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Flood Hazard and Risk Delineation of Ice-Related Floods: Present Status and Outlook

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ABSTRACT: Delineation of flood hazard and risk on maps can serve as a means of public education and as a basis for flood-damage-reduction measures aimed at the lessening future flood damages. Procedures and standards for flood mapping for open-water (ice-free) events have been performed by several jurisdictions and are well established. In many northern countries, rivers and streams are prone to ice-related flooding, and these flood events often result in higher water levels and more extensive damages than open-water events. Ice-related flood events are highly variable and difficult to evaluate, especially with respect to likelihood of site-specific re-occurrence and statistical frequency. In addition, field data and other information required for hydrotechnical modelling of flood risk are often unavailable, and standards for ice-related floodplain delineation are less developed. Therefore, many jurisdictions have not adopted guidelines and standards for producing flood hazard and risk mapping incorporating ice-related flood events, and ice-related flood maps are uncommon despite the reality of ice-jam flooding. In this paper, the present status of delineating ice-related flood events and barriers to delineating ice-related floods are discussed. Methodologies for evaluating flood risk along rivers prone to ice jamming are discussed and preliminary guidance provided for producing flood maps that include consideration of both open-water and ice-related floods.

RÉSUMÉ: La délimitation de zones inondables peut servir à des fins de formation, de développement durable et comme outil pour la mise en place de mesures d'atténuation du risque. Les procédures menant à l'élaboration de cartes d'inondation à l'eau libre (sans glace) sont bien documentées et ont été utilisées dans plusieurs contextes par plusieurs instances publiques et privées. Dans les pays nordiques, les cours d'eau causent également des débordements en présence de glace. Ces événements sont souvent associés à des niveaux d'eau et à des dommages plus importants que lors d'inondations à l'eau libre. Les inondations causées par les glaces surviennent de manière hautement variable et difficilement prévisible. Elles sont donc complexes à quantifier, particulièrement par rapport à l'évaluation de leur fréquence à un site donné. De plus, les données de terrain et les informations complémentaires permettant une modélisation hydrodynamique adéquate des phénomènes de glace menant à des inondations sont souvent manquantes et les procédures menant à la détermination des cotes d'inondation en présence de glace sont moins bien documentées que les cotes à l'eau libre. En conséquence, les instances œuvrant dans le domaine des inondations possèdent très peu d'outils permettant la détermination du risque hivernal et printanier associé aux glaces et la plupart d'entre elles sont réticentes à entreprendre des démarches permettant l'élaboration de cartes d'inondation en présence de glace. Cet article étale l'état actuel des connaissances permettant la détermination des niveaux d'eau pouvant être atteints en présence de glace et décrit les obstacles contraignant l'élaboration de cartes de zones inondables par les glaces. Des techniques permettant l'évaluation du risque d'inondation des cours d'eau en présence de glace et l'ébauche de lignes directrices ayant pour objectif la production de cartes d'inondation en pays nordiques sont présentées.

1. Introduction

Essential to the protection of people from natural hazards is the identification of areas potentially exposed to that hazard. A hazard creates vulnerability for sectors of society, the built environment (property and infrastructure), and the environment based on the sensitivity of those components to the hazard. One of the more devastating natural hazards is flooding. Flood hazards along river systems unlike some other types of natural hazards are generally predictable. Floods most likely occur on rivers that experienced flooding in the past. Despite this, knowledge of a flood hazard may not be common among residents due to the time since the last damaging event or their recent arrival in the area. Therefore, identifying and understanding flood hazards are key steps towards protecting public safety and mitigating the costs associated with flood damages, which can be expressed in the context of risk.

Types of floods include regional (stream) and urban floods caused primarily by precipitation and snowmelt runoff, coastal floods due to high tides and storm surges, basement and depression floods caused by high groundwater levels, floods associated with increased stage behind an obstruction to flow, and flood waves upon the upstream failure of a dam or release of a channel blockage. This paper focuses on identification of flood hazard and risk due to ice along rivers and streams.

Ice-related floods can be caused by distinct ice processes, among which the formation and release of ice jams is the most common. Ice jams are blockages to channel flow that cause a temporary rise in water levels that is higher in stage than floods during ice-free conditions with equivalent flow. On several rivers in northern climates, ice-related flood stages greatly exceed the water levels attainable with open-water events. The depth and extent of inundation contributes to the severity of flood damage to property and infrastructure (direct damages), whereas the rapid rise in water levels that can be associated with ice-jam formation and release can endanger public safety.

The purpose of this paper is to present an overview of flood delineation with respect to ice-related hazards along rivers. A secondary objective is to emphasize the need to consider ice-related floods when delineating flood hazard and (or) risk. Subsequent sections deal with ice-jam severity and damages, the approaches to mapping ice-related floods, the uses of flood delineation mapping, hydrotechnical considerations with respect to delineation, and future needs. These sections are followed by concluding remarks containing primary findings and recommendations.

2. Ice-Jam Flood Severity and Damages

2.1 Damage Potential

In northern countries, ice-jam events cause some of the largest and most destructive flooding on record along river channels of varying sizes and morphologies. In addition to damages sustained by floodwater inundation and swift moving water, the tremendous forces applied by large pieces of moving ice exacerbate flood damages and can create life-threatening conditions.

Depending on the season, ice-jam flooding can occur for a wide range of durations. In many cases, the flooding caused by an ice jam can be intense, but persist for a relatively short period. This is particularly true of spring breakup ice jams. Water levels typically drop following the release or melting of the ice jam that created the backwater. In the cases of freeze-up or midwinter ice jams, flooding can persist for several months while temperatures remain below freezing and ice jams remain intact (Beltaos et al. 2007a). The freezing of floodwaters impounded behind (and possibly frazil accumulations under) these lasting mid-winter ice jams also causes additional damages.

Damages caused by ice-jam flooding can include property, infrastructure, interference with navigation, impedance of hydropower generation, as well as adverse ecological impacts (Beltaos 2003, Ettema et al. 2009, Hicks 2008). Ice-jam flooding can also lead to indirect costs, such as traffic disruption, loss of industrial production and emergency costs. Once an ice jam has released, moving water and ice can exert horizontal and vertical forces on structures, which can result in bending, compression and impact forces, as well as buckling, uplifting, bed scour, and abrasion (Beltaos et al. 2007b). If the ice jam and associated backwater is contained within the banks, these damages are limited to in-stream infrastructure. Should the ice jam result in overbank flooding, especially in a developed area, the damage potential of moving ice can dramatically intensify.

2.2 Perth-Andover, New Brunswick

Situated on both banks of the Saint John River, New Brunswick, the village of Perth-Andover (pop. ~ 2000) extends between ~21 and 27 km upstream of Beechwood Dam. It is located ~300 km upstream of the river mouth and some 60 km south of Grand Falls. The drainage basin area of the Saint John River near the upstream limits of Perth-Andover (P-A for short) is 33 300 km^2 (Acres 1977). The Saint John River flows approximately 670 km, falling some 480 m from its headwaters upstream of Little John Lake in Maine, USA, to where it empties into the Bay of Fundy at Saint John (Inland Waters Directorate 1974). Hydropower developments were established along the Saint John River at Grand Falls (1927), Beechwood (1955) and Mactaquac (1968); there are also hydropower developments on the lower reaches of the Aroostook and Tobique rivers that flow into the Saint John River upstream of Perth-Andover.

Ice jams often form during the spring breakup of the ice cover at various locations along the Saint John River and its tributaries, causing large damages and, on rare occasions, loss of human life. Humes and Dublin (1988) determined that ice jamming was a contributing factor to 42% of all flood events in the Saint John River basin while ice-related events accounted for 69% of the total flood damage costs. Perth-Andover has been hit particularly hard in the past five decades, having experienced severe ice-jam related flooding in 1976, 1987, 1993, 2009, and 2012. According to Humes and Dublin (1988), the 1987 spring freshet caused ice-jam flood damage costs in the Saint John River basin of ~$ 30 million (1987$ or 54 million 2014 $; a major part of this cost was due to the P-A flood. [Canadian inflation data were obtained from the following link on Feb. 24, 2015: http://www.bankofcanada.ca/rates/related/inflation-calculator/].

