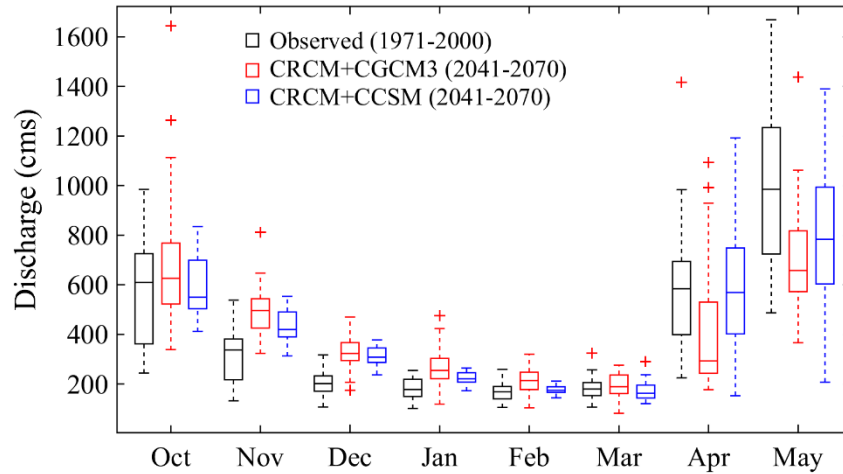


Figure 3-11: Average monthly historical flows (1971–2000 period) and the model simulation of future flows (2041-2070). The box plots illustrate the median and inter-quartile range and the upper and lower limits of the whiskers from two different GCMs.

A study by Das et al. (2017) using the cumulative degree days of melting and cumulative degree days of freezing approaches on future meteorological data from NARCCAP found that the average freeze-up in future will begin from the third week of October and average breakup will occur in April for the TFM. Since, our results suggest flows for April will be lower compared to historical flows, the probability of IJFs may be lower in the future. However, caution is needed in interpreting these results. Mechanical breakup events that lead to severe IJFs are driven by peak daily flows and though average monthly flow is projected to be lesser, extreme daily flow events are still probable. Thus, though probability of IJFs in general is expected to be lower, extreme IJF events including mid-winter breakups (Beltaos, 2002) can still occur under favorable hydro-meteorological conditions. A follow-up paper (Das et al., submitted) assess the future daily breakup flows and applies a hydraulic model for future risk assessment and hazard mapping that can assist in making proper land use plans and designing risk-based hydraulic structures and other mitigations measures for the TFM.

3.6 Conclusion

The study demonstrates significant hydro-climatic variability in the Athabasca River, which have implications for river ice processes. The reduced ice-jam flooding events in recent decades, especially since 1980 is associated with changing patterns in precipitation, temperature and discharge, among others. While there are decreasing patterns in precipitation and river flow across the basin, temperature has significantly increased. However, some months in the beginning of river freeze-up period show decreasing trend in air temperature with shifts towards early freeze-up. This study also developed a probability curve of overbank flow based on breakup discharge. Using a stochastic approach to evaluate the impacts of different magnitudes of discharge on ice-jam flooding is a novel approach, and may serve as an important benchmark for future IJF studies, especially for estimating future IJF probabilities. The simulation of a future period shows that the likelihood of ice-jam flooding in the future will be lower but extreme IJF events are still probable.

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3.8 Author contributions

PR and KEL conceived the rationale for the study. PR carried out setup of hydrologic model and KEL setup hydraulic model. PR performed simulations of both hydrologic and hydraulic models as well as other data analysis and interpretation. LM did trend analysis. PR wrote the paper. KEL, LM and HW commented on the manuscript and contributed to the text in later iterations.

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3.10 Appendices

Appendix A Introduction

Table A-1: Ice-jam floods in the ARB

Year	Description	Source
1875	Very large ice-jam flood at Fort McMurray	Alberta Environmental Protection (1993)
1876	Athabasca estuary submerged	Peters (2003)
1881	Ice-jam flood Fort McMurray	Alberta Environmental Protection (1993)
1885	Ice-jam flood Fort McMurray	Alberta Environmental Protection (1993)
1900	High water damage at Athabasca Landing and Grand Rapid	Peters (2003)
1919	Ice-jam flood at Fort McMurray	Peters (2003)
1925	Ice Jam downstream of Embarras near Embarras River	Doyle (1977)
	Ice-jam flood Fort McMurray	Alberta Environmental Protection (1993)
1928	Ice-jam flood Fort McMurray	Alberta Environmental Protection (1993)
1936	Ice-jam flood Fort McMurray	Alberta Environmental Protection (1993)
1940	Ice-jam flood at Whitecourt	Alberta Environment and Parks (2014)
1943	Ice-jam flood at Whitecourt	Alberta Environment and Parks (2014)
1948	Log jam at Embarras Portage flooded Snowbird Settlement 1m above bank	Peters (2003)
1949	Athabasca Delta spring nesting delayed by heavy floods	Peters (2003)
1958	Athabasca flooded from Ess bend, backwater rose 3m above bank at Embarras	Doyle (1977)
1960	Ice-jam flooding in the Athabasca	Thorpe (1986)
1962	Ice-jam flood from Athabasca River	Thorpe (1986)
	Ice-jam flood at Fort McMurray	Alberta Environmental Protection (1993)
1963	Ice-jam flood in Athabasca river, flood came overland from the Embarras River	Thorpe (1986)

	Ice-jam flood at Fort McMurray	Alberta Environmental Protection (1993)
1971	Floodwater in Athabasca	Bayrock and Root (1973)
	Ice-jam flood in April flooded Athabasca and breached west bank of Embarras River	PAD-PG (1973)
1972	April ice-jam floodwaters breaches the Embarras banks.	PAD-PG (1973)
	Ice-jam flood at Fort McMurray	Alberta Environment and Parks (2014)
1974	Ice-jam flood in Athabasca	Thorpe (1986)
1977	Ice-jam event in caused severe flooding in Fort McMurray	Hutchison and Hicks (2007)
1978	Ice-jam flood at Fort McMurray	Alberta Environment and Parks (2014)
1979	Ice-jam flood at Fort McMurray	Andres and Doyle (1984)
1986	Ice-jam flood at Fort McMurray	Alberta Environment and Parks (2014)
1990	May 1-5 ice-jam in Athabasca River	Peterson (1992)
1993	Ice-jam flood at Fort McMurray	Alberta Environment and Parks (2014)
1996	Ice-jam flood in late April-early May in Athabasca	Peters (2003)
1997	Significant flood occurred in Fort McMurray	Hutchison and Hicks (2007)

Appendix B River Ice modelling

Table B-1: Parameter ranges used in RIVICE for Monte Carlo Simulations

Parameters/ boundary conditions	Description	Units	Lower bound	Upper bound
<i>Parameters</i>				
PS	Porosity of slush	-	0.3	0.7
ST	Thickness of slush pans	m	0.1	0.3
PC	Porosity of ice cover	-	0.4	0.7
FT	Thickness of ice cover front	m	0.15	0.3

η_{ice}	Ice roughness	$s/m^{1/3}$	0.025	0.035
η_{bed}	River bed roughness	$s/m^{1/3}$	0.020	0.030
K1TAN	Lateral: longitudinal stresses	-	0.11	0.22
K2	Longitudinal: vertical stresses	-	7	10
<i>Boundary conditions</i>				
Qa	Upstream Discharge of Athabasca River	m^3/s	806.7 ^a	508.5 ^b
Qc	Discharge from Clearwater River	m^3/s	252.8 ^a	125.7 ^b
Wds	Downstream water level	m.a.s.l.	233	236
X	Location of the toe of the ice jam	Chainage (m)	15000	30000
V_{ice}	Incoming ice volume	$m^3 / \Delta t$	2050 ^a	417 ^b

^a denotes location for Gumbel pdf

^b denotes scale for Gumbel pdf

Appendix C Autocorrelation

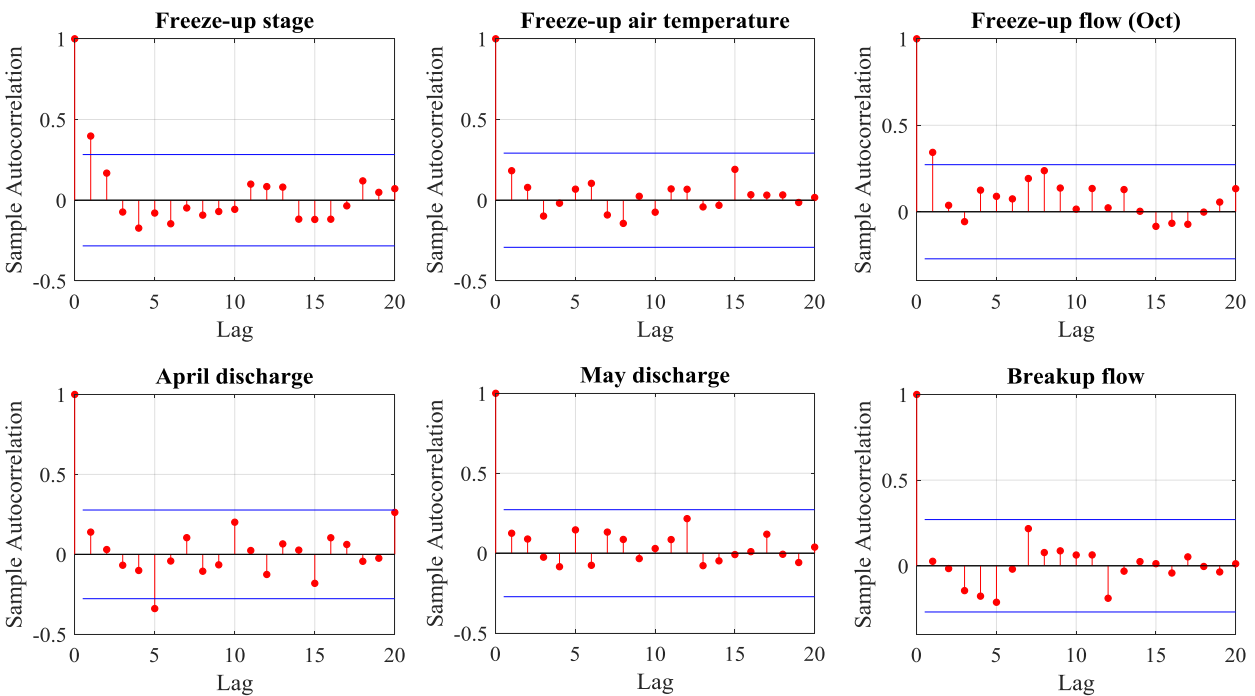


Figure C-1: Autocorrelation in trends analyses data

CHAPTER 4

EFFECTS OF CLIMATE AND REGULATION ON SPRING ICE-JAM FLOODING

Status: Submitted November 2017. Under Review.

Rokaya, P., Wheater, H., Lindenschmidt, K-E. (2018), Effects of regulation and climate change on ice-jam flooding, *Water Resources Research*, in review

4.1 Abstract

In cold region environments, ice-jam floods (IJF) pose a significant risk to local communities, economies and ecosystems. Previous studies have shown that the river flow regime plays a significant role in IJF probabilities. However, flow regimes in rivers are changing with changing climate and economic development resulting in diverse implications. Both climate and regulation are known to influence IJF probabilities but their relative impacts are poorly understood. This study presents a probability-based extension of the hydro-technical modelling approach that couples physically-based hydrologic and hydraulic models to assess the relative impacts of climate variability and regulation within a stochastic framework. This framework is evaluated at an IJF prone town on the Peace River in western Canada which has been regulated since 1968. Naturalized flows were generated for comparison, and using discharge-frequency and stage-frequency analyses, relative impacts of climate and regulation are quantified. Our results show flood risk probabilities would have been lower at the town of Peace River under natural conditions compared to present regulated conditions.

4.2 Introduction

The flow regime of a river shapes the structure and functions of river floodplains and deltas (English, 1984), and maintains its ecological integrity, sustaining a range of native biodiversity (Poff et al., 1997). Not only the volume of the flow but also flow variability, rates of flow change,

and magnitude of high and low flows are important (Pettit et al., 2001). Any flow alterations can not only impact geo-morphological processes, but also pose serious threats to evolution and conservation as some aquatic and riparian species might not be able to adapt in the new regime (Lytle & Poff, 2004). However, the new hydrological reality is that half of world's rivers have dams that have significantly modified river flow regimes and continue to do so. On average, two dams were built each day during the latter half of the 20th century (WCD, Nilsson et al., 2005; 2000). In the United States, Canada, Europe, and the countries of the former Soviet Union, 77 percent of the 139 largest river systems are strongly or moderately affected by regulation (Dynesius & Nilsson, 1994). River flows in a regulated river are primarily driven by human demands for hydropower, irrigation or municipal and industrial needs (Jasek et al., 2007; Oventhompson et al., 1982; Vörösmarty et al., 2000).

In cold region environments, river flow regimes are also associated with river ice processes. As one of the major components of the cryosphere, seasonal effects of river ice are observed in almost 60% of rivers in the northern hemisphere (Prowse et al., 2007). Whether stationary or moving, river ice interacts with river flow in many different ways, resulting in diverse implications on communities, economies, and ecosystems (Beltaos, 2000). A stable ice cover can cause additional resistance and reduce flow velocities (Beltaos & Prowse, 2009) whereas if ice freezes to the bed, groundwater flows can be blocked in some channel systems (Beltaos & Burrell, 2003). Similarly, higher (lower) flows in the river can result in thicker (thinner) ice covers whereas ice-jamming can result in higher water depths than open water conditions (Lindenschmidt et al., 2016). Thus, any shifts in river flow regimes will also affect river ice processes in cold regions (Beltaos, 2014). For example, after regulation began in the Peace River in western Canada, Conly and Prowse (1998) observed the alteration in the timing and duration of ice covers whereas Prowse and Conly (1998) noted changes in the strength and thickness of ice covers. Therefore, regulation can affect the nature of ice cover formation and breakup, ice growth, and severity of ice jams, as well as duration of ice covers (Beltaos & Prowse, 2009).

Ice-jam floods (IJFs) that occur during river ice breakup have significance for catchment ecology in some northern rivers and deltas such as the Peace-Athabasca Delta in Canada (Peters et al., 2006) and the Yukon Flats in the United States (Chen et al., 2014) but can also be devastating events for riverine communities. IJFs can cause extensive damage to buildings and properties and

even lead to injuries and mortalities (Lindenschmidt et al., 2016). As IJFs are known to result in two to three times greater water depths in rivers than open water floods under the same or lower discharge, they are more severe and disastrous (Prowse & Beltaos, 2002). Compared to open-water floods, IJFs are often sudden and difficult to anticipate which allows little time for the implementation of mitigation measures or even the evacuation of people (Beltaos & Prowse, 2001). The annual financial cost of river ice jams in North America is estimated to be about USD 300 million (French, 2018).

Though river ice jamming and IJFs are very irregular and complex phenomena, they are primarily governed by channel morphology, freeze-up conditions, ice characteristics, climatic factors, and spring flow (Andrishak & Hicks, 2008; Beltaos, 1997). Previous studies, such as those by Beltaos (2003), Beltaos et al. (2008), Beltaos and Carter (2009), and Beltaos (2014), have found that among other hydro-meteorological conditions, freeze-up stage and breakup flow play larger roles in ice-jam flooding. Thus, all the other factors being equal, the probability and magnitude of IJFs are higher if the freeze-up stage during ice cover formation is lower, and spring flow during ice cover breakup is higher (Beltaos, 1997; Beltaos, 1995).

In regulated rivers, natural flow regimes can be altered by dams, hydropower projects, and other flow control structures as well as flow diversion and water extraction (Huokuna et al., 2017). In hydropower reservoirs, larger than natural flows are released during the winter months (when energy demands are higher), and naturally occurring peak flows in spring and summer are dampened (when energy demands are lower). Due to high flows and relatively warmer water coming from a reservoir, ice covers in winter are nonexistent immediately downstream of the dam. The length of the open water reach depends on local hydro-thermal and climatic conditions (Huokuna et al., 2017). Further downstream, regulation results in a more dynamic freeze-up process than what would occur naturally. Depending on hydro-meteorological conditions, the initial ice cover may go through consolidation events, i.e. collapse and shove to a newly thicker ice cover, that might result in significantly higher backwater levels posing serious flood risks to riverine communities (Andres et al., 2003). Winter flows have been observed to increase 3 to 4 fold in regulated rivers (Jasek et al., 2017), and regulation led exacerbation of ice-jamming phenomenon and subsequent flooding have been reported in Canada (Beltaos et al., 2007), Romania (Rădoane et al., 2010), and China (Chang et al., 2016).

Climate also influences river flow, ice thickness, freeze-up conditions and stream morphology which govern river ice processes in general and particularly ice-jams and breakups events (Beltaos & Burrell, 2003). Climate change could potentially shift temperature zones, change precipitation patterns and alter local hydrological regimes (Beltaos & Burrell, 2003). Ginzburg (1992) and Soldatova (1992) have found a high correlation ($r^2 = 0.6-0.7$) between mean air temperature and ice cover duration in Russian rivers. In a warming world, a snowfall may transform into rainfall (Krasting et al., 2013) and an increase in air temperatures could result in a higher rates of evapotranspiration (Yip et al., 2012). Owing to changes in precipitation and temperature, volume and timing of runoff in a river can change (Barnett et al., 2005). Climate change can also affect the magnitude and frequency of extreme weather and hydrological events around the world (Dadson et al., 2013) including IJFs (Beltaos & Prowse, 2001; Prowse & Beltaos, 2002). As high latitude northern regions are more prone to climate warming (Schindler & Smol, 2006), the implications of air temperature rises on IJFs might be larger than on open water floods (Prowse & Beltaos, 2002). In a warmer world, the snow melt is anticipated to occur earlier in spring (Beltaos & Burrell, 2003; Parajka et al., 2010) resulting in the shift in timing and magnitude of peak spring runoff.

Globally, regulation has been reported to affect flow regimes in snow-fed rivers more than climate change (Arheimer et al., 2017). A study by Wisser et al. (2010) found that, though climate played a major role in global river discharge fluctuations to the oceans, human interventions have significantly, albeit gradually, impacted hydrological components in individual river basins. The largest human impact on hydrological systems has been due to regulated reservoir systems that drastically change flow regimes and other hydro-ecological processes (Wisser et al., 2010). It is, however, often challenging to distinguish between the relative impacts when both climatic and anthropogenic factors are at play. Direct relationships between large-scale climatic variables and hydrological regimes are often uncertain and can be further confounded by non-random flow release due to reservoir regulation (Albers et al., 2016). However, understanding the relative impacts of climate and regulation is imperative as it improves our ability to reduce flood risks. This will be even more crucial under changing climatic conditions.

The first step in reducing flood risk is to identify, understand and quantify flood hazard (Lindenschmidt et al., 2016). However, the state-of-the-art of on flood risk assessment is largely

based on open water floods. While open water flood frequency analysis methods are widely accepted, methodologies to determine the magnitude and frequency of IJFs are less defined (Kovachis et al., 2017). Burrell et al. (2015) have grouped the existing approaches into four main methods, i.e. biophysical, past flood extent, flood envelope and hydro-technical. Topographic and ecological indicators are used in the bio-physical method to assess past flood water elevations and extents. In the flood extent approach, flood stages and extents are reconstructed from historical surveyed data. The flood envelope method also uses historical data but all available data are combined to form an envelope of flood stages and extents. In the hydro-technical approach, flood profiles are derived from flow data using hydraulic/hydrodynamic analysis or modelling. Turcotte et al. (2017) present two additional methods, i.e. using direct stage-frequency analyses at the site of interest together with local ice observations when data are available or a morphological approach of using morphological or channel geometry indices when local data or observations are not available to identify hazard locations and then performing hydrodynamic simulations.

The hydro-technical approach provides an advantage over the other methods as it permits an evaluation of floods using various statistical return periods. This allows design events and protection to be standardized to a certain level of risk (Burrell et al., 2015). When adequate data are available, the hydro-technical method is considered to be the best existing approach for IJF hazard mapping and identification (Kovachis et al., 2017). However, hydro-technical methods use a deterministic framework whereas IJF processes are stochastic in nature and require a robust methodological approach that accounts for hazard probabilities. Therefore, in this study, we present a probability-based extension of the hydro-technical approach, a new method to investigate the relative impacts of climate and regulation on probability and magnitude of IJFs, presenting the Town of Peace River (TPR) in western Canada as a case study. The town is categorized as a 'high flood risk community' (AECOM, 2015) and has experienced several flooding events in the past, including 1973, 1974, 1979, 1982, 1986, 1992 and 1997 (Uunila & Church, 2015). A dam was constructed in 1972 in the headwater of the Peace River and lies approximately 400 km upstream of the town, see Figure 4-1. We generate naturalized flow regimes using a physically-based land-surface hydrological model, MESH (Pietroniro et al., 2007). Then we calculate the flood probabilities within a stochastic framework using the 1D hydrodynamic river ice model, RIVICE (Lindenschmidt, 2017b) under four different scenarios, i.e. regulated period I (1973-2002), regulated period II (1983-2012), naturalized period I (1973-2002), naturalized period II (1983-

2012) demonstrating the relative impacts of climate and regulation. IJFs also occasionally occur during the river freeze-up period and in mid-winter (Carr & Vuyovich, 2014). However, in this study we focus on IJFs at spring breakup which is of more concern since they are more common and can result in significant backwater effects (Beltaos & Prowse, 2009).

The paper is structured as follows: Section 2 discusses our stochastic modelling framework with a brief introduction of the hydrological and river ice models used in this study. It also discusses how river freeze-up and breakup dates are estimated under naturalized flow conditions. Section 3 presents our case study, a brief ice-jam flood history of the town as well as model setup, calibrations and validations for the study area. Section 4 discusses the results and findings. The paper ends with conclusions in Section 5.

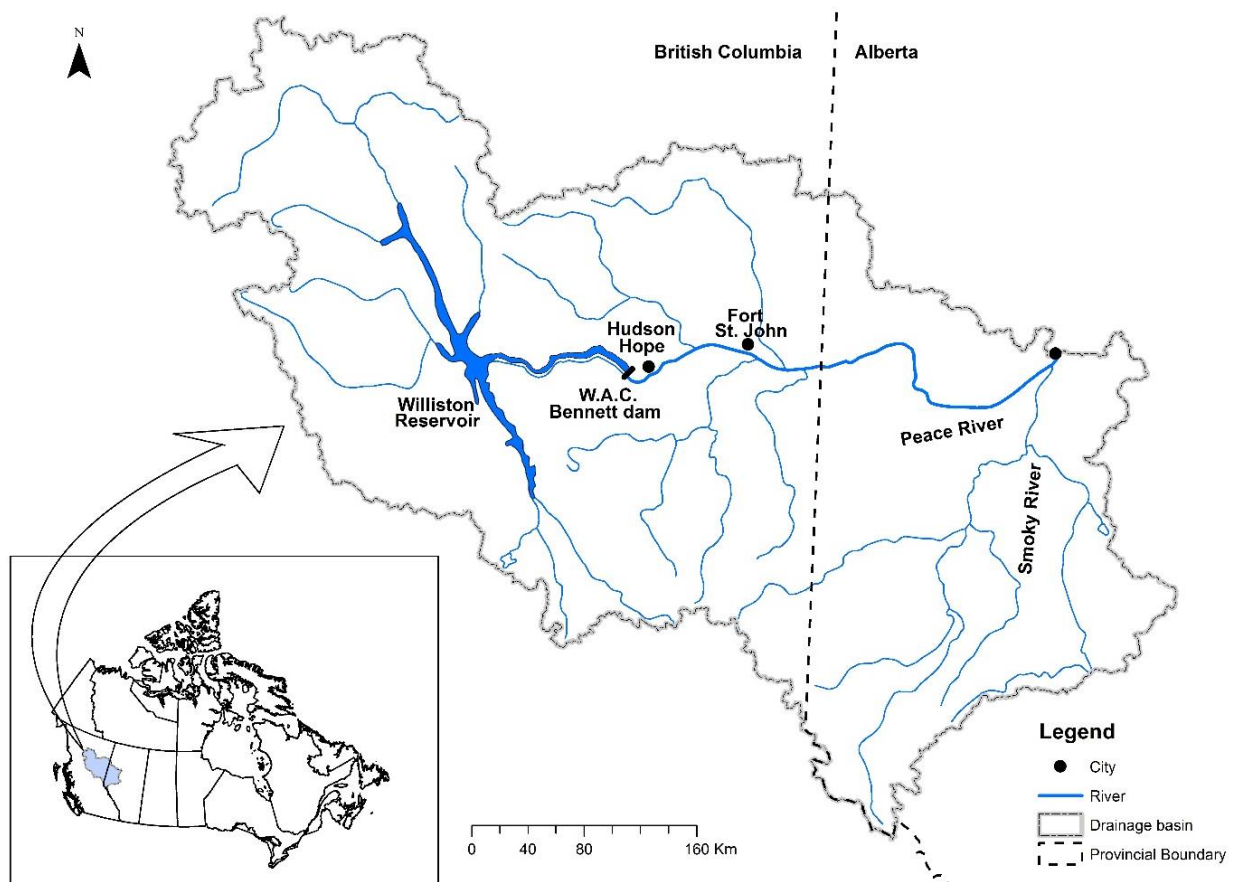


Figure 4-1: The study site

4.3 Methodology

4.3.1 Hydrological modeling to generate naturalized flows

To generate the naturalized flows for the post-dam period, MESH (Modélisation Environnementale–Surface et Hydrologie), a physically-based, land-surface hydrological modeling system, developed by Environment and Climate Change Canada (Pietroniro et al., 2007), was used. MESH is a coupled model that uses the Canadian Land Surface Scheme (CLASS) (Verseghy et al., 1993; Verseghy, 1991) to calculate the energy and water balance using physically-based equations for soil, snow, and vegetation canopy and WATFLOOD (Kouwen, 1988) to route overland flow and interflow from each grid cell to the outlet point of the drainage basin. For computational efficiency of large, complex and spatially heterogeneous basins, MESH uses the concept of Grouped Response Units (GRU) (Kouwen et al., 1993) to group together areas with similar physical characteristics such as land use and soil type. This method has been found more appropriate for large river basins because of its operational simplicity while retaining the basic physics and behavior of a distributed model (Pietroniro & Soulis, 2003). MESH has been widely used in different river basins in Canada (Davison et al., 2006; Davison et al., 2016; Haghnegahdar et al., 2014; Mekonnen et al., 2014; Yassin et al., 2017) including the Peace River (Rokaya et al., under-review; Rokaya et al., 2017).

4.3.2 River ice modelling to simulate ice-jams and breakup water levels

RIVICE (EC, 2013) is a one-dimensional hydrodynamic model that simulates major river ice processes including: border ice formation and breakup, ice cover initiation, evolution and leading edge stability, deposition/erosion of ice onto/from an cover, ice cover shoving due to hydraulic loading, hydraulic roughness of the ice cover and riverbed, and ablation of the ice cover. It can estimate the rate of frazil/slush ice generation, advancement of border ice across the channel and can approximate locations where velocity reduces significantly enough to allow ice deposition on the underside of the ice. In addition, it also simulates ice phenomena in separate subroutines which greatly reduces the computational requirements and allows for more efficient simulations. For further details on RIVICE, the reader is referred to Lindenschmidt (2017b). It has been widely applied in many Canadian rivers (Lindenschmidt, 2017a; Lindenschmidt & Sereda, 2014;

Lindenschmidt et al., 2012a; Lindenschmidt et al., 2012b; Rokaya et al., submitted) including the Peace river (Lindenschmidt et al., 2015; Lindenschmidt et al., 2016; Rokaya et al., under-review).

4.3.3 Stochastic Modelling Framework

River ice cover breakup and ice jam formation are highly complex and unpredictable phenomena. Thus, to assess the probable ice induced water levels, ensembles of water level profiles were simulated within a Monte Carlo (MOCA) framework using Model-Independent Parameter Estimation (PEST), an industry standard software package for parameter estimation and uncertainty analysis of complex environmental and other computer models (Doherty, 1994). This framework for river ice analyses is a novel method proposed by Lindenschmidt (2017a) and uses stage frequency distributions (SFD) as an objective function for model calibration and sensitivity analysis (Lindenschmidt, 2017c).

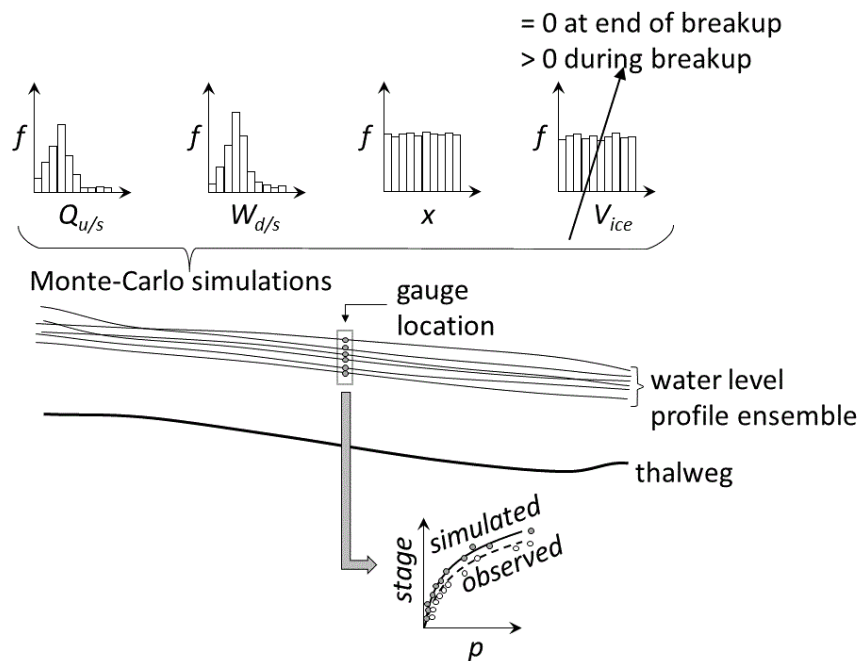


Figure 4-2: MOCA framework

Upstream discharge, downstream water level elevation, incoming ice volume and location of the ice jam toe are the four major boundary conditions in RIVICE (see Figure 4-2). A fifth boundary condition can be added if there are lateral flows emitted or diverted from the mainstem river channel. RIVICE also has several model parameters that represent slush ice and ice cover

characteristics, hydraulic roughnesses, and ice strength properties, as well as ice deposition and erosion velocity thresholds. The values were randomly extracted from the probability density functions (pdf) within certain ranges (uniform pdf) or location and scale factors (Gumbel pdf) for both boundary conditions and model parameters. A uniform pdf was used when *a priori* knowledge of a pdf shape was not known such as toe of the ice jam or model parameters, when extreme value data were available to construct their pdfs, such as discharge and stages, the Gumbel function was used (Lindenschmidt, 2017a).

The upstream discharge is known from the gauging station. However, water level at the downstream boundary is not always available. Similarly, incoming ice volume is also extremely difficult to estimate. Thus, downstream water level and incoming ice volume require further calibration which can be performed using stage frequency distributions as objective functions (see Figure 4-2 and Lindenschmidt (2017c) for further details). Values from a uniform distribution can be taken for the location of the ice jam toe. The range of cross-sections where jams lodge can be approximated from historical ice-jam events, satellite imageries and knowledge of channel morphology. The ranges of RIVICE parameters can be drawn from previous studies on the Peace River (Lindenschmidt et al., 2015; Lindenschmidt et al., 2016; Rokaya et al., under-review).

4.3.4 Breakup date and flows in naturalized conditions

Rivers freeze over at the start of winter when the air temperature drops. From an energy balance perspective, initial ice development and subsequent freeze-up process are determined by the ‘summer heat budget of the river and rate of autumn water-to-atmosphere cooling’ (Prowse, 1995). It is conceptually defined as ‘the time at which a continuous and immobile ice cover forms’ (IPCC, 2007). Breakups occur in spring when increasing temperature disintegrates the ice cover or increased flow dislodges it (Beltaos, 1997). The Water Survey of Canada provides a ‘B’ flag alongside their hydrometric data to indicate ice induced ‘backwater’ effects due to the presence of ice at or immediately downstream of the gauge in the river. Thus, the discharge with the first ‘B’ flag indicates the beginning of the freeze-up of the river whereas the last ‘B’ flag is indicative of the end of the ice cover season. In our study, the breakup date was considered to be the day with the highest discharge within ± 3 days of the last ‘B’ flag (Lindenschmidt, 2017a).

However, in naturalized flow conditions, in absence of 'B' flag, the cumulative degree days of melting (CDDM) was used to identify the probable ranges of breakup dates. CDDM, an empirical approach which is based on air temperature, is widely used to estimate breakup dates for future periods (e.g. Beltaos et al., 2006a; Das et al., 2017; Prowse & Beltaos, 2002) and, thus, can also be used to estimate breakup dates in naturalized flow conditions. The CDDM was calculated by adding all of the daily mean air temperatures above -5°C from the first of January to the end of April. The base value of -5°C instead of 0°C was suggested by Bilello (1980) for Canada and Alaska and is often used in Canadian rivers (Beltaos et al., 2006a; Beltaos, 1997).

The limited 11 years' breakup data from the pre-dam years showed that the value of CDDM lies between 16.2-126.8 $^{\circ}\text{C}$ -days, which shows a larger variation than the 40 years' post-dam data. The CDDM ranges from 2.4-99.6 $^{\circ}\text{C}$ -days in 1973-2012 post-dam period. A stochastic approach was adopted to estimate the breakup date and flow in naturalized flow conditions. At first, 100 random values were generated for each year from the pre-dam CDDM range so each year has 100 possible breakup dates. Then, these 100 breakup dates were matched with naturalized flows to obtain corresponding 100 breakup flows for each year.

Both the measured flow data from the TPR gauging station and simulated naturalized flows were grouped into two 30-years time periods, i.e. 1973-2002 and 1983-2012, to also assess any change over time that could be attributed to climate. Table 4-1 shows temperature, snowfall and precipitation data from three meteorological stations across the basin. It reveals temperature has been consistently higher by at least 0.2°C in the 1983-2012 period across all meteorological stations. Snowfall too follows similar pattern and shows that the 1983-2012 period received on average larger snowfall. Precipitation, however, does not show a significant difference. Then an Extreme Value Gumbel I distribution was used to determine cumulative distribution functions to flood discharge data (Thompson, 1999). To construct the frequency curves, the highest daily discharges during river ice-cover breakup period were selected for each studied year which usually occurs in April or May.

Table 4-1: Comparison of temperature, snowfall and precipitation across meteorological stations for two study time periods

Stations	Average annual temperature (°C)		Average annual snowfall (mm/year)		Average annual precipitation (mm/year)	
	1973-2002	1983-2012	1973-2002	1983-2012	1973-2002	1983-2012
Grand Prairie A	2.14	2.26	152.24	158.94	433.79	441.70
Fort St John A	2.24	2.48	181.43	193.89	451.94	456.20
Peace River A	1.42	1.64	110.57	125.36	388.99	390.71

4.4 Case Study and Data

4.4.1 Study area and flood history

The TPR (see Figure 4-1) is located in northwestern Alberta, Canada, along the Peace River at the convergence point of the Heart River and approximately 15 km downstream of the convergence point of the Smoky River. It is approximately 400 km downstream of the Bennett dam. It drains an area of approximately 194,374 km². The width of the Peace River varies with location, ranging from 500 m to 2500 m, and is characterized by intermittent islands and sand bars. There are numerous tributaries, most notably is the Smoky River which plays an important role in the formation of ice jams at the TPR by supplying a large amount of streamflow to the Peace River during the spring breakup (Lindenschmidt et al., 2016).

The town is particularly susceptible to ice jam flooding and has been classified as a ‘high flood risk community’ by the Peace River Basin Flood Mitigation Feasibility Study (AECOM, 2015). There were ice-jam flood events in 1973, 1974, 1979, 1982, 1986, 1992 and 1997 even after the construction of the dam in the headwaters which can attenuate the high flows (Uunila & Church, 2015). The damages from ice-jam flooding events can be very extensive, for example, the ice-jam flood that occurred in 1997 from April 19 to 23 resulted in more than \$47 million in damages and resulted in the evacuation of 4000 residents (Public Safety Canada, 2013).

The town relies on its dike system for flood protection and thus, in response to the historical flood events, has continually upgraded this system. After the flood event (with peak flow of 15,600 m³/s) in 1972, the dike was raised in 1974 to protect against a design flow of 17,839 m³/s. In 1981, the dike crests were further raised by 1-1.2 m after the annual exceedance probability of 1:100-year

open water flood was calculated to be 20,133 m³/s. However, a major open-water flood occurred in 1990. In 1992, when ice-jam flooding again overtopped the town's dikes, an additional 0.5m of freeboard was added to the existing dikes and was based on the revised design discharge of 21,200 m³/s. Again the dikes were overtopped and bypassed at several locations in the town when an ice-jam flood event occurred in 1997 near the Heart River bridge. As a result, an additional flood wall was built and the height of bridge was raised in 1999 (Bekevich, 1990). This was the last of the structural flood control measures implemented. However, it should be noted that the dikes crest elevations are not designed based on ice-jam flood events but rather on open water flood events, even though an ice-jam flood event can result in significantly higher water levels than open water floods (Lindenschmidt et al., 2016). Hence, ice-jam flooding is still a major concern for the communities in the TPR, despite having a dike system for flood protection (Lindenschmidt et al., 2015).