Table 1 lists 19 recorded flood events for the P-A area with the earliest being in 1887 and the most recent in 2012. The floods were caused by several factors, but all of the major events were associated with ice jamming, which was a contributing factor in 13 of the 19 events listed in Table 1. All but two of the 13 ice-jam related floods occurred after construction of the Beechwood Dam. Prior to 1976, recorded floods affecting the area did not produce the extent of damages associated with later floods. This is consistent with a recent quantitative assessment of the potential for jamming near P-A: Beltaos and Burrell (2015) found that jamming potential is considerably higher in the Beechwood headpond section (0 to ~30 km from the Dam) than farther upstream. This result stems from the low water surface slope and large channel width and depth, all typical features of reservoirs.

Table 1. Past Floods Affecting the P-A Area, New Brunswick.

Dates	**Causes; peak water level at Perth-Andover (H_P)**
Apr. 25-May 14, 1887	Ice jams, snowmelt, heavy rain
Mar. 17-23, 1902	Unusually early break up due to high temperatures, ice jams.
Aug. 8-14, 1912	A heavy rainfall throughout most of New Brunswick.
May 10-14, 1939	General spring freshet.
Apr. 30 - May 10, 1947	Heavy rains, mild temperatures and snowmelt.
Apr. 24-30, 1958	Heavy rain, Snowmelt
Dec. 20-22, 1973	Heavy rain, Ice jam, Wind
Feb. 2-3, 1976	Groundhog Day storm: heavy rain and wind
Mar. 31-Apr. 5, 1976	Heavy rain, Ice jam, Mild Weather, Snowmelt. H_P (Peak stage) = 78.15 m
Apr. 1-4, 1986	Heavy rain, Ice jam, Mild Weather, Snowmelt
Apr. 1-13, 1987	Heavy rain, Ice jam, Mild Weather. Snowmelt, H_P = 79.60 m
Apr. 6-10, 1989	Freshet. High tide, Ice jam
Apr. 6-18, 1991	Freshet, Ice jam
Apr. 11-28, 1993	Freshet, Heavy rain, Ice jam. H_P = 78.66 m
Apr. 14-26, 1994	Spring freshet, Heavy rain, ice jams, unusually cold winter forming thicker and stronger ice cover on most rivers.
Mar. 29-May 16, 2005	Heavy rain, Ice jam, Mild Weather
Apr. 23-May 2, 2008	Freshet, Heavy rain, Mild Weather, Snowfall, Snowmelt
Apr. 6-8, 2009	Ice jams, heavy rains, mild temperatures.
Mar. 23-24, 2012	Ice jam, Mild Weather, Snowmelt. H_P = 80.25 m

Source: New Brunswick Department of Environment and Local Government (2012); includes detailed descriptions of the flood events.

2.3 St. Raymond, Quebec

About 10 000 people live in St. Raymond de Portneuf located 50 km north-west of Quebec City, Quebec, Canada. The town was founded at the end of the 19th century upstream of the junction of two rivers, the St. Anne (watershed area of 761 km^2) and the Bras du Nord (774 km^2). A 3 m-high dam (used by various paper companies over the 20th century) is located 4 km downstream of town and the upstream limit of the reservoir reaches the downtown area. The low gradient of that reach contrasts with the steeper (0.3%) multichannel riffle-pool reach extending about 8 km upstream of town, and with the rapids-dominated reaches (0.6%) found further upstream.

Historically, St. Raymond has flooded every two years or so and about 40% of these events were associated with ice (Leclerc 1966). Several (open-water and ice-induced) flood-control interventions were made over the decades to protect St. Raymond from floods: (1) dikes and walls were erected, raised, repaired and extended, (2) the channel was dredged at several locations, (3) islands were removed, (4) the channel was straightened, and (5) an ice-control structure was built at the upstream edge of the downtown area. The latter is a 100 m long and 4 m high weir with 12 concrete piers built at the upstream edge of town (Figure 2.1).

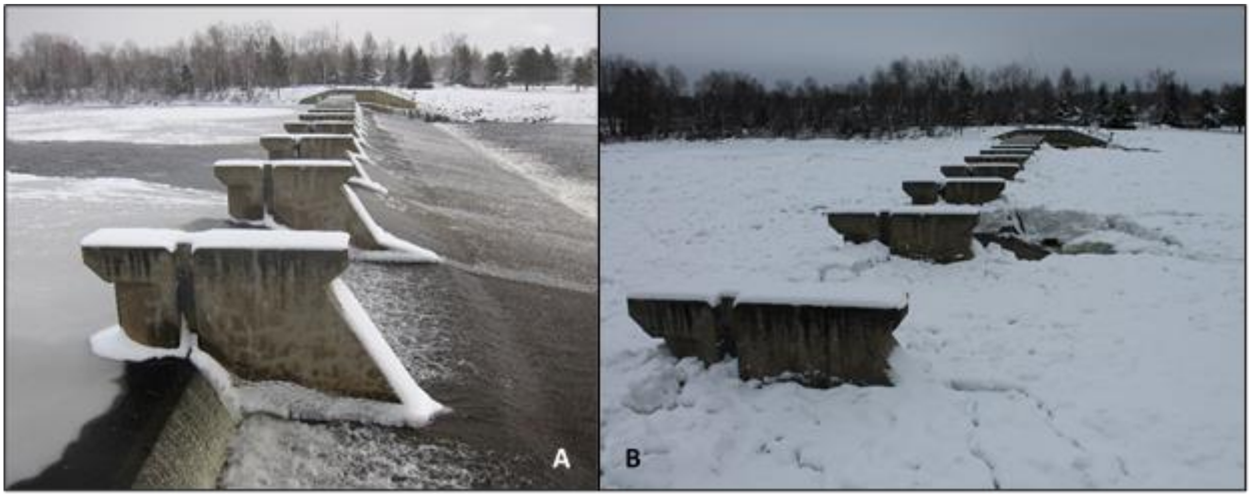

Figure 2.1. Ice-control structure in Saint-Raymond before (A) and after (B) freeze-up in December 2014.

The last flood mitigation intervention (2009) consisted of sewage pumps, valves, and a new dike, of which the level was set equal to the unprecedented frazil-induced (hanging dam combined with a winter runoff event) flooding event of 2003. This water level was evaluated to be 0.5 m higher than the 100-year open-water flood. Despite all the interventions, the new dikes were overtopped and the town was flooded by ice jams in March 2012 and April 2014. It appears that past flood control interventions have not specifically addressed the problem associated with the annual development of a large hanging dam in the downtown reach (Vergeynst et al. 2015). An ice cover quickly forms over that reach during the first winter cold spells and then, it intercepts the entire frazil ice production of upstream reaches that remain ice cover-free during many additional weeks. As a result, the ice-control structure is often submerged from downstream by massive, grounded frazil ice deposition (Figure 2.1B).

The combination of historical flood control interventions may have affected (positively or negatively) the frequency and intensity of floods in St. Raymond, but this impact is difficult to assess in the context of a naturally variable and recently changing climate combined with natural and anthropogenic channel modifications. St. Raymond citizens are now probably better protected against open water flooding, but ice-induced floods, not necessarily involving a breakup (or even a runoff) event, still represent a major concern.

The town executive has reacted to the 2014 ice-induced flood event: studies were requested and two groups (of citizens and multidisciplinary experts) were formed in order to explain the behaviour of the river and to propose tangible solutions that would reduce the risk associated with ice-induced floods.

2.4 Hay River, NWT

The Town of Hay River, NWT, is located at the junction of the north-flowing Hay River and Great Slave Lake. Ice jams have been extensively studied at this site for some time (Stanley et. al 1959, Stanley et. al 1963, UMA 1978, Jasper 1983, GWNT/IWD 1984, Gerard and Stanley 1988a and b, Wedel 1988, Gerard and Jasek 1990, Gerard et. al 1990, Jasek et. al 1993, and Jasek 1993). More recently, the University of Alberta undertook a monitoring and research program between 2005 and 2011 to develop breakup-forecasting tools for local emergency managers (Watson 2011, Brayall 2011, Kovachis 2011, Zhao 2012).

The Hay River splits into the East and West Channels, forming the Hay River delta, within the Town of Hay River. The Hay River typically experiences a classic mechanical breakup process as snowmelt runoff from the upper (southern) basin lifts and breaks the ice cover, flowing downstream (further north) where the ice is more intact. The ice runs jam up against the intact ice, obstructing flow until increasing backwater forces cause the ice jam to release. This continues downstream until the ice runs ultimately jam up against the intact ice cover in the delta, or the lake ice cover on Great Slave Lake. These ice jams often lead to flooding in the community and surrounding area. During the 116-year period of record between 1894 and 2010, ice-jam flooding occurred in 34 years. More recently, Hay River experienced some degree of breakup ice-jam related flooding every year from 2005 to 2010 (Kovachis 2010).

Following devastating flooding in 1963, the Hay River town center was relocated to higher ground (‘New Town’) upstream of the delta. Today, many people still live and work in the flood-prone areas. Some of the most at risk real estate is residential, commercial (commercial fishing outfits, packaging plants, etc.) and industrial (transportation yards and docks, etc.). Which area of town is most impacted by ice-jam flooding varies from year to year, depending on which of the East and/or West Channels the ice jam(s) pushes into, and where the jam arrests.

Ultimately, breakup ice-jam flooding is a common occurrence in the Town of Hay River. The Town maintains an active Flood Watch Committee to monitor breakup each spring, assess the risk to residents, and help inform emergency managers if evacuations become necessary. Resident evacuations have occurred on multiple occasions, most recently in 2008. However, there is no available flood mapping based on ice jam conditions to guide emergency management and future development efforts in the Town of Hay River.

2.5 Europe esp. Finland

Ice jams are common in northern Europe countries like Norway, Sweden, Iceland, and Finland but they may also happen in other northern countries such as Latvia and Estonia. Earlier ice jams occurred regularly in central Europe, but nowadays they are very rare (Mudelsee et al. 2003). At high altitudes, ice jams may cause damages as far south as Romania (Rădoane et al. 2010).

The severe ice breakup jams occurs mostly in large unregulated rivers in the North. The Tana River at the border of Finland and Norway runs from south to north. Ice jams occurs every year but the severity of the flooding caused by ice jams differs strongly from year to year. In 1959, there was a big ice jam flood in Karasjok village. Over 700 people were evacuated from their homes. In 1999, an ice jam caused flooding at the mouth of the tributary Utsjoki River and 13 estates were damaged (Lapland ELY-Centre, NVE 2010). The Torne River between Sweden and Finland is other example of large unregulated northern river. The majority of the flood damages at Torne River are caused by ice jams. At the mouth of the river are two towns, Tornio (Finland) and Haparanda (Sweden). In 1990, an ice jam caused high flood in the area of Tornio-Haparanda. For the Tornio town the estimated damages were about 1 million €. There have been reported severe damages because of ice jam flooding at the Torne River also 1922, 1934, 1936 1944, 1958, 1964, 1971, 1984, 1985, 1986, 1995, 2002 and 2006 (Lapland ELY-Centre, MSB 2010).

Ice breakup jams may occur also in rivers that are not located so north. Ice jam floods occur regularly in Ostrobotnia in the Western Finland. The ice breakup of the River Kalajoki in spring 2000 is described in a paper by Huokuna et al (2001). The worst ice jam situation developed in the main village of Kalajoki where seven houses were damaged. In the whole watershed of Kalajoki river, the damages to real estates, roads, bridges etc., were estimated to about 1 million €. In spring 2013, there were several ice jams in rivers in the Ostrobotnia area. The most threatening ice jam was formed in Pyhäjoki Village at the mouth of the Pyhäjoki River. On April 20th, a large ice jam released and moved to the river mouth forming a large ice jam. The flood rose very quickly and large ice sheets flowed to the village among houses (Figure 2.2). Several people had to be evacuated from their houses, which were surrounded by water and ice. Fortunately, no one was hurt but several houses and cars were damaged.

Figure 2.2. Ice jam flood in Pyhäjoki 2013.

Freeze-up ice jams are more common in rivers where discharge during freeze-up is high. Normally there is a large lake or reservoir in the watershed. The Kokemäenjoki River in western Finland is known for harmful winter floods. The winter flood 1974-1975 was exceptionally severe in the Kokemäenjoki River. A large ice jam formed in the river right at the centre of the town, and large areas were flooded and many houses damaged.

2.6 Lena River

The Lena is the easternmost of three great Siberian rivers that flow into the Arctic Ocean (the other two being the Ob and the Yenisei). The total length of the river is estimated at 4400 km while its basin area is calculated at 2 490 000 square kilometres. The small town of Lensk (pop ~25 000) is located on the left bank of the river, in the Sakha Republic of Russia, some 840 kilometres west of Yakutsk, the capital of that republic [from links accessed February 25, 2014: http://en.wikipedia.org/wiki/Lena_River and http://en.wikipedia.org/wiki/Lensk]. Lensk drew global attention in May 2001 because of massive ice jamming, as can be seen in the news item that follows:

Los Angeles Times, May 18, 2001,
by J. Daniszewski http://articles.latimes.com/2001/may/18/news/mn-65062

Russian Planes Bomb Ice Jam

Siberia: Assault begins as floods on Lena River worsen, submerging 90% of one town. Effect on wildlife is lamented.

MOSCOW — Russia's air force Thursday launched an unusual bombing campaign--over its own territory--to blast away huge ice dams that have worsened spring floods for tens of thousands of people along the Lena River in remote eastern Siberia.

"It may seem strange that we are bombing our own country, but it is not the first time," said Igor Tyurnev, a spokesman for the Emergency Situations Ministry, calling the action a necessity with 90% of the town of Lensk already under water.

"If the ice jam is not broken within the next two days, the level of water may continue to rise and cause more damage," he said.

President Vladimir V. Putin ordered waves of airstrikes, with supersonic Sukhoi-24 fighter-bombers dropping 1,100-pound bombs on the Lena about 50 miles downstream from Lensk. Officials said towns and small settlements all along the stretch of river that winds northward into the Arctic Ocean are threatened by the rising waters.

Authorities said 96 bombs were dropped Thursday without breaking the ice dams, and more bombings were planned today. They insisted that there was no danger to the public from the bombing.

"You have to understand, this is Siberia," another ministry spokesman, Sergei Bannikov, said in Moscow. "You drop a half-ton bomb and all you get is a hole in the ice, as if you are going fishing. The ice is that thick." He said some of the ice packs are 45 to 60 feet high, in a region where it is not unusual for temperatures to fall to minus 40 or even colder. "Very often, we have to combine bombings with planting explosives in the cracks of ice," Bannikov said.

Meanwhile, helicopters were delivering food and evacuating residents from flooded homes. In Lensk, a town of 27,000, officials said 18,000 people had already been evacuated from their homes and were being housed in 14 emergency centers in the area. The Lena River at Lensk reportedly is about 20 feet above flood stage. According to news reports, city officials said the water level had exceeded the worst-case predictions of experts and that a levee built in 1998 had been breached….The river, which is more than 2,700 miles long, appeared to be carrying a slow-moving parade of broken ice as it passed Lensk. Officials said the ice pack downstream from the town is about 25 miles long.

The preceding excerpt starkly portrays the destructive power of ice jams in large rivers and the devastation it can inflict on riverside communities and infrastructure. The damages caused by this flood have been estimated by Brackenridge et al. (2001) as 103 million in 2001 US dollars, amounting to 138 million in 2014 US dollars. On the other hand, Kusatov et al. (2012) cited Büchelle (2004) for a total damage figure of 7 billion rubles (~250 million 2001 US dollars, which is 2.5 times the previous estimate. [US inflation data were obtained on Feb. 24, 2015 from the following link http://www.usinflationcalculator.com/].

Figure 2.3 below shows that the 2001 peak water level exceeded by far all other ice-jam generated peaks in the period 1927 to 2005. It also shows that 2 of the 6 ice-jam floods that have been recorded in this ~70 year period, occurred very recently (1998, 2001) and produced the highest water levels.