Besides structural measures, there is also a memorandum of understanding between Alberta and British Columbia to guide the operating procedure of the dam during freeze-up and breakup periods of the Peace River at the TPR to prevent any possible ice-jam flooding (JTF, 2006). The operating procedures dictate that during the freeze-up period, the water level at the TPR should be maintained at or below 315 m with a target discharge of a range between 1400-1600 m³/s. This threshold has been selected so that, in case a 1:100-year secondary consolidation of the ice cover were to occur, the town dike system would still provide protection and would not be overtopped (Jasek et al., 2007). The breakup water level elevation threshold is set at 314 m with a flow threshold of 3200 m³/s at the TPR as a protection against calculated 1:100-year flood in spring (JTF, 2006). While calculating the flow at the TPR, the flows from non-regulated tributaries such as Smoky River are estimated and then flows from the PCN (target discharge minus tributary flows) are released accordingly to achieve target discharge and water levels at the TPR. Examples of cases when elevated freeze-up levels at the TPR were controlled by revised flow operation in the past are available from Jasek and Trevor (2009).

4.4.2 Hydrological model setup, data and calibration

GreenKenue (http://www.nrc-cnrc.gc.ca/eng/solutions/advisory/green_kenue_index.html), an advanced data preparation, analysis, and visualization tool was used to prepare the drainage database. For this, a digital elevation model was retrieved from Geogratias (<http://geogratias.gc.ca/>)

whereas land use data and soil data were obtained from GeoBase (<http://www.geobase.ca/geobase/en/data/landcover/index.html>) and Agriculture and Agri-Food Canada (<http://sis.agr.gc.ca/cansis/nsdb/slc/v3.2/index.html>), respectively. The model was setup with the spatial resolution of 0.125° resulting in 1850 grid cells with a drainage basin of 194374.2 km² with the outlet at the Peace River gauging station (07HA001), see Figure 4-1.

The latest version of the Global Meteorological Forcing Dataset (version 2) generated by Princeton University (Sheffield & Wood, 2007, 2008), which covers a period from 1901 to 2012 and provides all required forcing files for MESH such as air temperature, precipitation, incoming longwave radiation, incoming shortwave radiation, humidity, atmospheric pressure and wind speed was used in this study. The dataset is globally available at a spatial resolution of 0.25, 0.5 and 1.0 arc degrees and at 3-hourly, daily and monthly temporal resolutions (Sheffield et al., 2006). The data with 0.25 spatial resolution and 3-hourly temporal resolution were further interpolated at 0.125° to match the spatial resolution of the drainage database. The dataset is constructed by combining a suite of global observation-based datasets with NCEP/NCAR reanalysis and bias correction. The data are useful for understanding hydro-ecological processes and seasonal and inter-annual variability as well as to evaluate coupled models and other land surface prediction schemes (Sheffield & Wood, 2008). The discharge data are available from the Water Survey of Canada through Environment and Climate Change Canada's Hydat database (<https://ec.gc.ca/rhc-wsc/default.asp?lang=En&n=9018B5EC-1>) at daily time step.

The calibration process was performed using OSTRICH, which is an open source, auto-calibration and multi-algorithm parameters' optimization software (Matott, 2005). Within OSTRICH, a parallel version of the Dynamically Dimensioned Search (PDDS) (Tolson & Shoemaker, 2008) algorithm was used to calibrate 32 parameters of four dominant Group Response Units (GRUs). MESH was run at a 3-hourly time-step, matching the temporal resolution of input meteorological forcing data but output streamflows were generated at a daily scale for comparison and analysis. The model was first calibrated and validated for the pre-dam period. Nash and Sutcliffe (NS) Efficiency was used as an objective function. As continuous daily streamflow data are available since November 1957, the model was calibrated from 1958-1963. 1958 was considered a model spin up period thus the calibration period included October 1959-September 1963, whereas October 1963-September 1967 was considered as the validation time span. Both calibration and

validation showed good agreement between simulated and observed flows with NS and log(NS) values higher than 0.87 which demonstrated that the model is able to simulate both peak flows and low flows. The model was then run from 1973 to 2012 to generate naturalized flows. A second validation was performed on generated naturalized flows. BC Hydro regularly estimates total inflows to Williston Reservoir thus this data from BC Hydro was compared with model generated naturalized flows at the Hudson Hope gauge for 1973-2012 period.

4.4.3 RIVICE model setup and calibration

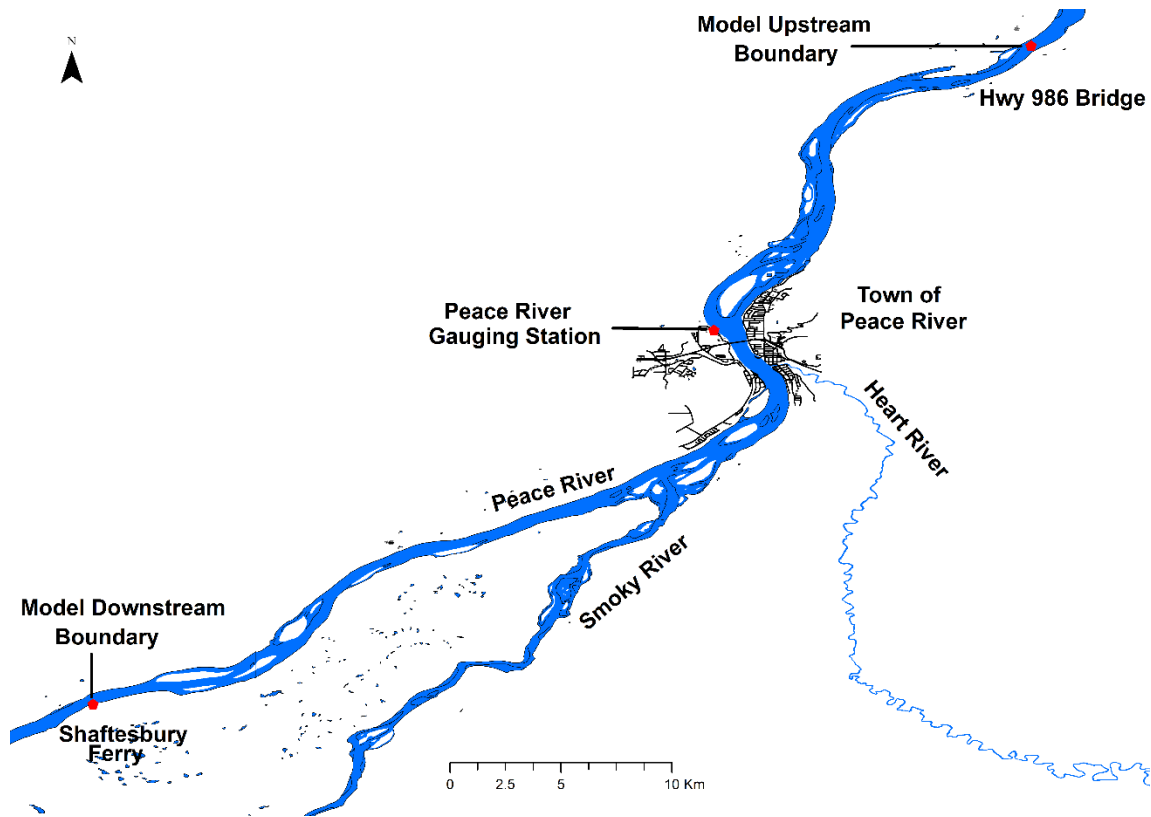


Figure 4-3: RIVICE modelling domain

The modelling domain extends approximately 47 km from Shaftesbury Ferry to the Hwy 986 Bridge (see Figure 4-3). The domain was divided into two reaches to reflect different river bed flow resistance due to the islands downstream of the Smoky River. The stretch upstream of the Smoky River confluence (0-15.3km) constitutes the first reach whereas the second reach extends downstream from the confluence (15.3 km) to chainage 46.5km. The initial parameter values and ranges include slush ice pan and ice cover porosities and thicknesses, hydraulic roughnesses and

ice strength properties along with the boundary conditions: upstream discharge, lateral flows, downstream water level elevation, incoming volume of ice and the location of the ice jam toe. A detailed discussion on the TPR model setup and parameterization is available from Lindenschmidt et al. (2015) and Lindenschmidt et al. (2016). The model was calibrated for the open water event of 1990, ice cover formation event of 1982 and ice-jam flooding event of 1992, and then validated for the ice jam flooding event of 1997. The model was run at a 30-second time-step.

4.5 Results and Discussion

4.5.1 Hydrological model performance

Figure 4-4a shows the results of the MESH calibration and validation for gauging station “Peace River at Peace River” (07HA001) at the Town of Peace River showing simulated flows having good agreement with measured flows at the gauging station. The NS value of 0.87 and log(NS) value of 0.89 was obtained for the pre-dam calibration years whereas for the pre-dam validation years, a NS value of 0.88 and a log(NS) value of 0.89 were obtained.

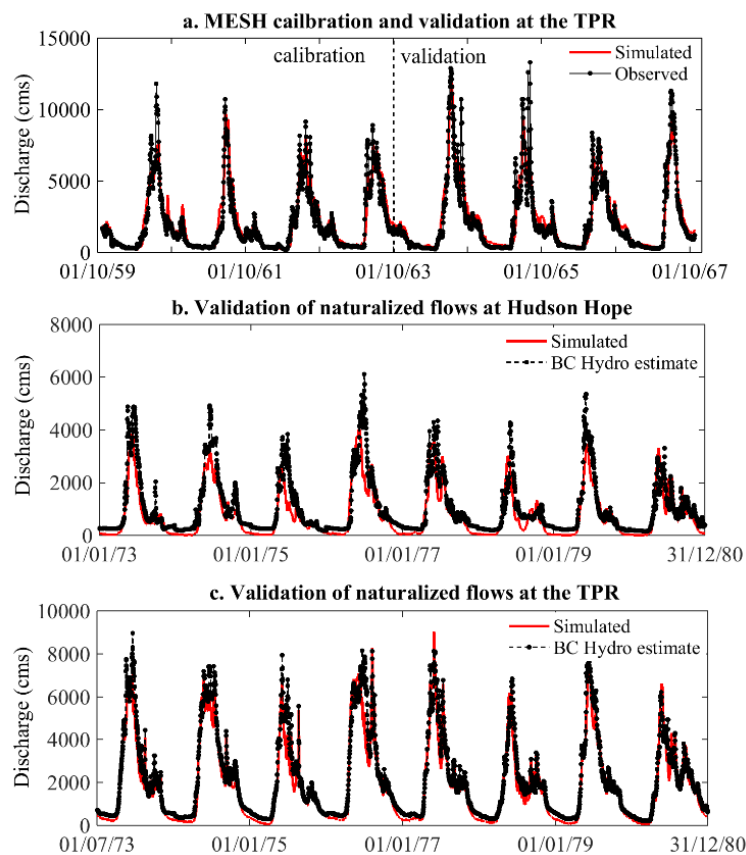


Figure 4-4: Hydrological model performance. (a) shows results of MESH calibration and validation during pre-dam years, (b) and (c) show model validation at Hudson Hope and the TPR, respectively, for the post-dam period

In regulated rivers, naturalized flows are often generated using the recorded storage levels and reservoir outflows. BC Hydro regularly estimates the total inflows to the Williston reservoir using this approach. Thus, at first, the daily inflows to the reservoir estimated by BC Hydro were compared with the simulated streamflows at Hudson Hope from the model for further validation (see Figure 4-4b). In a second step, the outflows estimated by BC Hydro were further routed downstream using MESH's 'controlled reservoir release' option. This feature ignores all the streamflows generated upstream of the reservoir location (a reservoir is added in the drainage basin) and just routes the user provided flow data from a separate reservoir release file. This approach has been previously used by Rokaya et al. (under-review); Rokaya et al. (2017) in the Peace River to route modified reservoir flows from the Bennett dam downstream to the Peace-Athabasca delta (PAD). Figure 4-4c shows the routed flows using this approach at the TPR and simulated naturalized flows from the calibrated and validated model, which matched reasonably well.

Figure 4-4b and Figure 4-4c show that our physically-based model is able to simulate naturalized flows for the post-dam period with good accuracy. Low flows and some peak flows are underestimated at Hudson Hope but this could be partly due to the model's calibration and validation against the gauging station at the TPR, a study site which is approximately 400 km downstream of Hudson Hope. Restricted by a data sharing agreement with BC Hydro, results from only a few years were available and shown in Figure 4-4b and Figure 4-4c. However, statistical analyses were performed on the whole data series of 40 years, i.e. 1973-2012 at Hudson Hope and the TPR between flows estimated by BC Hydro and simulated flows from the model. The comparison of performance measures for the 40 years period show a NS value of 0.69, coefficient of determination (R^2) of 0.76 and percent bias (PBias) of 27% at Hudson Hope whereas at the study site, TPR, NS of 0.89, R^2 of 0.92 and Pbias of 14% were obtained. Furthermore, since the study focuses on IJFs occurring during ice cover breakup period, it is crucial that the model is able to accurately simulated flows during this period. The historical data show that the breakup at the TPR occurs in April or May, thus, the model-generated daily flows for these two months for 40

years were also separately compared with the flows achieved by routing BC Hydro flow estimates. The result shows good performance with a NS of 0.91, $\log(\text{NS})$ of 0.78 and Pbias of -5.86%.

4.5.2 Ice-jam flood frequency and magnitude

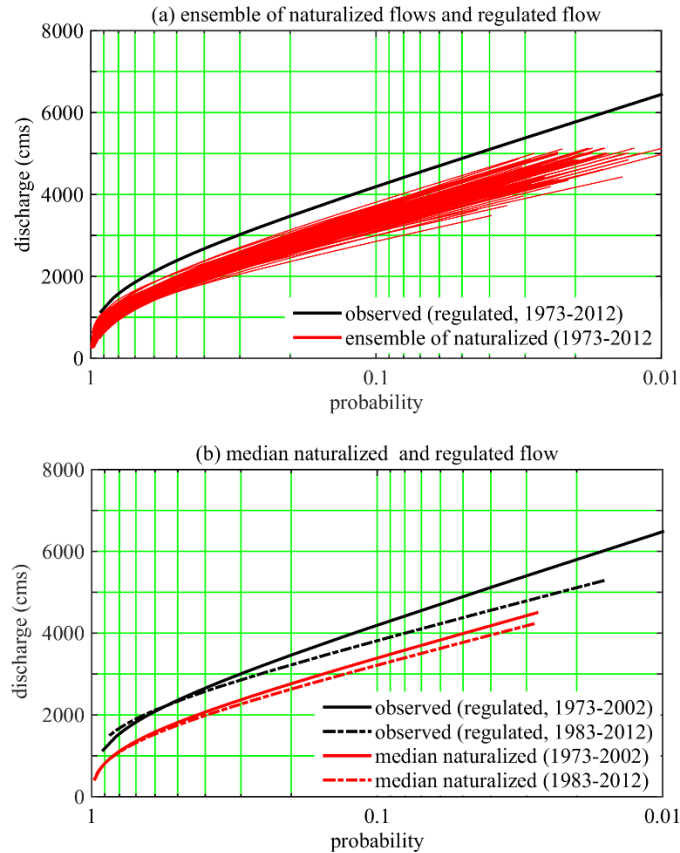


Figure 4-5: Discharge-return period curve for breakup flow as observed and simulated at the gauging station at the TPR (07HA001). (a) shows observed flows from the gauging station and ensemble of naturalized flows for 40 years' period (1973-2012) whereas (b) shows observed flows and median of naturalized breakup flow data for two study time periods.

Figure 4-5a shows the ensemble of flow frequency curves from naturalized flows and observed flows from the TPR gauging station for the post-dam construction period. It can be observed that streamflows during breakup under regulated flow conditions are higher than those under natural flow conditions. As observed in Figure 4-5b, even a discharge with a T=1:10 year return period for regulated flow conditions could be several hundred cubic meters higher than for naturalized conditions. Figure 4-5b also shows comparatively less influence of climate under naturalized flow

conditions when median flows of the naturalized period 1973-2003 and 1983-2012 are compared. Regulated periods between 1973-2002 and 1983-2012 show larger difference than naturalized conditions over the two study periods.

Caution should be taken in interpreting the results of flow frequency curves in regulated rivers. The frequency analysis is based on the assumption that streamflows follow certain statistical distributions that are based on the behavior of natural flow regimes whereas in regulated rivers, flow regimes can be confounded by non-random flow release due to reservoir regulation (Albers et al., 2016). Nevertheless, traditional stage-frequency relationships can still provide a general overview (Lindenschmidt et al., 2015). Moreover, breakup flows at the TPR are also largely contributed by other non-regulated tributaries such as the Smoky and Wapiti rivers whose contributions can often be larger in spring months compared to the regulated headwaters of the Peace River (Lindenschmidt et al., 2016). Furthermore, this study incorporates a stochastic modelling framework to generate ice-affected backwater staging conditions and does not solely rely on flood frequency analyses.

Note that estimating ice-jam flood frequency and magnitude is relatively challenging since ice-jamming and breakup are complex and stochastic processes. However, previous studies such as Beltaos (1995), Beltaos (1997) and Andrishak and Hicks (2008) have found that they are primarily governed by spring flow, freeze-up stage, ice characteristics, morphology of the river, and other climatic factors. Additionally, recent studies of the Peace River have shown that, among other factors, freeze-up stage and breakup flow play a dominant role, thus, all other conditions being equal, the probability and magnitude of ice-jam flooding in spring is higher with higher breakup flow and lower freeze-up stage (Beltaos, 2003, 2014; Beltaos et al., 2008; Prowse & Beltaos, 2002). Interestingly, we observed higher breakup flows due to regulation in both the 1973-2002 and 1983-2012 periods whereas winter flows have been observed to increase 3 to 4 fold resulting in higher freeze-up stage (Jasek et al., 2017). Thus, it is difficult to draw clear a conclusion if IJF probability in spring has increased or decreased and to what degree regulation has an effect from analyzing only breakup and freeze-up curves. Thus, this study highlights the limitations of relying solely on these factors to determine ice-jam breakup floods but more importantly, it highlights the usefulness of integrating river ice modelling tools, such as RIVICE, into the process, which can

help shed some light on the analysis of IJFs probabilities and magnitudes under regulated and natural conditions.