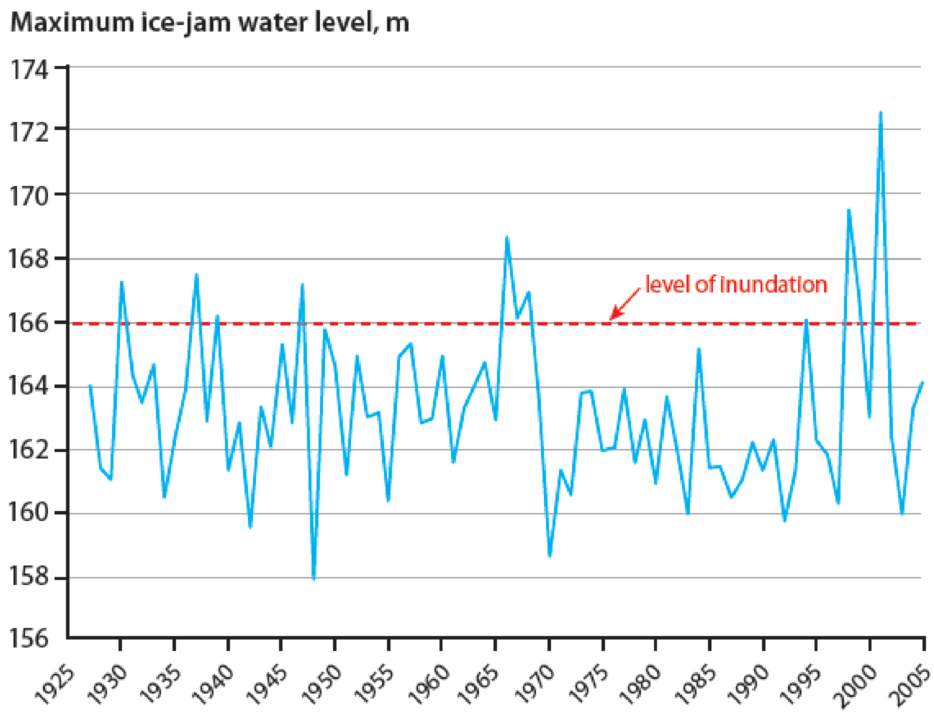

Figure 2.3. Time series of peak ice-jam water levels on the Lena River near the city of Lensk, Russia. The vertical axis represents water level referenced to a local datum. The red line refers to the local threshold of flood inundation, which was exceeded by ~6 m in 2001. Data provided by Dr. V. Vuglinsky, Russian State Hydrological Institute. Reproduced from Prowse et al. (2011).

Buzin et al. (2004) presented the results of extensive physical modelling experiments intended to investigate the mechanics of ice-jam formation and release on the Lena River near the city of Lensk and explore possible mitigation measures. The authors concluded that the most promising measure would be to artificially create ice jams ~ 20 km upstream of Lensk, after establishing that abrupt releases of such jams would not cause flooding at the town. They also mentioned construction of higher dykes to protect the city as an acceptable measure and it appears that this was actually implemented [Kusatov et al. 2012 mention that a 19 km “blocking dam” was built to protect the town from flooding, which is interpreted herein as being a dyke].

Kusatov et al. (2012) compared the 2001 Lensk event to similar ice-jam flooding that occurred in 2010 much farther downstream on the Lena River, between Tabaga and Yakutsk. They cautioned as to the efficacy of certain preventive interventions, which can on occasion actually induce formation of destructive ice jams. This advice is partially reflected in Buzin et al (2014) who found that activities against ice jams, carried out for many years on the Sukhona River near Velikii Ustyug and on the Lena River near Lensk and Yakutsk, do not result in considerable decreases in the heights of the maximum water level in jam-prone reaches of these rivers.

3. Uses of Flood Delineation Mapping

3.1 Flood Damage Reduction

Efforts to reduce the amount of damages to flood-susceptible infrastructure incurred during a flood event have been termed flood damage reduction. Discussion of flood damage reduction can be found in Belore et al (1990), Burrell (1995), and Davar et al. (2001). Efforts to reduce flood damages generally fall into two categories:

- structural measures, often termed flood control, involving the construction of engineering works to reduce the amount of flood water (e.g. flood dams and reservoirs) or to keep the flood water from inundating land and infrastructure (e.g. dikes and levees),

- non-structural measures involving financial incentives or disincentives with respect to floodplain development, provision of flood forecasts and warnings, and aspects of land use control (e.g. zoning, subdivision controls).

The non-structural approach is founded on the realization that flood damages result when floodplains required for the conveyance of flood flows are occupied and developed. Therefore, the aim of non-structural flood-damage-reduction measures is avoidance of flood hazard. Flood warnings and forecasts provide the opportunity to do emergency floodproofing of existing infrastructure and to take movable property and vulnerable people from the area expected to be flooded. Yet some floodplain infrastructure that cannot be moved remains vulnerable to flood damages. To avoid the costs of flood damages from escalating in the future, development on land prone to flooding can be discouraged by financial penalties and disincentives, or by zoning and other land-use controls. The flood regime of a river or stream needs to be evaluated to delineate areas of flood hazard. Once the areal extent of the flood hazard has been delineated, a sound basis for the adoption of flood-damage-reduction measures exists.

3.2 Canada Flood Damage Reduction Program 1976 - 2000

In response to increasing flood damages, the federal and provincial governments entered into a Canada Flood Damage Reduction Program (FDRP) starting in 1976, with the intent of preventing future flood damages by delineating flood risk areas [areas of flood hazard], and promoting the use of financial incentives and disincentives concerning flood susceptible development. Two flood zones generally were adopted: a floodway and a floodway fringe (flood fringe). The floodway is an area of greater flood flow velocities and deeper flood inundation where flood damage to the buildings and infrastructure can be expected to be greater. The floodway fringe is an area between the floodway and the outer boundary of the flood risk area where flood damages to buildings and infrastructure would be less severe. The intent was to produce flood risk maps based on two flood zones, which were defined by hydrotechnical studies involving hydrologic estimation of flows and hydrodynamic modelling of those flows to define flood profiles along the river for statistically determined design floods. Once an area was mapped and designated by the federal and provincial government Ministers, there was to be no financial support for new undertakings in higher risk floodway, and restrictions on financial support in the lower risk floodway fringe.

Under the FDRP, the mapped areas were termed flood risk areas, as the likelihood of an event was described by a statistical parameter that defined the return-period or probability of an event. This may not be sufficient with respect to the current definition of risk, which is defined in terms of likelihood of occurrence and consequence. Likelihood is a qualitative description of probability and frequency whereas a consequence is the outcome of an event or hazardous situation. Consequences of a flood, also called flood damages, are loss of life, property damage, injuries, and loss productivity that can result from exposure and susceptibility to a flood hazard.

The federal program began to wind down circa the year 2000. Many jurisdictions recognize that the 'flood risk' maps produced under the FDRP should be updated due to increased data availability (e.g., longer hydrometric records), improvements in analytical and mapping techniques, and increased knowledge of climatic change. Updated inundation mapping would allow development of strategies to reduce vulnerability of people and property that could be affected by floods, to share or distribute the costs associated with future flood damages, and to avoid developing social, cultural or economic assets in locations that can be adversely affected by floods (Herbert et al. 2014). Some provinces (for example, Alberta, Quebec, and Newfoundland and Labrador) have maintained flood-mapping programs and have produced flood inundation mapping since the termination of the FDRP.

4. Approaches to Flood Hazard Delineation

4.1 Mapping approaches

There are four basic approaches to flood-hazard-area delineation:

a. <u>Biophysical Approach</u>. The biophysical approach uses topographic and ecosystem information to evaluate the extent of past and future flooding. The approach involves the identification of low-lying areas bordering rivers using topographical information and verifying the occurrence of past flooding, and extent thereof, by field investigations of vegetation, soils, and debris lines. Depending upon the scope of the investigation, biologists, soil scientists, morphologists, and foresters may be consulted. The biophysical approach can be applied to ice-jam flooding. Physical evidence of past ice-jam floods could include vegetation trim lines and ice scars created by ice jamming and movement. This method often is relegated to preliminary investigations of flood hazard (NRCC 1989). However, providing the sufficient biophysical evidence exists, methodical investigations can be used for a definitive delineation of flood-hazard areas for flood management.

b. Past Flood Extent. One of the easiest and defendable means of delineating a flood hazard is to map the areal extent of a major past flood event. Accurate flood-hazard-area delineation does, however, depend upon the information on flood extent and (or) depth having been collected near peak floodwater levels. Flood profiles are prepared by plotting flood elevations (obtained by levelling water levels during the flood and high water marks in the field or shown in photographic records) against river distance. Aerial extent can be determined from aircraft or satellite imagery collected during the flood event, and by plotting flood profiles against topography. The past-flood-mapping approach has the advantages of being easily understood and defendable, as the event has already occurred. It is applicable to ice-jam floods. For example, the areal extent of 1976 and 1987 ice-jam floods at Perth-Andover (see subsection 2.2) were mapped.

c. Flood Envelope Approach. The flood envelope approach consists of surveying evidence of past flooding, regardless of cause, and plotting the obtained elevations against river distance to derive an envelope curve of maximum flood levels. The envelope curve is an assumed flood profile that can be applied to topographical information to determine the extent of flood hazard. The flood envelope approach is similar to the mapping of a single historic flood event, except that the flood profile may be based on several different flood events. Therefore, it is particularly applicable in areas of limited data availability for application of other approaches to flood-hazard-area delineation. There may be past accounts of historical flooding, ice scars and other physical evidence, and personal accounts that could be used to ensemble enough information for evaluation of flood hazard and for delineation of a flood-prone area based on methods such as described by Burrell et al. (1988) and Stanley and Gerard (1992).

d. Hydrotechnical Approach. The hydrotechnical approach involves the use of applied hydrology to derive design floods and then applying the design flood information to a hydraulic/ hydrodynamic analysis to obtain flood profiles. Statistical design floods can be based upon either analysis of storm input or discharge records. The hydrologic study and hydraulic/ hydrodynamic modelling usually requires field data for model calibration and the use of specialized software by experienced professionals. As many of these professionals are professional engineers, this method is sometimes considered the engineering approach to flood-hazard delineation. The advantages of the methodology are its applicability to areas where information on past flooding does not exist or is insufficient for flood-hazard delineation, and its use of hypothetical statistically derived flood events, particularly as the statistical determination of event frequency facilitates risk assessment. The hydrotechnical approach requires considerable information gathering and data collection/ analyses, and therefore tends to be more expensive than other approaches to flood-hazard-area delineation. Section 5 of this paper discusses the hydrotechnical approach in more detail, especially as it applies to ice-jam flooding.

The inherent element of judgment in any determination of flood risk or damage zones suggests adoption of different mapping techniques appropriate to the needs of different locations (Wolman 1971). The purpose of the delineation and the budgetary considerations may also affect the choice of methodology. All four approaches outlined above can be applied to the delineation of ice-related floods.

4.2. Jurisdictional Flood Criteria

Hydrology of Floods in Canada. Although not a standard, the NRCC publication "Hydrology of Floods in Canada: A Guide to Planning and Design" (NRCC 1989) provides design flood criteria for highway bridges and culverts, floodplain management, urban drainage, and tidal and lake structures. The information was condensed where available from flood criteria used across Canada for various types of works, and were extracted from information obtained from a 1980 questionnaire (NRCC 1989). For highway bridges, five of the eight jurisdictions that responded stated they used the 100-year return-period as the criterion for design of major bridges. Exceptions were Manitoba and Ontario which used a range of return periods from 50 to 100 years for its main crossings, and Nova Scotia which based their bridge design on 0.6 m above the maximum high water mark (NRCC 1989). With respect to floodplain delineation, most Provinces adopted an outer limit for the floodplain based on a 100-year return-period or higher historic flood event. Exceptions were British Columbia and Saskatchewan which based floodplain delineation on 200-year and 500-year return period flood events, respectively (NRCC 1989), and Manitoba which used a 160-year return-period flood event for Winnipeg (NRCC 1989). In eastern Quebec and Atlantic Canada, the 20-year return-period flood was used to define the floodway, with other jurisdictions using a depth of flow or flow velocity to define the floodway (NRCC 1989). The criteria used for the design of flood protection works varied among jurisdictions and depending upon the type of project. Some jurisdictions based their flood protection levels on the elevations of past floods, whereas the 100-year return-period flood level was given as the basis of the design criteria in Quebec and New Brunswick (NRCC 1989). The 100-year and 20-year return-period flood events are defined as the flood that would occur once every hundred or 20-years, respectively, given a long period of record, and assuming that underlying conditions do not change. The 100-year and 20-year return-period floods are determined from frequency analyses that relate the magnitude of flows to their frequency of occurrence using a probability distribution.

Recent National Assessment. The consulting firm MMM Group Limited (MMM Group Limited 2014) for the federal Department of Public Safety prepared a 2014 report titled "National Floodplain Mapping Assessment – Final Report". The report summarizes information on criteria used for floodplain delineation across Canada, as summarized in Table 2.

Table 2. Criteria used in Canada for Flood Hazard Area Delineation.

Province or Territory	Criteria used for Flood Hazard Delineation
British Columbia	The design flood level is the 200-year return-period event. The flood construction level is minimum elevation of a standard dyke or the elevation where construction can begin, and is determined by adding 0.3 m to the design maximum peak level and 0.6 m to the design maximum daily flood level.
Alberta	Alberta uses the maximum of the 100-year return-period flood lines or a flood of record to define the extent of the flood hazard area. As ice jams can significantly impact water levels, the 100-year return-period water levels must be based upon the greater of ice-impacted water levels or open-water levels.
Saskatchewan	Saskatchewan uses the 500-year return-period flood, with an additional 0.5 m freeboard for defining the safe building elevation.
Manitoba	Manitoba has retained the 100-year return-period flood, or flood of record if greater, for floodplain delineation, with the 160 year return-period used for Winnipeg.
Ontario	Ontario uses the flood resulting from Hurricane Hazel (1954) or Timmins rain (1961) transposed over a specific watershed, the 100-year flood, or a greater flood (including ice-jam floods). Hurricane Hazel is used primarily in central Ontario, including Toronto, which has a flood peak usually 3 to 5 times that of the 100-year return-period flood. In eastern Ontario, including Ottawa, the 100-year return-period flood is generally used.
Quebec	Quebec uses a return period flood of 100-years for floodplain delineation and for setting a requirement for flood proofing. No development is allowed below the 20-year flood levels.
New Brunswick	Under the Canada-New Brunswick Flood Damage Reduction Program, the 100-year or 1973 flood has been used to define the flood risk area. [Flood risk maps were also produced based on a flood envelope approach (see text)].
Nova Scotia	For previous mapping, the 100-year and 20-year return-period floods have been used to define the flood risk area and floodway, respectively.
Prince Edward Island	The main concerns are coastal flooding and erosion. A slope hazard limit along PEI streams is usually higher than what a 100-year flood level would be.
Newfoundland and Labrador	Flows used for the purpose of flood risk delineation is usually the 100-year and 20-year return-period floods, but these flows are often projected to 2020, 2050 and 2080 based on climate-change projections.
Yukon	Design flood flows can be estimated using single-station flood frequency analyses, but no standards existed in 2014 with respect to return periods.
Northwest Territories	For FDRP mapping, the 100-year return-period floods have been used. All elevations lower than the flood level were recently identified as the floodway fringe.
Nunavut	No flood risk mapping.

4.3 Standards for Flood Mapping Studies

Hydrologic and Hydraulic Procedures for Floodplain Delineation. These guidelines were developed by Environment Canada for the Flood Damage Reduction Program (see sub-section 3.2). The guidelines defined flood -hazard areas based upon the 100-year return-period open-water flood event, although greater historic floods could be used for designation of the flood-hazard area (Environment Canada 1976). Despite this provision, there seems to have been a reluctance to designate a flood risk [hazard] area based on an ice-jam event. For example, the flood-risk area at Perth-Andover (see subsection 2.2) was based on the 100-year open-water flood event, despite that fact that the 1976 ice-jam flood was much greater in extent and depth.