4.5.3 Backwater level profile calibration and validation

An open water flood event of 1990 at the TPR was first calibrated using an upstream discharge of 12,700 m³/s and downstream water level elevation of 313.53 m.a.s.l. Though a maximum discharge of 16,500 m³/s was recorded at the gauging station at the TPR, a flow of 12,700 m³/s was used for the calibration as high-water marks were available for this mean discharge of 12,700 m³/s. The upper Peace River and the Smoky River contributed 55% and 45% of the total flow, respectively. Figure 4-6a shows good agreement between simulated and observed water levels across the modelling domain.

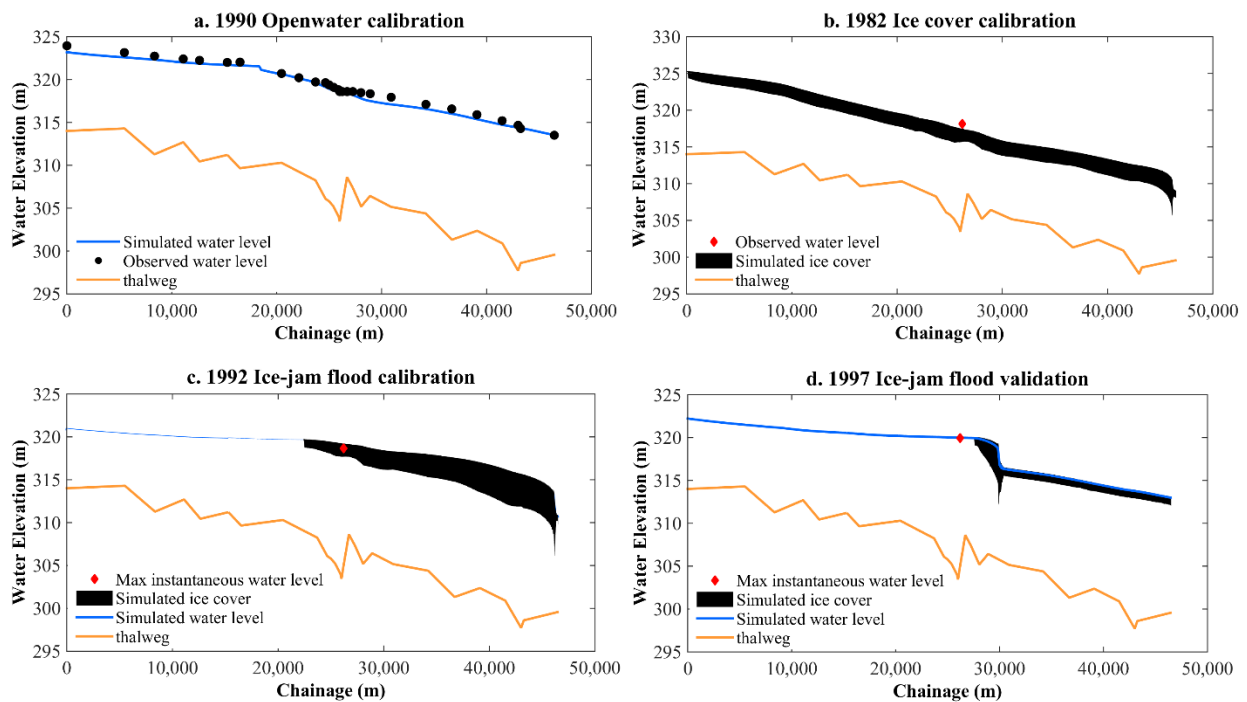


Figure 4-6: River ice model calibration and validation

The freeze-up/breakup event of January 1982 was used for ice cover calibration. A rapid increase in river flow was observed on 7 January 1982 due to large amounts of water was released from the Bennett Dam. This increased discharge resulted in breakup of the thin ice cover and formed an approximately 9 m thick ice jam 20 km downstream of Dunvegan. The jam quickly released

increasing the water level elevation to 318.15 m.a.s.l. at the TPR. Using the discharge of 2,500 m³/s as observed at the TPR gauging station with downstream water level elevation of 309 m.a.s.l. and ice volume of 54.72 million m³, estimated by Lindenschmidt et al. (2015), the ice cover calibration was performed. Figure 4-6b shows a good fit between the simulated ice induced and observed water levels.

After the open water and ice cover calibrations, an ice jam flood event observed at the TPR in late February 1992 was used for ice-jam flood calibration. The initial ice jam was formed a few kilometers upstream of the TPR which failed releasing a large surge of water and ice floes resulting in another ice jam forming approximately 23 km downstream of the TPR. As a result of the ice jam, there was significant backwater staging which resulted in the overtopping of the dikes at several locations and flooding in some parts of the TPR. To simulate this event, an upstream discharge of 2,820 m³/s, downstream water level elevation of 310.7 m.a.s.l and incoming ice volume of 28.8 million m³ was used as estimated by Lindenschmidt et al. (2016). The location of the toe of the ice jam was assumed to be close to the most downstream cross-section. Figure 4-6c shows good agreement between simulated and observed water levels at the TPR gauging station.

The model was validated using the IJF event of April 1997. An ice jam was formed downstream of the confluence of the Peace and Smoky rivers between the town's bridge and Bewly Island as a result of the breakup of the ice cover along the Peace River by the high discharges of water and ice from the Smoky River. Because of this jam, there was a backwater flow into the Heart River which breached the town's dikes at several locations resulting in estimated flood damages of \$20 million. A discharge of 4,620 m³/s and water level elevation of 309 m.a.s.l. were used as upstream and downstream boundary conditions. The incoming ice volume was estimated to be 3.2 million m³ and the toe of the ice jam was estimated to have been located between the bridges and Bewly Island Lindenschmidt et al. (2016). Figure 4-6d shows a good fit between simulated and observed water levels at the TPR gauging station.

4.5.4 Downstream water level calibration

IJF modelling studies in the past have relied on water levels at freeze-up as a downstream boundary condition, and often used a uniform distribution (Lindenschmidt, 2017c; Lindenschmidt & Chun, 2013; Lindenschmidt et al., 2012b), however, the stage at the breakup period in spring could differ

by several meters compared to the freeze-up stage at the onset of winter. Thus, in this study, we calibrated the downstream water level at breakup using the MOCA framework. For the calibration, the upstream discharge is available from the TPR gauging station which is a combined flow from the Peace, Smoky and Heart rivers. The flow recorded at the last day of the 'B' flag was used to indicate the end of the ice cover season. The calibration was performed against the water level at the TPR gauging station at the last day of the 'B' flag. Among the remaining three boundary conditions, the incoming ice volume was assumed to be zero, whereas values generated from the pdf of estimated downstream water level at freeze-up and the location of ice-jam toe were used for the initial run. Previously, calibrated and validated model parameters were used to represent river ice processes. Each model setup included 35 runs from which one SFD was generated for the location of the gauge thus, 100 SFDs required 3500 model evaluations. The distribution parameters, scale and location, of the downstream water level was adjusted until the simulated SFD matched the observed SFD. Downstream water level for regulated and naturalized conditions were calibrated separately. Post-dam discharge and water levels were used in the regulated scenario whereas discharge and water level from pre-dam years were used for naturalized conditions. Figure 4-7a and Figure 4-7b show good agreement between the simulated SFD and observed SFD at the TPR gauging station for downstream water level calibration for both regulated and naturalized conditions. Figure 4-7c highlights the importance of calibrating downstream water levels. It shows that the traditional approach of estimating downstream water levels by transferring freeze-up stage from the known gauge location using slope and distance can be a significant underestimation. Rokaya et al. (under-review) also used a similar method and found calibrated water levels to be approximately 2 m higher than estimated downstream water levels at freeze-up in their study of the PAD.

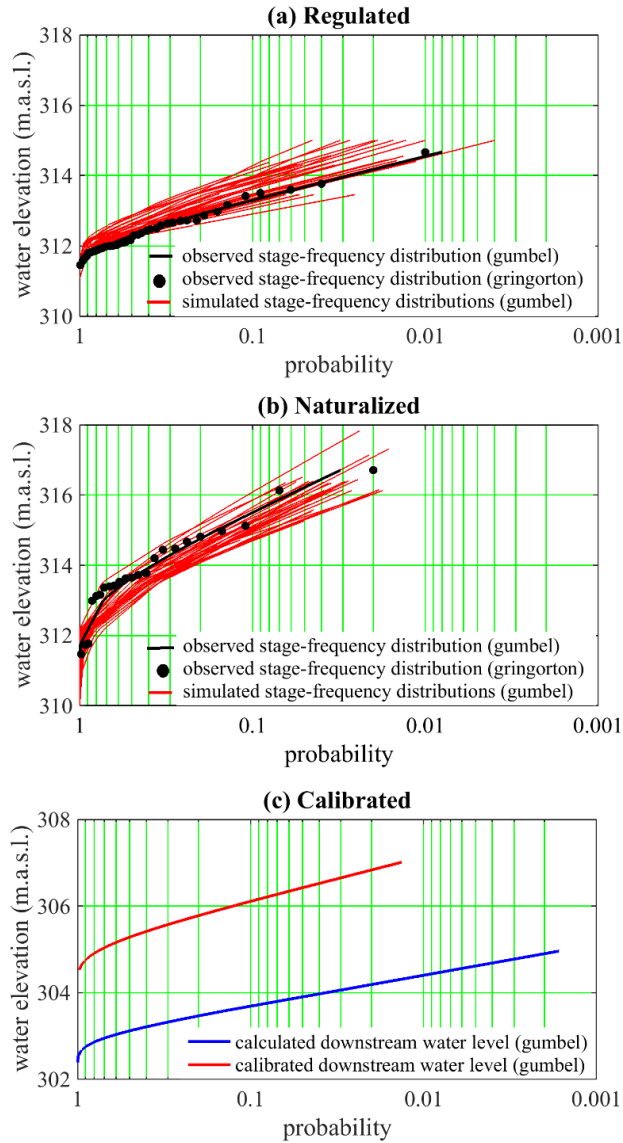


Figure 4-7: Downstream water level calibration. Ensemble of simulated stage frequency distributions (red line) with the observed stage frequency distribution (black line) with plotting positions (black dots) for (a) regulated and (b) naturalized conditions. (c) shows calibrated and estimated downstream water levels.

4.5.5 Ice volume calibration

After achieving satisfactory results for downstream water level calibration at breakup, the incoming ice volume was calibrated using the same approach. However, among the boundary conditions, flows at instantaneous maximum water level at breakup was used instead of flows at the last 'B' flag for the upstream discharge along with calibrated downstream water levels.

Incoming ice volume was included, and the pdf of the location of the ice-jam toe was used. The simulation results were compared against instantaneous maximum water levels observed at the TPR gauging station. Instantaneous maximum water levels are provided by Water Survey Canada’s hydrometric tables which indicate maximum water level recorded at the gauging station which can be significantly higher than averaged daily maximum water levels. Similar to the downstream water levels, calibrations were performed for both regulated and naturalized conditions. Figure 4-8 shows good agreement between the simulated and observed SFD at the TPR gauging station for ice volume calibration for both regulated and naturalized conditions.

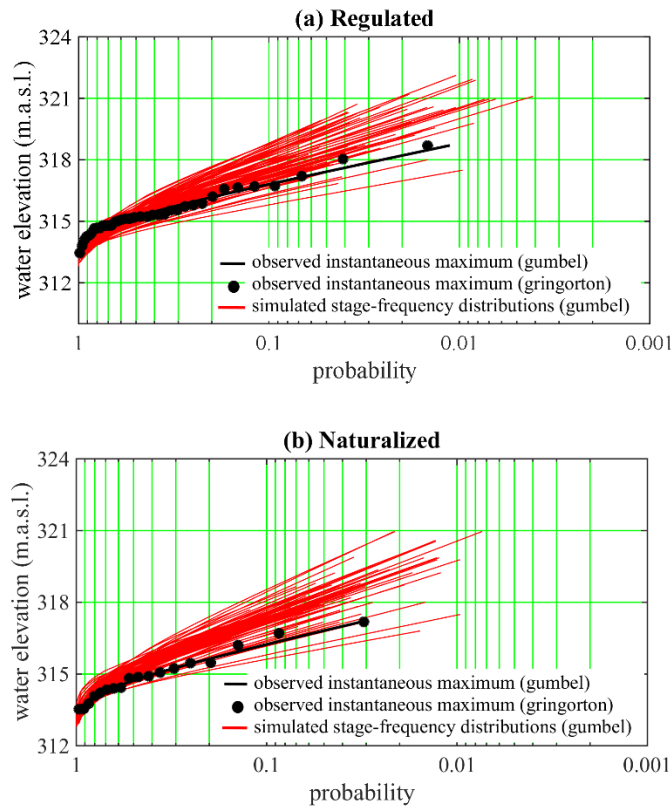


Figure 4-8: Incoming ice volume calibration. Ensemble of simulated stage frequency distributions (red line) with the observed stage frequency distribution (black line) with plotting positions (black dots) for (a) regulated and (b) naturalized conditions.

The histogram of the ensembled distributions is provided in Figure 4-9, from all simulation values whose ensemble envelope best coincided with the observational data stage frequency distribution. The ice volumes ranged between 2 and 25 million m^3 with a mean ≈ 12 million m^3 for regulated conditions, whereas in naturalized conditions, the ice volume spanned from 5 and 32 million m^3

with a mean ≈ 17 million m^3 . The calibrated ice volume is larger than what previous studies have reported. Lindenschmidt (2017c) found ice volume to range from 0.5 and 21 million m^3 with a mean ≈ 5 million m^3 for the Athabasca River at Fort McMurray with a drainage basin of 132,588 km^2 . In previous studies of the Peace River at the TPR, (Lindenschmidt et al., 2016) reported the mean ice volume to be approximately 6 million m^3 for regulated conditions. However, the above-mentioned studies used water level at freeze-up as a downstream boundary condition whereas this study calibrated downstream water level at breakup. As we demonstrated above, estimations based on freeze-up stage can be underestimated and thus lesser ice volume can result in higher backwater levels in constricted channels. Nevertheless, this ice volume estimation does not account for ice erosion, thus, actual ice volume can be somewhat lower than what we report. Figure 4-9 also shows a substantial decrease in ice volume due to regulation. Thermal erosion of the ice cover underside could be more prevalent due to high winter flows in regulated conditions. Furthermore, the incoming ice floes from upstream stretch can also be captured in the reservoir.

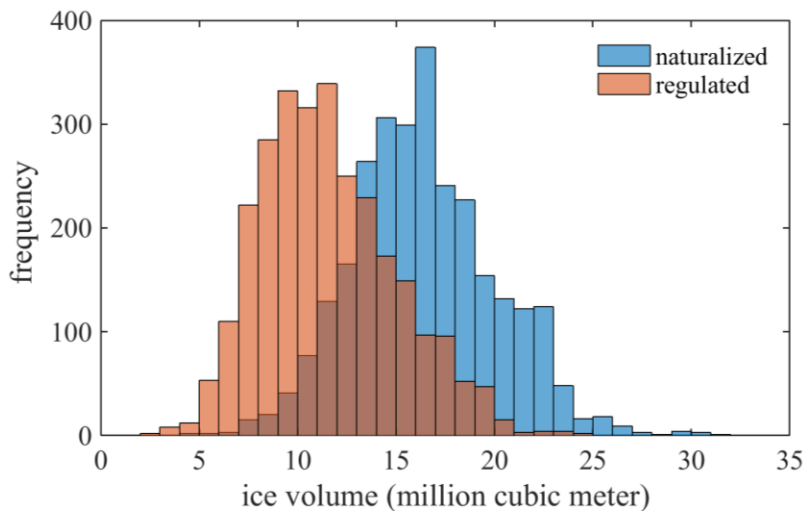


Figure 4-9: Histogram of inflowing ice volumes creating ice-jams along the Peace River at the TPR

4.5.6 Ice-jam flooding probability at the TPR

Figure 4-10 shows the stage-frequency curves of median flows of 1050 model evaluations each for four different scenarios, i.e. regulated period I (1973-2002), regulated period II (1983-2012), naturalized period I (1973-2002), and naturalized period II (1983-2012). The results are compared at the gauging station (07HA001), located at the TPR. The results reveal significant differences

between naturalized and regulated time periods. Stage-frequency distributions (SFD) are higher for regulated scenarios than for their corresponding naturalized scenarios. For a 10-year ice-jam flood event, the results show that, backwater levels can be approximately 1 m higher in regulated scenarios than in natural conditions.

There are also differences in SFDs between two-time periods in both regulated and naturalized scenarios. For both scenarios, 1973-2002 period produced approximately 1 m higher backwater levels compared to 1983-2012. This was an interesting observation as there was little difference in both snowfall and total precipitation between these two-time periods, although mean annual temperature was approximately 0.22°C higher (Peace River A meteorological station). The higher temperatures may have contributed to lower spring snowpacks (e.g. through mid-winter melt events) thus reducing backwater levels. In fact, the analyses of streamflow data from the Smoky River, the largest unregulated tributary to the Peace River showed that spring flows in April and May were on average 10% lower in the latter 1983-2012 period. However, additional research is required to better understand the interrelationships between temperature and precipitation changes (on a variety of temporal and spatial scales) and ice-jam flooding in this region.

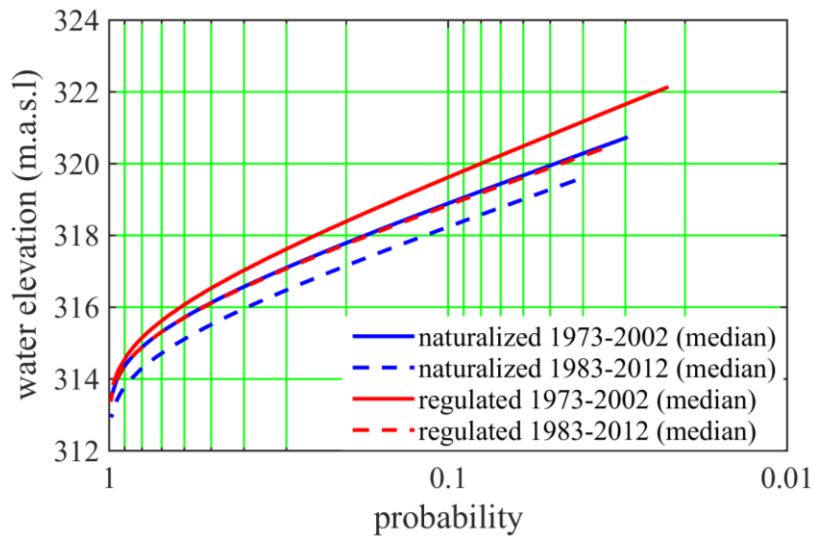


Figure 4-10: IJF probabilities at the TPR. Lines show median of ensemble of simulated stage frequency distributions for four different scenarios.