FEMA Guidelines and Specifications for Flood Hazard Mapping Partners Appendix F: Guidance for Ice-Jam Analyses and Mapping April 2003. Although the policy and standards have been superseded, the document contains useful guidance. Ice jams can contribute significantly to flood hazards in northern US rivers where thick ice covers can develop during the winter (FEMA 2003). Where ice jamming has resulted in historical flooding within a community, an intensified reconnaissance effort is recommended to collect data on locations, dimensions and causes of ice jams, frequency of occurrence, and associated ice volumes, river stages and discharges. The guidance document states that different approaches to analysis may be used to establish flood elevations in areas subject to ice-jam flooding (FEMA 2003). When sufficient data exists, a direct approach is suggested consisting of stage-frequency analyses and then combining open-water and ice-period stage-frequency by one of two different methods. Hydraulic modelling of ice jams can be done using the ice-cover option in the US Corps of Engineers' HEC-RAS model, with input values of ice thicknesses, Manning's n for the underside of the ice cover (recommended range 0.015 to 0.045 for sheet ice and 0.04 to 0.07 for ice jams), and the specific gravity of ice (recommended value of 0.92). Where upstream conditions can generate the needed volumes, floating equilibrium jams should be assumed (FEMA 2003). Where grounded ice jams are known to have occurred, the analysis can be performed assuming between 95% and 100% of the main channel is blocked. The flood profiles are to be produced for the composite ice-jam and free-flow stage-frequency analysis (FEMA 2003).

Ontario Technical Guide River & Stream Systems: Flooding Hazard Limit - 2002. Flooding hazards means the inundation of areas adjacent to a river system not ordinarily covered by water. In Ontario, the extent of the flood hazard is based on the modelled flood event resulting from a transposed major design storm such as the Hurricane Hazel storm (1954) or the Timmins storm (1961), the one hundred year flood, or a greater flood that occurred at a specific location. An ice-jam flood can be used to define the flood hazard providing it is greater than the 100-year return-period flood and the major storm flood (OMNR 2002). Section G of the technical guide contains detailed discussion of ice jam computations, stage-frequency analyses, and annual flood probability distribution (OMNR 2002). To develop ice-related frequency distributions that can be employed with reasonable confidence, detailed site reconnaissance, historical and environmental data collection, and careful evaluation of ice data is required (OMNR 2002). At sites which lack a reasonably long term history of ice observation, or for which changes have or will be made to the stream and/or streamflow, peak winter streamflow data would have to generated or ice-related stage-discharge curves would have to be prepared (OMNR 2002). As ice-related flooding is significant in many rivers Ontario, the use of well-documented computational techniques and ice-jam models was expected to become more commonly used by consultants and regulatory agencies in floodplain delineation despite limitations existing then in data availability and modelling expertise (OMNR 2002).

Handbook on good practices for flood mapping in Europe. General aspects and features of flood maps, with examples from all over Europe, are discussed in the handbook (EXICAMP 2007). The content, use, and scale of different types of flood hazard maps (e.g., flood extent map, floodplain map, flood depth map, flood velocity map) are discussed. Although ice jams are recognized as a cause of river flooding, no specific measures for delineation of ice-related floods are provided.

European Flood Directive 2007. In 2007, the European Parliament and the Council of the European Union passed a directive on the assessment and management of flood risks, commonly known as the 'Floods Directive' (European Commission 2007). Maps are to include detail on the flood extent, depth and level for three risk scenarios (high, medium and low probability).

Alberta Flood Hazard Identification Program Guidelines – July 2011. The potential for ice-jam flooding exists in all parts of Alberta, with past ice-jam flooding having most notably occurred at the Town of Peace River, City of Fort McMurray, and the City of Calgary. Therefore, the guidelines specify that the potential occurrence of ice jams has to be evaluated during a flood hazard study using historic information from archived documents and newspapers and by interviewing long-time residents (Alberta Environment 2011). Alberta guidelines recognize that the design flood, that is the flood event used to delineate a flood-hazard area, can be due to open water or due to ice-jam flooding. Alberta's Flood Hazard Identification Program uses the 100-year return-period flood or the 100-year return-period water elevation if an ice jam is used as the design event, as the standard benchmark for flood management (Alberta Environment 2011). The 100-year return-period ice-jam level should be determined based on a probability distribution of the annual maximum recorded ice-jam stages (Alberta Environment 2011). In the case of ice-jam flooding, areas with depths of flooding ≥ 1 m constitute the floodway (Alberta Environment 2011).

CDA Dam Safety Guidelines. The Canadian Dam Association (CDA) published dam safety guidelines in 1995, and revised them in 2007 and 2013 (CDA 2007a, 2013). The CDA also produced a series of Technical Bulletins that suggest methodologies and procedures that qualified professionals can use to analyse dams and assess their safety, including *Hydrotechnical Considerations for Dam Safety (2007)* (CDA 2007b). The Guidelines contain principles applicable to all dams and processes for the management of dams. It is stated in the Guidelines that reservoir ice or ice and debris carried by the river to a run-of-the-river project could create a hazardous situation depending upon the amount and thickness of the ice cover and the characteristics of a dam and discharge facilities.

National Floodplain Mapping Assessment – Final Report 2014. In addition to reviewing the present-day criteria, the consulting firm MMM Group Limited recommended performance and technical standards for a future flood-damage-reduction program, using three levels of standards: high for urban and diked areas, medium for rural areas, and low for unpopulated areas (MMM Group Limited 2014). The minimum performance standard for delineation is the annual series 100-year return-period flood, but for developed urban areas, mapping of flood depths (maximum 0.5 m intervals), velocity (maximum 0.5 m/s intervals), and the product of velocity and depth (maximum 0.4 m^2/s intervals) is recommended (MMM Group Limited 2014). Hydraulic analysis is required to address complicating factors such as ice, ice jams, scour/sedimentation, and debris blockage (MMM Group Limited 2014). Despite this, ice-related flood events are not specifically mentioned in the proposed technical standards.

4.4 Risk Assessment

A common definition of risk is that risk is the combination of probability and consequences. According to the EU Floods Directive, flood risk is the combination of the probability of a flood event and of the potential adverse consequences for human health, the environment, cultural heritage and economic activity associated with a flood event (European Commission, 2007). According to the Canada Flood Damage Reduction Program 1976-2000 (FDRP), a flood risk area is an area delineated as being prone to flooding. Considering the current definition of risk, the FDRP flood risk is more like a flood hazard area. FDRP is described in the sub-section 3.2.

Flood risk is typically assessed by estimating flood damages for different flood scenarios. Flood damages may be divided into direct/indirect and tangible/intangible damages. Direct flood damage covers all varieties of harm, which relate to the immediate physical contact of floodwater to humans, property and the environment (Messner and Myer 2006). Indirect flood damages are losses that occur due to the interruption of some activity by the flood (e.g., loss of industrial production and transportation delays), and the extra costs of emergency and other actions taken to prevent flood damage (Floodsite 2007). Damages, which can be easily specified in monetary terms, such as damages on assets, loss of production are called tangible damages. Casualties, health effects or damages to ecological goods and to all kind of goods and services, which are not traded in a market, are far more difficult to assess in monetary terms. They are therefore indicated as intangibles (Floodsite 2007). Because of methodological difficulties, estimations of flood damage are generally made only for direct and tangible damages.

Different approaches may be used to define water levels for flood scenarios, which are needed for flood-risk assessment. Statistical analyses of observed values may be used for certain areas if there are enough observed values available. In the case of rivers, there are seldom enough observed stage and flood observations available for direct definition of flood stages by statistical analyses. Typically, flood elevations for river locations have to be defined by using numerical hydraulic models and the observed values may be used for model calibration.

GIS technology provides tools for flood-damage estimation. Some of the flood damages can be estimated by GIS overlay analysis using information about estimated flood extension and flood depth together with vulnerability data, such as GIS datasets for buildings and basic infrastructure. For example, flood damages for buildings may be expressed in monetary terms by using synthetic water depth-damage functions and market values for different kind of buildings. In addition, the number of inhabitants on flooded area or the length of roads under floodwater may be found out by GIS analyses.

An accurate digital terrain model is needed for flood risk assessment and flood mapping. The information of terrain elevation is needed as input for flow models but especially it is needed when flood damage assessment or flood maps are produced. New digital elevation models are mainly produced by airborne laser scanning (LIDAR) technology. These new elevation models enable approaches to flood-damage estimation that have not been possible with reasonable accuracy before.