Climate and regulation effects on ice-jam flooding are one of the most debated issues in the Peace River. Many studies (e.g. Beltaos, 2014, 2017; Peters & Prowse, 2001; Prowse & Conly, 2002;

Wolfe et al., 2005) have attempted to quantify their relative impacts on the downstream PAD, which is an ecologically important Ramsar site in Canada. As high elevation perched basins of the PAD can only be recharged by IJF events, there is a growing concern of reduced frequency of IJFs (Peters & Prowse, 2001; Prowse & Conly, 2000). Paleolimnological studies have identified climate as the major contributor (Timoney et al., 1997; Wolfe et al., 2005), while physically-based studies have suggested regulation as a main reason for the reduced frequency (Beltaos, 2014, 2017; Prowse & Conly, 2002). Nevertheless, climate has been attributed as a major cause for reduced breakup flows and regulation for increased freeze-up stage (Beltaos et al., 2006b; Romolo et al., 2006a; Romolo et al., 2006b). Our study site, which lies approximately 400 km downstream of the reservoir and approximately 800 km upstream of the delta, shows similar findings in terms of climatic effects. In both regulated and naturalized conditions, there are reductions in flood frequency and stage-frequency curves between two study periods. However, our results are contrary to previous studies at the downstream Peace Point that suggest regulation has had no or little effects on breakup flows. The findings of this study show that water levels during ice-jam breakup at the TPR are higher due to regulation compared to naturalized conditions. The IJF history of the town also shows that there has been an average of one spring IJF event every 4.8 years for the past last 44 years of regulation (1973-2017).

4.6 Conclusion

A novel integrated modelling framework that couples physically-based hydrologic and hydraulic models to assess IJF risk in a probabilistic approach has been presented. As IJFs are common in northern hemisphere, this approach can be applied to other rivers and locations to account for the stochastic nature of IJF processes. However, one limitation of this approach is that it requires longer historical data for model calibration and validation which might not always be available. The relative impacts of climate and regulation on IJF are quantified using this probability-based hydro-technical approach. This study suggests that breakup flows would have been lower in a natural setting. Results from the river ice modelling support this finding. Though there are some differences in SFDs in two-time periods, this study shows that flood risk probabilities would have been still lower under naturalized conditions compared to present regulated conditions. Both study periods, i.e. 1973-2002 and 1983-2012, show that breakup water levels are approximately 1 m higher during regulated conditions.

4.7 Acknowledgement

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4.8 Author contributions

KEL conceived the rationale of this study. PR carried out the modelling work and data analysis with support from KEL. PR wrote the manuscript. KEL and HW commented on the manuscript and contributed to the text in later iterations.

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CHAPTER 5

PROMOTING SUSTAINABILITY OF A DRYING DELTAIC ECOSYSTEM IN A REGULATED RIVER

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5.1 Abstract

The regulation of rivers has always been a controversial issue, with potential benefits but also environmental impacts. In western Canada, the construction of W.A.C. Bennett Dam in the headwaters of the Peace River has raised concerns over the ecological health of the Peace-Athabasca Delta (PAD), a socio-economically and ecologically important delta with national and international significance. The major concern is the reduced frequency of ice-jam floods which are particularly effective in replenishing the high-elevation basins of the PAD. Previous studies have suggested that releasing water at opportune times from the dam could promote ice jam flooding in the delta; however, ice-jam flood events can also be severe and devastating to river-side communities and economies. Thus, a critical and challenging question is how can we promote flooding in the downstream deltaic ecosystem where it is essential without necessarily increasing flood risk in upstream communities in the Peace river? This study reviews previous approaches, and explores possible reservoir operation schemes with an integrated hydrologic and hydraulic river ice modelling approach to minimize flood risk and maximize flood potential at desired locations. We demonstrate that, by increasing reservoir release in the breakup period, it is possible to increase the likelihood of ice-jam flooding in the PAD without necessarily causing ice-jam

floods in the upstream communities. However, the timing of the flow release, taking into account the receding ice front and the local hydro-meteorological conditions, is critical.

5.2 Introduction

The flow regime of a river shapes the structure and functions of its floodplains and deltas, and maintains its ecological integrity, sustaining the range of native biodiversity (Poff et al., 1997). Not only flow volume but also flow variability, rates of flow change, and magnitude of high and low flows are important. Any flow alterations can affect geo-morphological processes and may pose serious threats to evolution and conservation as some aquatic and riparian species might not be able to adapt to a new flow regime (Lytle & Poff, 2004). However, the hydrological reality is that half of world's rivers have dams that have significantly modified river flow regimes (WCD, 2000). In Canada alone, there are 15,000 dams, of which 933 are categorized as 'large' dams (CDA, 2017) under the definition of the International Commission on Large Dams. The regulation of rivers has always been a divisive issue with arguments for both potential benefits and environmental impacts.

In western Canada, the construction of W.A.C. Bennett Dam in the headwaters of the Peace River in 1968 has raised concerns over the ecological health of the Peace-Athabasca Delta (PAD) (Beltaos, 2014; Prowse & Conly, 2002). The PAD, one of the largest inland freshwater deltas in the world, is a very productive ecosystem, and has international significance as a Ramsar site and UNESCO World Heritage site (Peters et al., 2006a). However, in addition to regulation, climate has also been identified as a factor underlying the recent changes in the hydro-ecology of the PAD (Timoney et al., 1997; Wolfe et al., 2005). The major concern is over the reduced occurrence of ice-jam floods which are particularly effective in recharging high-elevation 'perched' basins of the PAD (Peters & Prowse, 2001; Prowse & Conly, 2000). In these perched basins, evapotranspiration rates are higher than precipitation, with negligible groundwater contribution, which makes them dependent on flood water for replenishment (Peters et al., 1999). Though open-water floods might raise water levels in the lower portions of the PAD, previous studies such as NRBS (1996) and PAD-TS (1996) have found that only ice-jam flood events can inundate the perched basins. High staging during ice-jam events can block the usual northward drainage of the system resulting in reverse flows in the delta channels, and perched basins may become inundated depending on the water level elevation achieved (Peters & Prowse, 2001; Peters et al., 2006a).

However, floods in general and ice-jam floods in particular in cold regions can also be severe and disastrous for local communities and economies. Along the Peace River, historical records show that the Town of Peace River (TPR) is particularly susceptible to ice-jam flooding. Even after the construction of the dam in the upstream headwaters, there were ice-jam flood events in 1973, 1974, 1979, 1992 and 1997 (Uunila & Church, 2015). The damages from these events can be very extensive, for example, it is estimated that the event of 1997 alone cost \$47 million and forced 4000 residents to evacuate (Public Safety Canada, 2013). Hence ice-jam flooding is a major concern for the communities in the TPR, despite having a dike system for flood protection (Lindenschmidt et al., 2016).

Thus, a critical and challenging question, as discussed by Rokaya et al. (2017), is how can we promote flooding in the downstream deltaic ecosystem, where it is essential, without necessarily increasing flood risk in upstream communities in the Peace River? In the past, there have been efforts to reduce flood risks in the TPR (JTF, 2006; Jasek et al., 2007) or occasionally to recharge the PAD (Prowse et al., 1996; Prowse & Demuth, 1996; Prowse et al., 2002); however, an integrated approach has not been presented yet, to the best of the authors' knowledge. This study reviews previous approaches, and explores possible reservoir operation schemes with an integrated hydrologic and hydraulic river ice modelling approach to minimize flood risk and maximize flood potential at desired locations. We demonstrate that, by increasing reservoir release in the breakup period, it is possible to increase the likelihood of ice-jam flooding in the PAD without necessarily causing ice-jam floods in the upstream communities. However, the timing of the flow release, taking into account the receding ice front and the local hydro-meteorological conditions is critical.

5.3 Site description

5.3.1 Study Site

The Peace River begins in the eastern slopes of the Rocky Mountains of northern British Columbia, see Figure 5-1. The river is 1923 km long and has a total drainage area of 293,000 km² at Peace Point. The headwater streams, many of glacial origin, drain into the Williston Reservoir (70x10⁹ m³) encompassing 24% of the total basin area of the Peace River (Peters & Prowse, 2001). The annual average flow (1960 to 2010) is 2090 m³/s as measured at the gauging station at Peace Point.

The average annual precipitation is about 467 mm (at Fort St. John) and typical summer (July) and winter (January) temperatures are 16°C and -18°C, respectively (Prowse & Conly, 2002).

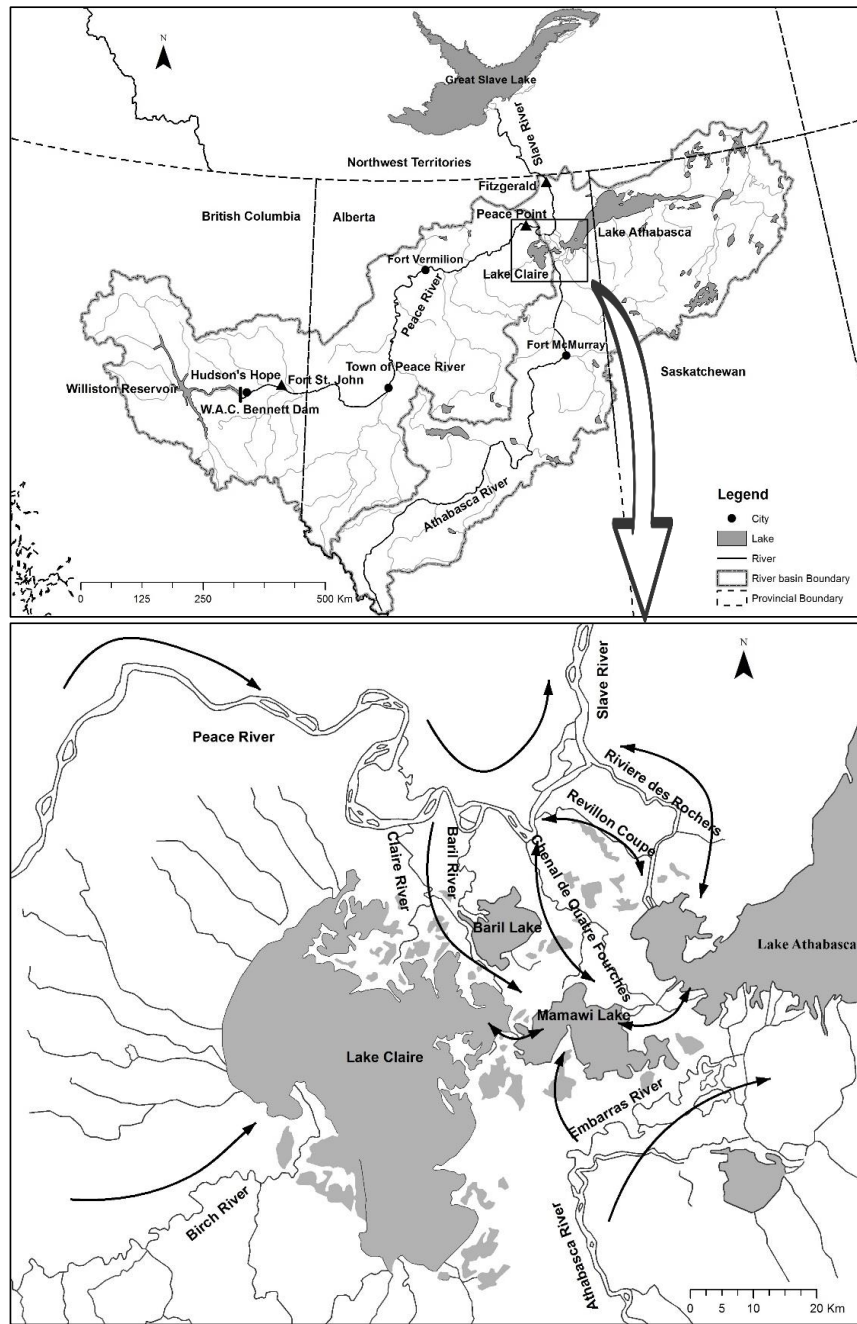


Figure 5-1: Map of the Peace River basin and the PAD. The black arrows in the PAD indicate the flow direction whereas two-headed arrows indicate the potential flow reversal directions, adapted from Peters et al. (2006a).

5.3.2 Hydrological connectivity of the Peace River and the PAD

The PAD (~6000 km²) consists of three smaller deltas: the Athabasca (1,960 km²), Peace (1,680 km²), and Birch delta (168 km²), along with three large lakes (Claire, Mamawi and Baril), see Figure 5-1. Prairie River and Chenal des Quatre Fourches connect lakes Claire and Mamawi to Lake Athabasca. Rivière des Rochers, Revillon Coupé, and Chenal des Quatre Fourches are the three major channels that drain the system into the Peace and Slave rivers (Peters et al., 2006a).

The Peace River can influence the water levels in the PAD through one of the following mechanisms as suggested by Peters et al. (2006a), Peters and Buttle (2010), BC Hydro (2013) and others: a) direct inflows into the PAD during flow reversals in the connecting channels during high open-water conditions, b) a “hydraulic dam” effect in which intermediate to high Peace River water levels impede the outflow in the connecting channels during open-water conditions, and c) dynamic ice-jamming in the lower reach of the Peace River that can lead to overbank flooding and the supply of water to the PAD.

The PAD consists of thousands of small lakes and wetlands which, based on their level of connectivity with the river channels and lakes, have been categorized as open, restricted or isolated (also known as ‘perched’) basins (Prowse et al., 2002). Since evaporation in the delta is generally larger than precipitation (with groundwater contribution being negligible), the recharge of the perched basins is highly dependent on floodwater (Peters et al., 1999). Only during ice-jam events, depending upon the final elevation achieved, may the rising water inundate perched basins (Peters & Prowse, 2001). For a detailed description of the flood hydrology of the PAD, see Peters et al. (2006a).

5.3.3 Earlier measures to recharge the PAD

Given the ecological importance of periodic flooding of the PAD, the Peace-Athabasca Delta Technical Studies (PAD-TS) group considered several water management options to artificially flood some portions of the delta (PAD-TS, 1996; Prowse & Conly, 2002). These approaches include both structural and non-structural measures. As an example of a structural measure, first a temporary dam was constructed on the west arm of the Quatre Fourches in 1971 to raise the water levels in the lakes and adjacent perched basins. However, it hindered fish migration and affected water quality, and thus, was subsequently removed (Prowse & Conly, 2000). Then, as a

replacement, two rockfill weirs were constructed on the Rivière des Rochers and Revillon Coupé in 1976. These weirs were comparatively successful in restoring the water levels on the delta lakes and channels to their pre-regulation states (Prowse et al., 1996); however, many perched basins still continued drying (Prowse & Demuth, 1996).

A second approach was to use ice to artificially flood the delta. In the first phase, immediately after regulation, there were attempts to construct an ice-based impoundment on the Rivière des Rochers to create an obstruction to large open-water flows. Notably, the focus was on open-water floods then, as the importance of ice-jam floods was not yet fully understood (Prowse et al., 2002). In the second phase in the 1990s, the role of ice-jam floods was recognized and the focus shifted towards ice-jam flood replication initiatives. Though major flooding in the PAD only results by ice-jam events in the mainstem Peace River, attention was centred on the smaller channels within the PAD. A mix of surface flooding (flood freezing) and spray ice techniques were tested in late-winter of 1993 in the Chenal des Quatre Fourches which augmented the ice cover thickness but did not result in flooding (Prowse et al., 1993). The evaluation by Prowse et al. (1996) found the spray ice technique to be more effective in producing large quantities of ice to block the large, deep channels. However, no jamming occurred due to the subsequent mild spring melt and runoff. In the following winter of 1994-1995, the spray ice method was again used on the west arm of Chenal des Quatre Fourches, but unfortunately, it was only a partial success due to unfavorable climate and flow regulation that year (Prowse & Demuth, 1996)

5.3.4 Past efforts to prevent the flooding of the TPR

The TPR largely relies on its dike system for flood protection which has been continually upgraded in response to historical flood events. In the aftermath of the 1972 open-water flood with a peak flow of 15,600 m³/s, the town dike was upgraded in 1974 to protect against a design flow of 17,839 m³/s. In 1981, 1:100-year annual exceedance probability of an open-water flood was calculated to be 20,133 m³/s and thus dike crests were raised by 1-1.2m. However, in 1990 a major open-water flood occurred. Again, in 1992, an ice-jam flood overtopped the dikes, thus, an additional 0.5m of freeboard was added based on the newly calculated design discharge of 21,200 m³/s. But an ice-jam flood occurred near the Heart River Bride in 1997, overtopping and bypassing the dikes at several locations. As a protection measure, the bridge was raised and an additional flood wall was built in 1999 (Bekevich, 1990). This was the last of the structural flood control measures

implemented. However, note that the dikes are designed for 1:100-year annual exceedance probability of open-water events, not for ice-jam floods which can cause significantly higher water levels and may result in overtopping of many sections of the existing dike system (Lindenschmidt et al., 2016).

5.3.5 Previous use of dam for flood protection and promotion

Flow control measures have been implemented jointly by Alberta Environment and BC Hydro to prevent ice-jam flooding in the TPR (JTF, 2006). Flows are continually monitored and regulated during freeze-up and breakup periods. Along with the Bennett dam, the adjacent Peace Canyon Dam is also used for flow control (Jasek et al., 2007). The major focus of these initiatives has been to minimize flood risks at the TPR and maximize power production without any consideration for flood promotion in the PAD.

One of the major recommendations of the Northern River Basins Study was a modified flow operation of the Bennett Dam to increase the probability of ice-jam formation and subsequent breakup events near the PAD (Prowse & Conly, 2000). Beltaos et al. (2006b) also suggested ‘reduced freeze-up stages’ and ‘increased spring flows when a mechanical breakup event appears to be likely’ as two possible mechanisms to recharge the PAD. In fact, in the spring of 1996, when all the hydro-meteorological conditions were deemed favorable, increased flows were released from the dam which resulted in the first major flooding in over two decades in the PAD (Prowse et al., 2002). Thus, for future work, Beltaos (2003) suggested the use of calibrated models to investigate the usefulness of revised flow operation in promoting ice-jam flooding in the PAD.

5.4 Data and methods

5.4.1 Meteorological data

In this study, a global meteorological forcing dataset for land surface modelling developed at Princeton University (Sheffield & Wood, 2007) was used as meteorological forcing inputs for the hydrological model MESH which includes precipitation, air temperature, pressure, specific humidity, wind speed and incoming longwave and shortwave radiations. The data set has a long temporal and global coverage. It is currently available globally at 0.25, 0.5 and 1.0 arc degrees and at 3-hourly, daily and monthly resolutions for the period 1948-2008 with an experimental update

(version 2) for 1901-2012 (Sheffield et al., 2006). The dataset is constructed by combining a suite of global observation-based datasets with NCEP/NCAR reanalysis and bias correction. The data are useful for understanding hydro-ecological processes and seasonal and inter-annual variability as well as to evaluate coupled models and other land surface prediction schemes (Sheffield & Wood, 2008).

5.4.2 Discharge and water level data

Water Survey of Canada, through Environment and Climate Change Canada's Hydat database (<https://ec.gc.ca/rhc-wsc/default.asp?lang=En&n=9018B5EC-1>), provides real-time and standardized hydrometric data at a daily time step. The real-time flow data are available for the past 18 months at any current time whereas the standardized data sets were available up to 2012 and in some gauging stations up to 2014. Some water level data are available from the website whereas long-term historical records can be requested from relevant Water Survey of Canada's provincial offices.

5.4.3 Hydrological Modeling

MESH

Modélisation Environnementale–Surface et Hydrologie (MESH), a semi-distributed physically-based land-surface hydrological model developed by Environment and Climate Change Canada (Pietroniro et al., 2007) was used for the hydrological modelling applications in this study. In MESH, the Canadian Land Surface Scheme is used to simulate the vertical water and energy fluxes to calculate the total surface runoff in each grid which is then routed between the grid cells and across the river network for the entire basin using WATFLOOD (Haghnegahdar et al., 2014). For computational efficiency in large, complex and heterogeneous river basins, it uses the Grouped Response Unit approach, i.e. combining areas of similar hydrological behavior. This method has been found more appropriate for large river basins because of its operational simplicity while retaining the basic physics and behavior of a distributed model (Pietroniro & Soulis, 2003). MESH has been widely used in different river basins in Canada and further details on model structure, setup and performance are available in the literature (e.g. Davison et al., 2006; Davison et al., 2016; Haghnegahdar et al., 2014; Mekonnen et al., 2014; Yassin et al., 2017).

MESH set up

The drainage database with an outlet at Peace Point was prepared using GreenKenue (http://www.nrc-cnrc.gc.ca/eng/solutions/advisory/green_kenue_index.html). The digital elevation model, land use data and soil data were obtained from Geogratia (<http://geogratia.gc.ca/>), GeoBase (<http://www.geobase.ca/geobase/en/data/landcover/index.html>) and Agriculture and Agri-Food Canada (<http://sis.agr.gc.ca/cansis/nsdb/slc/v3.2/index.html>), respectively. The parallel version of Dynamically Dimensioned Search algorithm (Tolson & Shoemaker, 2007), using a multi-algorithm auto-calibration program OSTRICH (Matott, 2005), was used for model calibration with the Nash and Sutcliffe (NS) Efficiency as an objective function. MESH was run at a 3-hourly time-step, matching the temporal resolution of input meteorological forcing data but output streamflows were generated at a daily scale for comparison and analysis. The model was first calibrated and validated for the pre-dam period (1959-1963 for the calibration and 1964-1967 for the validation) and after achieving good results ($NS > 0.8$) for both periods, it was further validated for the post-dam period from 1972 to 1982 which also yielded satisfactory results. Then the validated model was run for the entire post-dam period from 1972 to 2011. A controlled reservoir release feature was added in the post-dam simulation to ignore runoff generated upstream of the reservoir which is replaced with user-defined flow from the reservoir outlet. This does not affect areas in the basin that are outside the influence of the dam. For instance, the flows in the Smoky River and other downstream tributaries will remain unaffected. For further details on the model setup of the Peace River basin, the reader is referred to Rokaya et al. (2017).

5.4.4 River Ice Modelling

RIVICE

RIVICE, a one-dimensional hydrodynamic model, uses an implicit finite-difference numerical method to simulate river ice processes and phenomena such as ice generation, ice transport, ice cover formation, hanging dam development and ice jam progression along the river (ECCC, 2013). Ice-jams are modelled by coupling ice dynamics with river hydraulics as outputs from meteorological and river bathymetrical input parameters (Lindenschmidt & Chun, 2013). Detailed information on the model structure, setup, calibration and application of the Peace and Athabasca

ivers is provided in Lindenschmidt et al. (2015), Lindenschmidt et al. (2016), Lindenschmidt (2017b) and Lindenschmidt (2017c).

RIVICE set up

The modelling domain for the PAD extends from Peace Point to approximately 10 km downstream of the confluence of the Peace River and Rivière des Rochers near the outlet of Scow Channel. This long stretch of approximately 120 km was selected since all the lateral flows between Peace Point and the PAD as well as many of the identified historical ice-jams are located here. Details of four likely ice-jam lodgment sites along the Peace River can be found in Demuth et al. (1996). Cross section data were available from field surveys carried out by Water Survey Canada in 1994, 1995, 1999 and 2001 along the lower portion of the Peace River and the upper portion of the Slave River. The initial parameter values and ranges include slush ice pan and ice cover porosities and thicknesses, hydraulic roughness and ice strength properties along with the boundary conditions upstream discharge, downstream water level and lateral flows for calibration and validation were adopted from the previous numerical modelling studies of the PAD performed by Beltaos (2003). The model was run at a 30-second time-step. It was first calibrated for the ice-jam event of 1996 and then validated for 1997 event. During these two events, measurements and observations were carried out during and after the ice jams which heavily relied on daily aerial reconnaissance. Short summaries of the 1996 and 1997 events, along with the description of river and ice conditions, are available from Beltaos (2003).

Stochastic Modelling framework

Once RIVICE was calibrated and validated for the lower Peace River and upper Slave River for both open-water and ice-jam flood events, ensembles of water level profiles were simulated within a Monte Carlo (MOCA) framework using Model-Independent Parameter Estimation (Doherty, 1994) for further river ice analyses. There are four major boundary conditions and several model parameters whose distributions are essential to run RIVICE in a stochastic framework. The four boundary conditions include upstream discharge, downstream water level, toe of the ice jam and incoming ice volume (see Figure 5-2). For both boundary conditions and model parameters the values were randomly extracted from the probability density functions (pdf) within certain ranges (uniform pdf) or range of location and scale factors (Gumbel pdf). When data were available to

construct their pdfs (such as discharge and stages), the Gumbel function (Thompson, 1999) was used but when *a priori* knowledge on pdf shape was not available, a uniform pdf was used. This method is discussed in detail by Lindenschmidt (2017c).

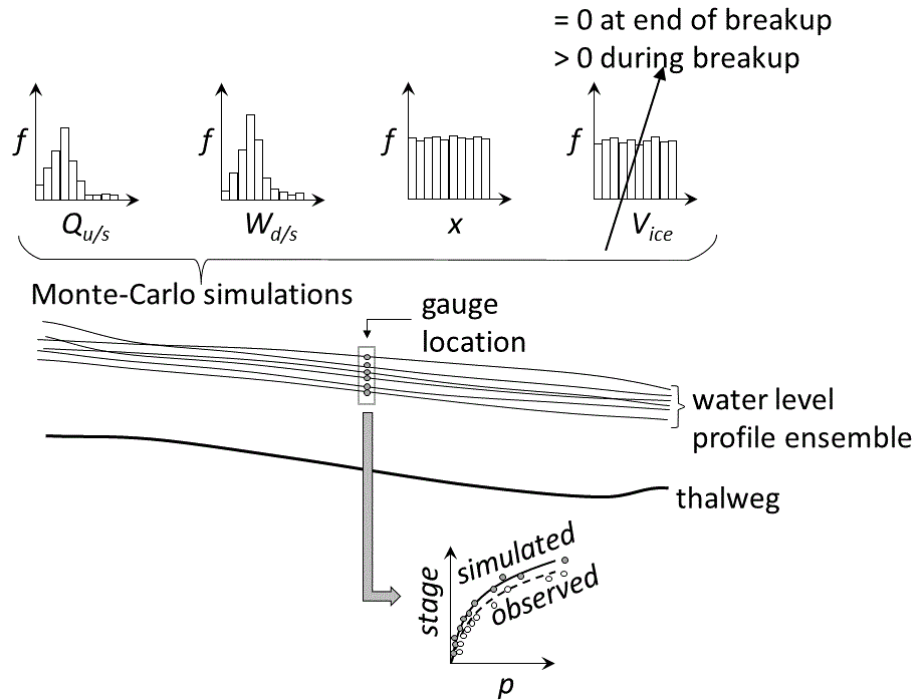


Figure 5-2: Conceptualisation of MOCA calibration strategy. $Q_{u/s}$ is upstream discharge, $W_{d/s}$ is downstream water level, x is the location of the toe of the jam, V_{ice} is incoming ice volume and p is return period. Line and dots in the stage-return period graph denote Gumbel and Gringorton distributions, respectively.

The upstream discharge is known from the Peace Point gauging station but the toe of the ice jam location and incoming ice volume are extremely difficult to measure or even estimate. There is no gauging station downstream of the confluence of the Peace River and Rivière des Rochers (the downstream modelling domain). There are a few water level measuring stations at or near the upstream delta channels but they do not have consistent data especially during the breakup period which limits their use. And the only reliable gauging station is at Fitzgerald but it is around 100 km downstream of the modelling domain. Thus, incoming ice volume and downstream water level require calibration. For the toe of the ice jam location, values from a uniform distribution were taken. The range of values were selected large enough to incorporate previously identified ice jam

locations by Demuth et al. (1996). Since reverse flows from the mainstem Peace River to the central delta lake has been observed during previous ice-jam flood events, when water levels at the former is higher than the latter locations (Peters et al., 2006a), negative lateral flows were added as an additional boundary condition. Since, there is no direct measurement of lateral flows in these delta channels, uniform distributions were generated for three major delta channels, the Chenal des Quatre Fourches, Revillion Coupé and Rivière des Rochers, based on previous available flow records for different years as reported by Beltaos (2003) and Peters (2003).

The model parameters used in this framework consist of 11 different parameters that represent slush ice (porosity of slush and thickness of slush pans), ice cover characteristics (porosity of ice cover, thickness of ice cover front, downstream ice thickness), hydraulic roughness (Nezhikhovskiy ice roughness coefficient and Manning bed roughness coefficient), ice strength properties (lateral:longitudinal stresses and longitudinal:vertical stresses) and deposition and erosion velocity thresholds. As *a priori* knowledge on the pdf shapes of these parameters were not known, a uniform pdf was used for each. The ranges for these parameters were drawn from previous studies on the Peace and Athabasca rivers such as Lindenschmidt et al. (2015), Lindenschmidt et al. (2016), Lindenschmidt (2017b) and Lindenschmidt (2017c) which have published the tables with parameters and their appropriate ranges for the Peace and Athabasca rivers.

5.5 Results and discussion

5.5.1 Hydrological Modelling

Hydrological Model Calibration and Validation

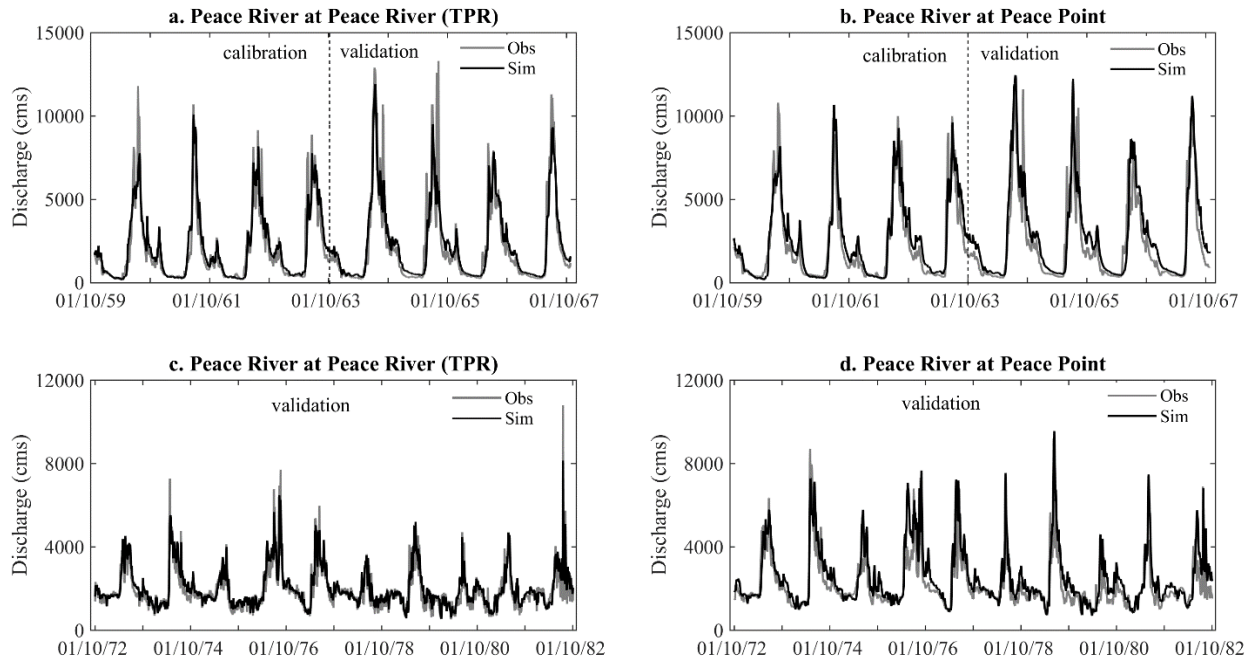


Figure 5-3: Hydrological model calibration and validation. 3a and 3b show daily simulated and observed flows at the TPR and Peace Point, respectively, for pre-dam years. 3c and 3d show simulated and observed flows validated during the post-dam period from 1972 to 1982, respectively.

The MESH model performed reasonably well for both the calibration and validation years. NS of 0.87 and 0.84 and $\log(\text{NS})$ of 0.89 and 0.82 were obtained for the respective gauging stations at the TPR (07HA001) and Peace Point (07KC001) for the calibration timespan. For the validation in pre-dam years, NS of 0.88 and 0.79, and $\log(\text{NS})$ of 0.89 and 0.81 were achieved for the respective gauging stations at the TPR and Peace Point (see Figure 5-3a and Figure 5-3b). Further validation was performed for the post-dam period of 1972-1982 which resulted in NS value of 0.82 and 0.64 and $\log(\text{NS})$ values of 0.79 and 0.59 at the TPR and Peace Point, respectively (see Figure 5-3c and Figure 5-3d). The model performance was also compared only for April and November month where most breakup and freeze-up events occur. The results show R^2 of 0.68 and 0.76 for April for Peace Point and the TPR, respectively. R^2 of 0.46 (Peace Point) and 0.73 (TPR) were obtained for November.

Revised flow operation

In the spring of 1996, when all the hydro-meteorological conditions were considered favorable, additional flows (from 1100 to 1600 m³/s) were released between April 25 and May 3 which resulted in the first major flooding of the PAD in over two decades. The approximate increase of 50% flow from the reservoir raised the water level by 0.27 m in the lower reach of the Peace River near the PAD. It was a significant flow augmentation available to flood the PAD considering that the river was already in a flood crest state (Prowse et al., 2002).

In the perched basins of the PAD, the primary source of recharge is precipitation and over-bank flow whereas open-water evaporation and evapotranspiration are the main water losses (Peters et al., 1999). Since evaporation is larger than precipitation with negligible groundwater flow, perched basins are estimated to dry up within 5-7 years without flood recharge (Prowse et al., 1996). Peters et al. (2006b) performed a detailed study of persistence of water within these isolated perched basins. Their findings show that 0.8 m deep ponded water lasted for about 5 years in a cool-dry period of the 1920s whereas in the post-1974 flood era, it lasted slightly longer. For the wet period during the 1940s and 1950s, water persisted for up to 9 years.

Thus, building on the findings of previous studies, this study explored a revised reservoir operation scheme in which additional flows (50% increase) were released for 10 consecutive days during the breakup period every 5 years. Flows were released based on the travel time of approximate 7 days from Hudson Hope (close to the reservoir outlet) to Peace Point to supplement the breakup flow. The breakup flow was considered to be the highest discharge within ± 3 days of the last 'B' value. The 'B' value, which is provided by Water Survey Canada along with hydrometric data, denotes ice induced 'backwater' effect due to the presence of ice at or immediately downstream of the gauge in the river. Thus, the discharge with the first 'B' value indicates the beginning of the freeze-up of the river whereas the last 'B' value is indicative of the end of the ice cover season. As the dam has been in operation since 1972, flow was modified for eight years, i.e. 1976, 1981, 1986, 19991, 1996, 2001, 2006 and 2011. The resulting hydrographs for 1976, 1981 and 1986 are presented in Figure 5-4.