Flood maps may be categorized according to what information is presented on a map. According to the EU Floods directive, flood maps are divided into flood-hazard and flood-risk maps. On a flood-hazard map, at least flood extent and flood depths have to be presented. Flood-risk maps shall show the potential adverse consequences of the flood scenario. The indicative number of inhabitants potentially affected by the flood, and the type of economic activity of the area potentially affected and the installations (which may cause accidental pollution in case of flooding and potentially affect protected areas) have to be presented on a flood-risk map.

Ice-jam floods offer additional challenges for flood risk assessment compared to open-water floods. The estimation of flood levels for certain flood probability is difficult for ice-jam floods. Freezing water may cause some extra damages to houses in the case of freeze-up jams. Overbank flow that may result from the release of an upstream ice jam could have very high velocity and result in serious damage to structures and property, while damages may be caused to houses and infrastructure by moving ice sheets. These damages are difficult to take into account in flood risk assessment.

4.5 Woodlands County and Whitecourt – an example of ice-jam frequency analysis

As part of the Alberta Environment and Sustainable Resources Development (ESRD)'s Flood Hazard Identification Program, flood-hazard areas are identified and mapped for at-risk communities in Alberta. Although most design floods in these studies are classic open-water flood scenarios, ice jams do create the most extreme flood conditions in several communities. The ESRD Flood Hazard Identification Program Guidelines do not currently specify a best practice for performing ice-jam frequency analyses to determine design ice-jam flood conditions (100-yr or 1% chance of occurrence each year) and water level profiles for floods of different return periods. The most recent ESRD Flood Hazard Study completed using design ice-jam flood conditions was in 2015 for the Town of Whitecourt and surrounding Woodlands County (Northwest Hydraulic Consultants Ltd. 2015).

Downtown Whitecourt is built at the confluence of the McLeod and Athabasca Rivers (Northwest Hydraulic Consultants Ltd. 2015). Ice jams create the most severe floods on the McLeod River, while the most severe floods on the Athabasca River are open-water events. The Athabasca River is braided near Whitecourt, allowing for multiple flow paths to convey flows around ice accumulations. As a result, ice jams forming in this reach are less consequential. The most severe flooding in Whitecourt occurs when the McLeod River breaks up dynamically while the Athabasca River remains ice covered. This can cause the McLeod River ice to accumulate and jam against the intact Athabasca River ice, which historically has caused flooding in the Town.

In the Woodlands County - Whitecourt Flood Hazard Study, the procedure used for the ice-jam frequency analysis on the McLeod River begins by determining the relative frequency of a dynamic breakup occurring on the McLeod River while an intact ice cover remained on the Athabasca River for ice jams of all magnitudes. It assumes that the probability of occurrence of an ice jam on the McLeod River was dependent on the McLeod River breaking up prior to the Athabasca River.

The values of the more extreme breakup discharges (first day with no ice effects following breakup) were found to be well represented by a normal distribution, and using the Monte Carlo technique, a population of 10000 random breakup discharges were generated using the mean and standard deviation of the adopted normal distribution.

Ice-jam flood frequencies and profiles were developed using the ice-affected water levels synthesized from the discharge data. Two ice-affected rating curves were developed to span the range of ice-affected conditions (simple ice cover rating curve and ice-jam rating curves). Both ice rating curves were developed using HEC-RAS (steady state ice-jam profile), assuming default strength parameters and adjusting roughness to match observed ice high-water marks. Non-dimensional depth and non-dimensional discharge values were also compared to published data for documented ice jams in Canada, validating the ice-jam strength parameters and ice-jam roughness values. It was assumed that a fully developed ice jam may form along any portion of the study reach, so that the extent of any particular ice jam does not affect the delineation of the potential flood extents along the full study reach. An important additional input is the empirically-assessed probability of ice-jam occurrence in any one year, which is utilized in conjunction with the probability distribution of breakup flow to develop the water level – frequency relationship. The described approach is one of several possible methodologies of determining design ice-jam flood conditions (100-yr return period or 1% chance of occurrence each year) and flood profiles for ice jams of various return periods.

5. Hydrotechnical Considerations

5.1 Hydrotechnical Engineering Approach

The objectives of a hydrotechnical study pertaining to flooding are to identify fully the causes of flooding and to recommend suitable mitigation measures. Herein, the focus is on flooding that results from ice jams, typically jams that form during the spring breakup of the ice cover, combined with large freshet flows driven by snowmelt and/or rainfall. However, one should be aware that ice-jam flooding can also occur during the winter as a result of mid-winter thaws and severe rain-on-snow events that, in turn, trigger mid-winter breakup of the ice cover. More rarely, flooding may also be caused by freeze-up jams as a result of unusually high flows, either due to natural hydro-climatic occurrences or due to regulation (or both).

Ice-jam flood mitigation may involve one or more measures, selected from an array of structural and non-structural options, such as ice/flow control structures, floodplain delineation and flood proofing (Burrell 1995, Tuthill 2013). Assessing the risk of ice-jam flooding is an essential step in regulating floodplain development, identifying effective ice-jam mitigation measures, and anticipating the impacts of building new river structures or removing old ones. As with open-water flooding, the risk at a particular location is quantified by developing a stage-frequency relationship. However, several characteristics of ice events render them less than amenable to traditional stage-frequency analyses. The complex hydro-meteorological and structural processes that lead to ice-jam formation, progression, and release are highly site-specific. Therefore, parametric regional equations, such as those developed for open-water flood frequency studies, do not apply.

Though each hydrotechnical study is shaped by site-specific features of the jamming problem, there are several components that are likely to be common to all such studies. These include: (a) collection of all relevant historical information, (b) field reconnaissance and documentation of channel morphology and bathymetry, (c) identification of flood damage potential, as it relates to existing local infrastructure, (d) data analysis and interpretation, (e) flood risk assessment, and (f) recommendations for specific mitigation measures that are cost-effective and feasible from the engineering and societal points of view.

5.2 Ice-jam flood hydrology and frequency analyses

As noted earlier, a key aspect of a flood-damage-reduction study is flood-risk assessment, which in turn hinges on development of the ice-influenced stage-frequency relationship for the site of interest. Ideally, this relationship would be based on past water level measurements, but very often such measurements are incomplete or non-existent, as described next (see also review by Beltaos 2010).

Historical data sources can be of the societal type, such as resident recollections and photos, newspaper archives, or records kept by long-term government, religious, or private agencies (e.g., the Hudson's Bay Company trading posts in Canada). Particularly valuable are photographs of high water marks attained during flood events or even actual high water marks on buildings or bridges that have been maintained over the years and can be readily surveyed for elevation.

Environmental evidence can also provide useful historical data, such as ice scars on trees, damaged vegetation, and ridges of bank material formed by ice shoves. Of these, ice scars on trees are the most useful because they are most likely to indicate peak stages while annual ring patterns provide clues as to the year when the scar formed. Caution must be exercised in interpreting tree scar evidence because occasional ride-up of ice blocks and ice sheets may indicate much higher stages than were actually attained by the water surface during a freeze-up or breakup event. There is also a tendency for scars to become less abundant and to indicate higher elevations as one goes back in time. Gerard (1989) mentions tree loss from bank erosion, beaver activity, and destruction by ice jams as contributing factors. Such ambiguities may cause errors in identifying flood and non-flood years, as found by Smith (2003).

Where available, the most reliable historical data can be found in records of nearby hydrometric stations (*instrumental* evidence). Typically such gauges record water level, which can be converted to flow discharge via a rating table or curve, which is based on comprehensive current metering near the gauge site. Rating tables only apply to open-water conditions, but mean daily flow is typically reported for the entire year. The presence of ice effects on river stage is clearly indicated in the records, so as to warn users that associated flows are mere estimates and not as reliable as open water values. Gaps in hydrometric records are much more frequent for ice-related events because hydrometric gauges are often damaged by ice, usually when an ice jam forms nearby. Not only does this cause the ice-influenced stage record to be shorter than the open-water record, but the missing data are often associated with extreme events.