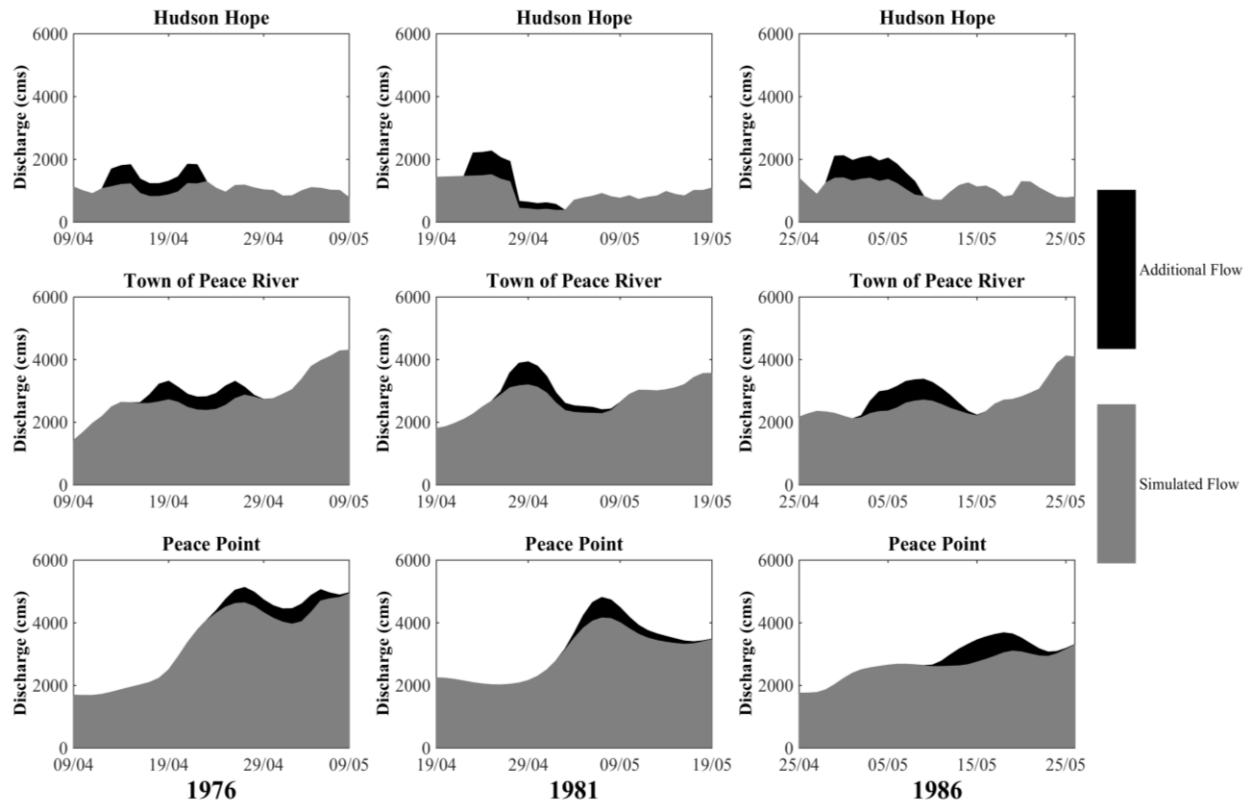


Figure 5-4: The increased flow release at Hudson Hope and simulated flow increase at the TPR and Peace Point for 1976, 1981 and 1986.

The results show that the 50% flow increase from reservoir translated to 12.4-20.8% (average 16%) at the TPR and 8.8-15.5% (average 11.7%) at Peace Point, respectively (details in Table C-1). The findings are in line with previous studies. Prowse et al. (2002) simulated the 1996 ice-jam flood event where 50% additional flow from the reservoir resulted in 11% flow increase near the PAD. However, it is to be noted that an increased flow does not necessarily result in an ice-jam flooding since ice-jam flood events are highly complex and unpredictable phenomena primarily governed by channel morphology, water level at freeze-up, ice characteristics, meteorological conditions and spring flows (Beltaos et al., 2006a). However, Beltaos (2003) has calculated a minimum discharge of 4000 m³/s to be one of the conditions for ice-jam breakup flooding in the PAD. Interestingly, in 1981, 2001 and 2011, increased reservoir releases resulted in more than 4000 m³/s of flow at Peace Point when simulated flows were lower than 4000 m³/s.

5.5.2 River Ice Modelling

Open-water calibration and validation

The model was first calibrated for an open-water event of 2001 and then validated with the observed data from 1994 and 1999. As a part of PAD-TS, cross sections were surveyed along the lower Peace River and the upper Slave River. During these surveys, water level elevations were also measured across several reaches that were used in this study for calibration and validation purposes. The surveys were performed in September and October during the open-water season. Thus, for calibration and validation, an average flow during these surveyed months was approximated for upstream discharge. For the 2001 open-water calibration, an upstream discharge of 1200 m³/s and downstream water level of 206.5 m.a.s.l. were used. For the respective validation years 1994 and 1999, upstream discharges of 1530 m³/s and 1910 m³/s and downstream water level of 205.70 and 206.30 m.a.s.l. were used. The incoming ice volume and toe of the jam were not used due to ice free season. Figure 5-5a and Figure 5-5c shows very good agreement between simulated water level profile and measured water levels during for the calibration and validation events.

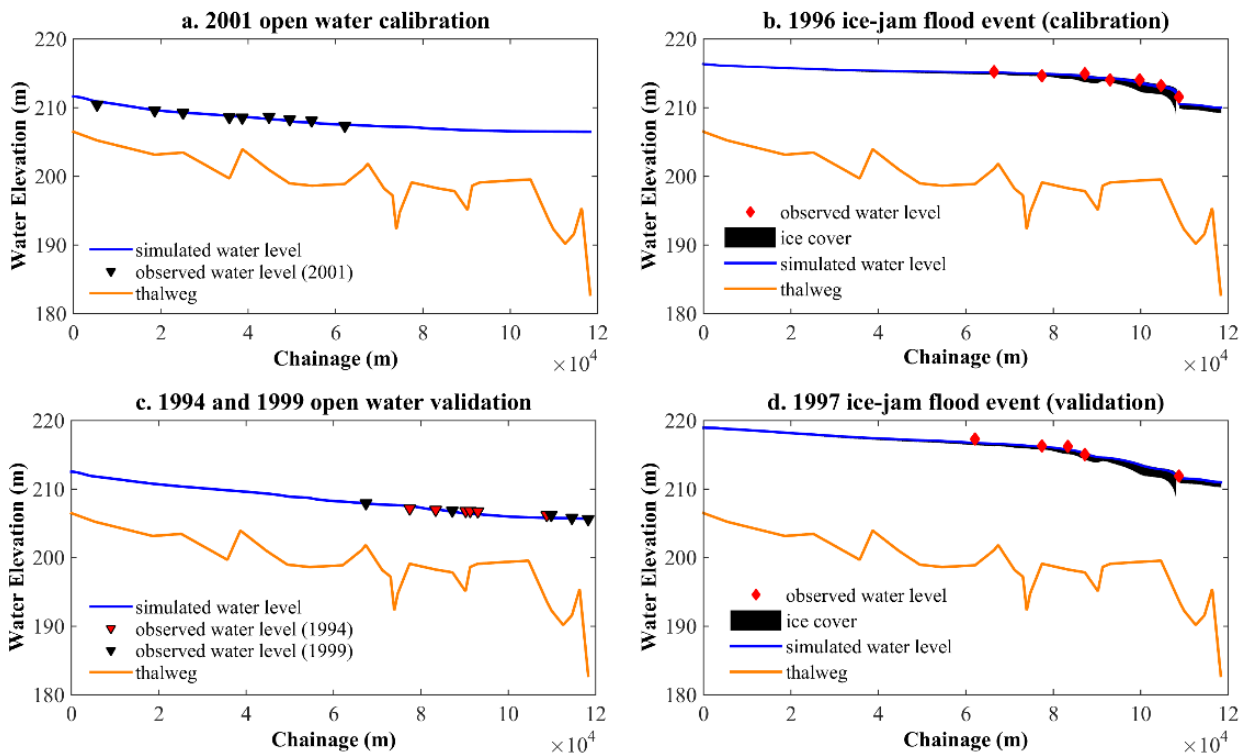


Figure 5-5: Open-water and ice jam calibration and validation along the Peace River in the PAD. (a) shows the calibration of the open-water event of 2001 and (b) shows the validation for the 1994 and 1999 open-water events. (b) and (d) show the calibration and validation for ice jam flood events of 1996 and 1997, respectively.

Ice jam calibration and validation

After the model was calibrated and validated for the open-water events, the ice-jam flood events of 1996 and 1997 were used for calibration and validation, respectively. Though ice-jam floods have also been observed in a number of other years such as 1963, 1965, 1972, 1974 and 2014, the lack of data limited the simulations to these events. Both events were previously modelled by Beltaos (2003) using a numerical model known as RIVJAM that computes the water surface and thickness profiles of a jam in a given river reach using field data obtained during those events. Thus, detailed flow and ice conditions including toe of the ice jam locations and lateral flows (reverse) in the delta channels are reported in the paper along with some of the model parameters that describe slush ice and ice cover characteristics, hydraulic roughness and ice strength properties.

For the 1996 calibration year, the upstream discharge of 4500 m³/s and the downstream water level of 210 m.a.s.l. were used. That year the toe of the ice-jam location was at the confluence of the Peace and Slave rivers. The incoming ice volume was estimated to be 28.8 million m³. In the validation year 1997, 5130 m³/s was used as the upstream discharge and 211 m.a.s.l. as the downstream water level. That year the toe of the ice jam location was observed 2 km below the outfall of Scow Channel in the Slave River whereas incoming ice volume was estimated to be 40.32 million m³. Figure 5-5b and Figure 5-5d shows that there is also a good agreement between the simulated water level profiles and the measured water level data along the river chainage in both calibration and validation events.

Downstream water level calibration

As discussed in the previous data and methods section, data on the downstream water level at breakup were not available as there is no gauging station below the confluence of Peace River and Riviere des Rochers. Thus, the downstream water level was calibrated to generate the pdf for MOCA runs using a method reported by Lindenschmidt (2017a, 2017c) and illustrated in Figure

5-2. In this method, several model evaluation runs were performed to generate water level profiles. Then the stage frequency distribution (SFD) was established from the simulated water levels at the gauge location and compared to the SFD of the measured water level data from the gauging station. This process is repeated until the simulated SFD is in good agreement with the observed SFD.

For the downstream water level calibration at breakup, the upstream discharge is obtained from the gauging station at Peace Point (07KC001). As only Peace Point has reliable water level data at breakup, simulated water levels at breakup were compared with the water levels observed at Peace Point at the last 'B' value. The flows at the last day of the 'B' value observed at Peace Point were used for the upstream discharge. As evaluations were carried out for the last day of 'B' value, the incoming ice volume was assumed to be negligible. The pdf of water level at freeze-up was used for the initial run for the downstream water level calibration and with each simulation results, distribution parameters, scale and location were adjusted until the median of the resulting ensembles of simulated SFD matched with the observed SFD. It is a very computationally expensive process as to get one set of SFD, 35 model runs were required. Thus, to produce an ensemble of 100 SFDs, 3500 model runs were performed.

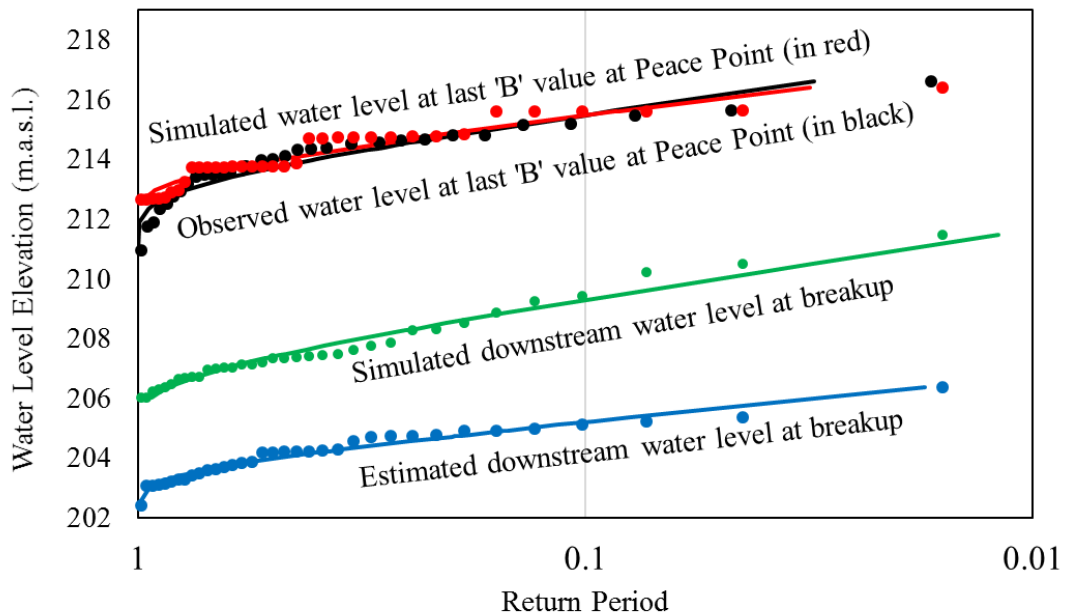


Figure 5-6: Downstream water level calibration. Black and red colors represent observed and simulated SFD at Peace Point, respectively which were used for calibration. Green color shows

calibrated SFD whereas blue denotes estimated SFD. Lines and dots in all represent Gumbel and Gringorton plots, respectively.

Figure 5-6 shows good agreement between the median of the simulated SFD and observed SFD at the gauging station in Peace Point. The blue line and blue dots show downstream Gringorton plotting positions and Gumbel SFDs, respectively shifted from the upstream gauge based on distance and slope. The estimated downstream SFD is several meters lower than the calibrated downstream SFD for different return periods. Thus, the figure demonstrates that the downstream water level at breakup is a very sensitive boundary condition and needs calibration as simple estimations might result in over or underestimations.

Ice volume calibration

A similar calibration strategy was applied for ice volume. Among four boundary conditions, the upstream discharge was available from the gauging station at Peace Point. But for ice volume calibration, flows at breakup were used instead of flows at last 'B' value and simulation results were compared against observed ice-induced instantaneous maximum water levels. A uniform distribution that incorporates all four previously identified potential ice-jam lodgment sites was used for the toe of the ice-jam location. For the downstream water level, the Gumbel SFD of calibrated downstream water level from previous result was used. Model evaluations were performed by generating SFDs at the Peace Point gauge location and comparing the simulated SFD with observed SFD of instantaneous maximum water level observed at Peace Point gauging station. The calibration was repeated several times adjusting distribution parameters until simulated SFD was in good agreement with the observed SFD (see Figure 5-7).

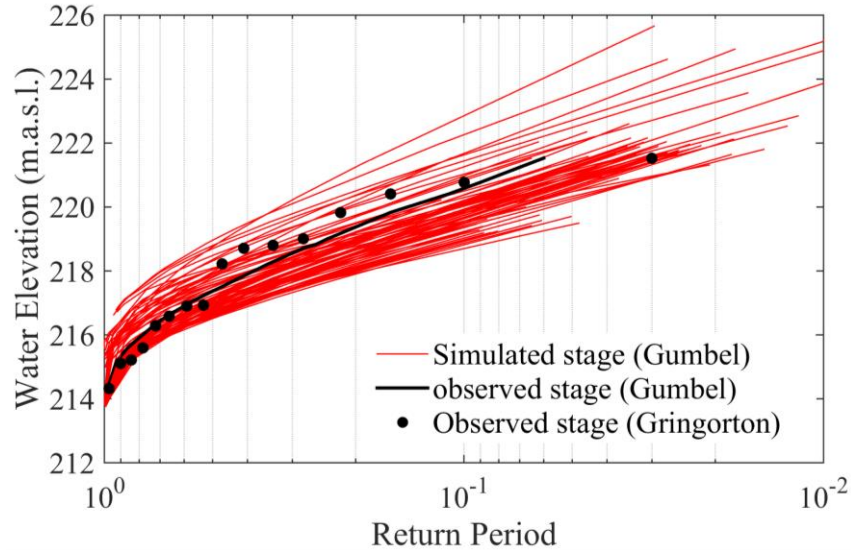


Figure 5-7: Ice volume calibration. Black and red lines denote observed and simulated instantaneous maximum SFD at Peace Point.

Probabilities of the flooding in the PAD

RIVICE was run within the stochastic modelling framework after the downstream water level and incoming ice volume were calibrated. A Gumbel pdf was used for the upstream discharge, downstream water level and incoming ice volume whereas a uniform pdf was used for the lateral flows in deltaic channels, the toe of the ice jam location and other 11 RIVICE model parameters. Two sets of scenario runs were performed with 1000 model evaluations for each. Both model evaluations included a unique parameter set drawn from Gumbel or uniform distributions. The first 1000 consisted of the business-as-usual scenario in which the simulated discharge pdf at breakup obtained at Peace Point was used as the upstream boundary condition. In the second scenario, instead of simulated discharge, the modified-simulated discharge pdf (representing increased reservoir release at 5-year intervals simulated by MESH) at breakup was used. All other boundary conditions and internal parameters sets were kept identical so that the influence of increased upstream discharge in ice-jam flooding probability in the PAD can be assessed.

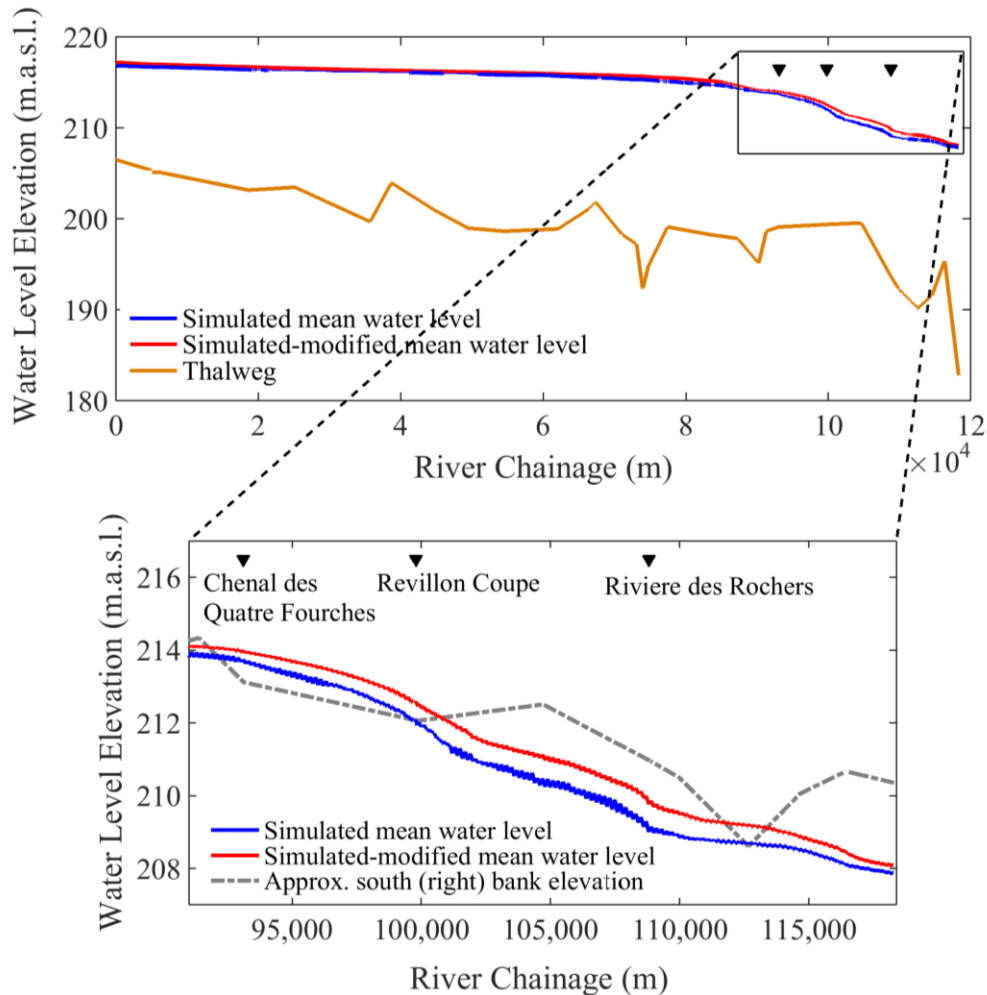


Figure 5-8: Simulated water level profiles along the study reach of the Peace River

Figure 5-8 shows the mean simulated water level from 1000 business-as-usual scenario (blue line) and 1000 increased reservoir release scenario (red line). When compared with the south (right) river bank elevations where perched basins and deltas are located, both scenarios can likely result in overbank flooding during an ice-jam event. However, with increased flow release from the reservoir, water levels can increase by nearly a meter. In lateral tributaries, such as Chenal des Quatre Fourches, the water levels with increased reservoir release were found to be 0.2 m higher whereas in Revillon Coupé, a half a meter increase can be obtained. In a low-lying delta such as the PAD, even an additional increase of several centimeters can have significant potential in flooding a large portion of the delta, and, depending upon the final elevation achieved, may recharge the high-elevation perched basins.

These findings support the previous hydrologic studies which have concluded that breakup flows play an important role in ice-jam flooding (e.g. Beltaos, 2003, 2014; Beltaos & Carter, 2009; Beltaos et al., 2008; Prowse & Beltaos, 2002) and increased flows from reservoir at opportune times may potentially enhance ice-jam flooding in the PAD (e.g. Beltaos, 2003; Beltaos et al., 2006b; Prowse & Conly, 2002). Recent analyses of river ice processes by Sheikholeslami et al. (2017), Zhang et al. (2017) and Lindenschmidt and Chun (2013) using regional and global sensitivity analyses methods have also found breakup flows to be one of the most important and sensitive boundary conditions in hydraulic models resulting in higher backwater levels.

Prowse and Demuth (1996); Prowse et al. (2002) simulated flow release and enhanced flooding of the PAD for the 1996 ice-jam flood event suggesting the potential of controlled flow release in recharging the perched basins of the PAD. This study has further demonstrated through hydrologic and hydraulic modelling works that it is technically feasible to promote sustainability of the downstream deltaic systems of the PAD through appropriate reservoir operating schemes.

5.5.3 Pre-conditions for ice-jam flooding

One of the major challenges in promoting ice-jam flooding in the PAD is to protect the river-side communities such as the TPR and Fort Vermillion from potential flood risks. There is already an operating procedure to monitor and control freeze-up and breakup conditions of the Peace River at the TPR to prevent any possible ice-jam flooding, agreed to by Alberta and British Columbia (JTF 2006). The agreement's objective is to maintain the water level during freeze-up period at or below 315 m with a target discharge of 1400-1600 m³/s, whereas the breakup water level is aimed not to exceed an elevation of 314 m.a.s.l. with a flow threshold of 3200 m³/s at the TPR as a protection against the 1:100-year flood (Jasek et al., 2007). Examples of the cases when elevated freeze-up levels at the TPR were controlled by revised flow operation in the past are documented by Jasek and Trevor (2009). In our study, we have focused on increased flow release during the breakup period at the PAD. The historical record from gauging stations at the TPR and Peace Point shows that there is a significant time lag between the two. The average breakup in the TPR occurs around mid-April whereas it is around the second week of May at Peace Point. Thus, releasing additional water during the breakup period in the PAD will not increase the risk of ice-jam flooding in the TPR as the receding ice front will already have progressed downstream. This is also a reason

why we did not carry out RIVICE simulations to calculate potential ice-jam flood risk for the TPR in this study.

However, beside TPR, there are also several communities downstream, noticeably at Fort Vermillion but also along many locations in the Peace River near the PAD (see Figure 5-9), which also require protection against ice-jam flooding. Although historical data at the Peace River gauging station at Fort Vermillion are seasonal and often incomplete, there is a continuous flow (since 2006) and water level (since 2012) record in recent years which can be helpful to understand recent breakup dates and patterns. Alternatively, each year, ice jam progression and recession fronts are continuously monitored by Alberta Environment and Parks using Moderate-Resolution Imaging Spectroradiometer (MODIS) (Alberta Government, 2017), thus, additional flows from the reservoir can be released once the ice front has receded downstream of Fort Vermillion to prevent any possible ice-jam flooding.

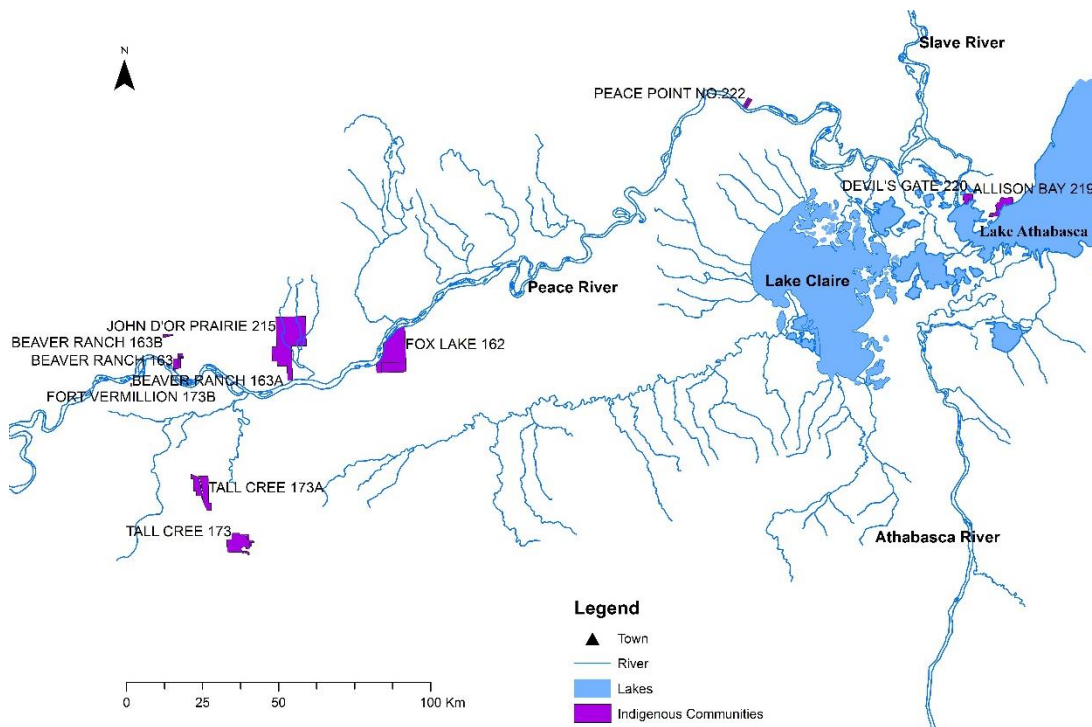


Figure 5-9: Indigenous communities along the Peace River

The third important aspect to consider for the promotion of ice-jam flooding in the PAD is the local hydro-meteorological conditions. There is no set of institutionally agreed and enforced conditions to promote flooding in the PAD. However, there have been a number of field

experiments in the past, notably in the spring of 1996, which resulted in the first major flooding in 20 years in the PAD when an additional 500 m³/s flow was released for a week after estimating hydro-meteorological conditions were favorable (Prowse et al., 2002). Previous research on the ice-jam flooding of the PAD such as Beltaos et al. (2001), Beltaos (2003) and Beltaos et al. (2006a) has already outlined some of the conditions for the occurrence of the ice jam flooding. These include ice jam formation within the lower reach of the Peace River near the PAD, breakup flow exceedance of 4000 m³/s and early enough occurrence of the breakup event in the season that it is of the mechanical type. In their study of the ice regime of the lower Peace River and ice-jam flooding of the PAD, Beltaos et al. (2006b) have also estimated a freeze-up stage of approximately 213.0 m as an ideal pre-condition for a dynamic breakup event.

5.6 Conclusion

In this study, we showed that the hydrological model MESH is capable of simulating streamflows of a large and heterogenous basin. We also demonstrated that, by increasing reservoir release during the breakup period, it is possible to increase the likelihood of ice-jam flooding in the PAD, without necessarily resulting in ice-jam floods in the upstream communities of the TPR. Thus, it is possible to promote sustainability of downstream ecosystems using appropriate reservoir operating schemes in regulated rivers. The timing of the release, however, is of great importance and needs to be taken into account considering the ice cover breakup recession and other hydro-meteorological conditions. Similarly, the travel time of the released flow from the reservoir to the downstream deltaic reach should also be taken into consideration.

From our river ice analysis within the stochastic modelling framework, we also demonstrated that the increased flow release from the dam can result in significant higher water levels in the lower delta reach. In the case of ice-jam flooding, it is well known that even a small discharge can result in higher water levels depending on other hydro-meteorological conditions. To address the uncertainties within the modelling work, we did not rely on a single model run but rather employed an ensemble of over 1000 simulations. Further work is recommended to examine what magnitude of discharge under ice jam conditions can be released without impacting the communities in Fort Vermilion and further downstream along the Peace River.

5.7 Acknowledgments

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5.8 Author contributions

KEL proposed the idea of this study. PR carried out hydrological and hydraulic simulations as well as analyses and interpretations of the results. PR wrote the manuscript, and KEL and HW contributed texts and feedback.

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5.10 Appendices

Appendix C Results and Discussion

Table C-1: The increased flows at Hudson Hope and subsequent flow augmentation at the TPR and Peace Point.

		1976	1981	1986	1991	1996	2001	2006	2011	Avg.
Hudson Hope	Avg. flow	552.3	458.4	504.9	458.0	630.0	605.4	468.8	542.7	527.5
	increased (m ³ /s)									
	Avg. percent increased	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0

TPR	Avg. simulated flow increased (m ³ /s)	519.8	431.1	473.7	444.1	603.9	569.6	439.7	524.4	500.7
	Avg. percent increased	15.9	16.9	12.4	12.7	17.8	18.4	13.8	20.8	16.1
Peace Point	Avg. simulated flow increased (m ³ /s)	489.8	414.2	462.3	436.1	602.3	534.0	408.5	513.8	482.6
	Avg. percent increased	10.8	12.5	9.4	8.7	13.9	13.9	8.8	15.5	11.6

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

This dissertation investigated the impacts of climate and regulation on ice-jam flooding of the northern rivers and inland deltas. Chapter 2 reviews all the peer-reviewed publications on IJFs published up to October 2017 by analyzing the data available from the Web of Science. It assesses the nature and scope of scholarly research on IJF, and suggests an agenda for research that better integrates IJF challenges with research opportunities. This chapter also highlights the recent advances in IJF research but also existing gaps, challenges and opportunities.

Chapter 3 studies the implications of hydro-climatic trends on river ice processes, particularly on ice-covers freeze-up and breakup along the Athabasca River in Fort McMurray. Using a stochastic approach in a 1D hydrodynamic river ice model, a relationship between overbank flow and breakup discharge was established. Furthermore, the likelihood of ice-jam flooding in the future (2041–2070 period) was assessed by forcing a hydrological model with meteorological inputs from Canadian Regional Climate Model driven by two global climate models. Our results show that the probability of ice-jam flooding in the future will be lower but extreme IJF events are still probable.

Chapter 4 discusses the effects of regulation and climate in the frequency and magnitude of IJFs presenting the Town of Peace River in Alberta, Canada as a case study. A novel modelling approach that couples physically-based hydrologic and hydraulic models to assess ice-jam flood risk in a stochastic framework is presented. Naturalized flows are generated for the comparison, and using discharge-frequency and stage-frequency analyses, relative impacts of climate and regulation are quantified. The results show that in both regulated and naturalized conditions, there are reductions in flood frequency and stage-frequency curves between two study periods with 1983-2012 showing lower curves than the 1973-2003 period suggesting some climatic impacts. However, the water levels during ice-jam staging at the TPR are approximately 1 m higher due to regulation compared to naturalized conditions.

Chapter 5 addresses the conundrum of promoting IJFs in the downstream deltaic ecosystem, where they are essential, without necessarily increasing flood risk in upstream communities in the Peace River in western Canada. This chapter reviews previous approaches, and explores possible reservoir operation schemes with an integrated hydrologic and hydraulic river ice modelling approach to minimize flood risk and maximize flood potential at desired locations. The results show that with increased flow release from the reservoir, water levels can be increased by nearly a meter. In lateral tributaries, such as Chenal des Quatre Fourches, the water levels with increased reservoir release were found to be 0.2 m higher whereas in Revillon Coupé, a half meter increase can be obtained. In a low-lying delta such as the PAD, even an additional increase of several centimeters can have a significant potential in flooding a large portion of the delta, and, depending upon the final elevation achieved, may recharge the high-elevation perched basins. These findings support the previous hydrologic studies which have concluded that breakup flows play an important role in ice-jam flooding (e.g. Beltaos, 2003, 2014; Beltaos & Carter, 2009; Beltaos et al., 2008; Prowse & Beltaos, 2002) and increased flows from the reservoir at opportune times may potentially enhance ice-jam flooding in the PAD (e.g. Beltaos, 2003; Beltaos et al., 2006; Prowse & Conly, 2002).

One important methodological contribution is the introduction of probability-based extension of the hydro-technical modelling approach that couples physically-based hydrologic and hydraulic models to assess the relative impacts of climate and regulation within a stochastic framework. This offers more robust assessment than previous deterministic approaches. Prowse and Demuth (1996); Prowse et al. (2002) simulated flow release and enhanced flooding of the PAD for the 1996 ice-jam flood event suggesting the potential of controlled flow release in recharging the perched basins of the PAD. This dissertation has built upon previous studies and demonstrated that it is feasible to promote sustainability of the downstream deltaic systems through appropriate reservoir operating schemes. Finally, as ice-jam flooding, both at present and future remains a major concern in northern IJF prone communities a probability curve of overbank flow based on breakup discharge is presented. Using a stochastic approach to evaluate the role of flow magnitudes on probability of IJF is a novel approach, and may serve as an important benchmark for future IJF studies, especially for estimating future IJF probabilities.

6.2 Future Work

Despite significant advances in river ice hydrology, our understanding related to several aspects of IJFs still remains limited. More research is required on changes to the breakup regime of rivers and consequences to the frequency and severity of IJFs (Beltaos & Prowse, 2001). Though importance of river ice in producing hydrologic extremes, such as low flows and floods has been documented for a small number of site-specific cases, no regional assessments of its large-scale importance have ever been conducted (Prowse & Beltaos, 2002). Similarly, IJF delineation still remains a significant challenge (Kovachis et al., 2017) even for streams and small rivers (Turcotte et al., 2017). IJFs are controlled by meteorological conditions and are thus sensitive to changes in prevailing climate (Prowse & Beltaos, 2002). Projected future decreases in south to north air-temperature gradients suggest that the severity of ice-jam flooding may be reduced, but this could be mitigated by changes in the magnitude of spring snowmelt (Prowse et al., 2011). However, despite recent advancements, there is still progress to be made in quantifying the effects of a changing climate on the ice regime and IJF of northern rivers (Beltaos & Burrell, 2015).

Determining probable maximum backwater staging from ice-jam floods still remains a significant challenge. While open water discharge and water levels can be associated with a smooth deterministic curve, backwater levels from ice accumulations or the more severe ice jam events cannot be associated due to the stochastic nature of river ice processes. The reason for the stochasticity in the discharge/water level relationship is that similar backwater level profiles can occur through different water and ice flow conditions leading to ice jamming. One approach to capture the stochasticity is to embed a deterministic river ice model into a Monte-Carlo Analysis framework and generate hundreds of probable simulations each having a different set of parameters and boundary conditions to estimate probable maximum backwater staging. But further research is required to demonstrate this proof of concept or explore other methods.

Data limitations have been one of the major challenges in ice-jam flood (IJF) research. Particularly, monitoring and documenting ice cover breakup events have remained a major obstacle as these events can be extremely dangerous for human observation. However, in recent years, remote sensing has offered an opportunity to monitor and document complex river ice processes. Further applications of remote sensing tools will help in understanding complex river ice processes but also provide valuable data for calibration and validation of river ice models.

In this dissertation and many other studies of river ice modeling when using Monte Carlo simulations, boundary conditions and parameters are usually sampled independently from their probability distributions. However, in many cases, the parameters are correlated with one another. Saltelli and Tarantola (2002) have proposed an algorithm to identify most important inputs in the case of dependent variables, Kucherenko et al. (2012) proposed a new method based on the Sobol method to estimate the global sensitivity indices with dependent parameters that can be used in complex hydrological models, and the Generalized Likelihood Uncertainty Estimation method (Freer et al., 1996) which has also been employed to detect correlated parameters (Ratto et al., 2001). Future work should adopt sampling methods that consider correlation effects.

It has also been demonstrated that additional reservoir releases at opportune times can result in increased water levels in the PAD without increasing IJF risks in upstream communities of the TPR. Further studies are recommended on two fronts. First, ecological studies are needed to assess the probable water levels in the PAD that are essential to support the range of native vegetation and aquatic species. Second, soft measures such as additional reservoir releases, as proposed in this study, could be cost-effective and environmentally-friendly solutions compared to any structural measures that are likely to be expensive and have negative impacts on river ecology. But, such studies need to be accompanied by further economic assessments to demonstrate the financial implications of the proposed approaches.

Identifying, understanding and quantifying flood hazard is the first step in reducing flood risk (Lindenschmidt et al., 2016). An integrated flood risk management framework will also include an assessment of vulnerability of local people and communities that are susceptible and exposed to flood hazard. Future work should focus on assessing flood inundation, vulnerability assessment as well as potential economic damages. Recently, Das et al. (submitted) and Das et al. (2017) have used the potential future flow estimated in Chapter 4 for the FTM in Athabasca River to assess IJF risks under future climate scenarios which included detailed flood inundation mapping. Similar assessments are recommended in other areas which have been identified as high flood risk areas.

During the literature review, it was also observed that only one article out of 188 publications addressed social aspects of IJF. This limited research on social aspects of IJF shows that, unlike open-water flood, IJF research is still in its infancy in incorporating the human dimension. On the

positive note, it suggests untapped opportunities to integrate knowledge, methods and tools from social science research in enhancing IJF risk resiliency.

The understanding of potential impacts of climate change on river ice processes in general and IJFs in particular also remains limited. Further research is required in coupling river ice models with climatic (such as Global and Regional Climate Models) and hydrologic models for detailed quantitative predictions of climate change impacts on IJFs. Such an assessment also needs to consider different sources of uncertainties in model outcomes. Future work should adopt an ensemble approach and evaluate the potential implications within a stochastic framework.

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