For any known or estimated flood stage, a probability of exceedance can be calculated by assigning inserting appropriate rank and record length in a suitable probability formula, such as the Weibull equation (White and Beltaos 2008). However, data from environmental, societal, and instrumental sources are not homogeneous because each type may have a different "perception stage", below which flood events go unnoticed. Consequently, it would not be correct to assign the same record length to all ice-jam peak stages, regardless of source. Methodology on how to combine such data into a single set and assign the correct exceedance probabilities has been developed by Gerard and Karpuk (1979) and is also discussed in the review by Gerard (1989). Sources of historical data are often environmental such as tree damage (ice scars), and physical evidence of ice shoves or societal such as hydrometric records, witness recollections, and archival material (newspaper accounts, damage reports).

Where the available historical stage data are sparse, it may be possible to generate the stage-frequency relationship indirectly (Gerard, 1989). Indirect approaches combine flow frequency estimates with a synthetic stage-flow rating relationship for ice-affected conditions. Historical flow data are far more readily available than peak ice-influenced stages because the spatial variability of flow is much smaller than that of ice-jam water levels. Consequently, the flow at an ungauged site may often be deduced from records of upstream and downstream hydrometric gauges, or even from regional estimates, whereas ice-jam stage data cannot be meaningfully transposed. Once a rating relationship is developed, the frequency of a particular flow can be translated into a frequency of the corresponding stage as will be described later in this section.

The synthetic approach should be based on a thorough understanding of local channel morphology and ice jamming processes. For a case study of breakup jamming in the Winooski River at Montpelier (USA), Tuthill et al. (1996) found that, for flows below ~60 m^3/s, a sheet ice cover can be expected to remain in place on the river, given sufficiently cold temperatures (Figure 5.1).

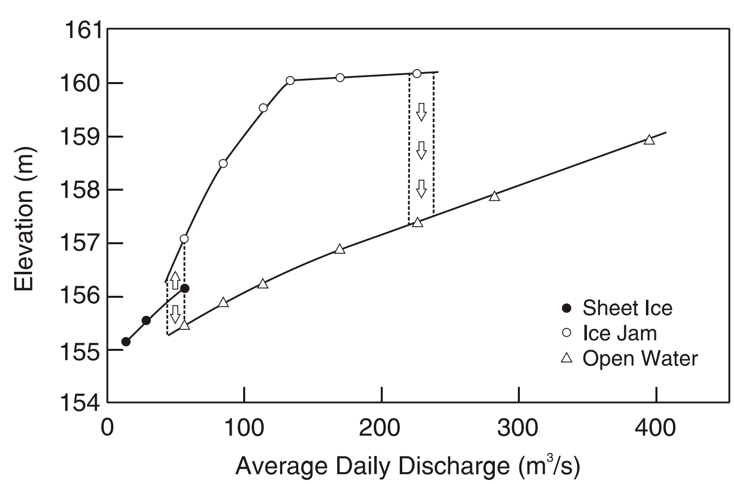

Figure 5.1. Stage – discharge relationship for breakup ice jams, taking into account non-jam conditions at low and high flows, respectively (Tuthill et al., 1996, with changes).

Above ~60 m^3/s, the ice cover breaks up and ice jams may form but they become unstable and release at ~230 m^3/s (ice clearing flow); stage will drop to reflect open-water conditions. Beyond ~140 m^3/s, the jam stage exceeds bankfull and further rise is subdued as the ice and water spread onto the floodplain. Between ~60 and ~140 m^3/s, analytical or numerical models of ice jams can be used to develop the ice-affected curve, as indicated in the next section.

It is emphasized that the flow thresholds defining the lower and upper ends of the ice-jam range are not constant values but vary from year to year, and from site to site, depending on local hydraulics, antecedent hydro-climatic conditions, ice properties, and degree of thermal decay of the ice cover during the pre-breakup period. Consequently, the limiting flow values indicated in Figure 5.1 (60 and 230 m^3/s) are mere mid-points of what, in reality, are ranges of varying breadth. This feature is qualitatively indicated by the pairs of dotted lines in Figure 5.1; the respective ranges can be extensive under certain hydro-climatic conditions.

The exceedance probability, $P_J(H)$, of an ice-jam stage, H, during any one ice season can be calculated from (Gerard and Calkins 1984):

$$P_J(H) = P(Q_{H,J})P(J) \qquad [5.1]$$

in which $P(Q_{H,J})$ is the exceedance probability of the discharge ($Q_{H,J}$) that corresponds to H under ice-jam conditions (Figure 5.1); and P(J) is the probability of a jam occurring near the site of interest in any one year. The combined probability, $P_i(H)$, for ice-influenced stage under both jam and no-jam conditions (mutually exclusive events) is obtained from:

$$P_i(H) = P(Q_{H,J})P(J) + P(Q_{H,NJ})P(NJ) \qquad [5.2]$$

in which the suffix NJ denotes the "no-jam" condition. The exceedance probability of the annual peak stage, P(H), occurring either during ice-covered or during open-water conditions, can then be calculated as:

$$P(H) = P_i + P_o - P_i P_o \qquad [5.3]$$

in which the suffix "o" denotes open-water conditions.

Under this approach, the peak breakup (or freeze-up) stage is assumed to take one of two possible values once the flow is specified, i.e. H_J or H_{NJ}. These variables are represented by the upper or the lower line in Figure 5.1; often, the lower line is defined by the sheet-ice curve, which may extend all the way to the ice-clearing flow value.

Beltaos (2012) noted that empirical evidence does not support this assumption because the area between the upper and lower lines is filled with data points when actual occurrences are plotted. Consequently, a Distributed Function Method (DFM) was developed, such that:

$$P_i = 1 - \int_0^1 \phi(\theta) dP_Q \qquad [5.4]$$

where P_Q is the cumulative probability distribution of the breakup or freeze-up flow and θ is a normalized stage variable, defined as:

$$\theta \equiv (H - H_{NJ})/(H_J - H_{NJ}) \qquad [5.5]$$

The function $\phi(\theta)$ is given by

$$\phi(\theta) = (k+1)\theta - k\theta^2 \qquad [5.6]$$

in which k is a site-specific coefficient; values known to date derive from application of the DFM to four sites and range from 0.6 to 0.9. The higher values indicate reduced susceptibility to jamming. Details on practical use of the DFM and its limitations are provided in Beltaos (2012).

5.3 Ice-jam hydraulics and equilibrium modelling

As noted in the preceding section, application of a synthetic stage-frequency analysis requires knowledge of the upper line in the stage-discharge graph of Figure 5.1. This line represents the highest possible stage that can be attained during breakup (or freeze-up) for any given flow and can be estimated using the concept of an equilibrium ice jam.

In steady-state conditions (constant flow) and in a wide channel (as most natural streams are), given enough ice supply, the worst potential ice jam in terms of associated stage can be evaluated on the basis of shear stresses (mainly associated with the channel gradient) and mechanical ice properties (angle of internal friction between ice blocks). The equilibrium reach of an ice jam, as presented by Pariset et al. (1961, 1966) and Beltaos (1983), represents the central section between its toe (downstream support with large ice blocks and sheets) and its head (upstream boundary where new drifting ice pieces are arrested). When the ice supply persists, the newly arrested rubble thickens over time by shoving and compression until the internal resisting forces are equal to the external driving forces. As the jam lengthens in the upstream direction, its central section remains in this state of equilibrium, which has the maximum potential thickness and causes the maximum possible water depth for the given flow. This depth is controlled by river bathymetry, slope, and width, as well as by the thickness and underside roughness of the jam; the latter has been statistically confirmed to be linearly correlated with its thickness (Nezhikhovskiy 1964, Beltaos 2001).

It is therefore possible to evaluate empirically (for a reach of relatively uniform geometry and gradient) the potential breakup water level or ice-induced flood level using the water depth (H) of an equilibrium ice jam, as shown in Eq. 5.7 or Figure 5.2 for a quick estimate.

$$\frac{H}{S_oB} \approx 0.96\left[\frac{(q^2/gS_o)^{1/3}}{S_oB}\right]^{0.82} + 4.79\left[1+\sqrt{1+0.22\left[\frac{(q^2/gS_o)^{1/3}}{S_oB}\right]^{0.82}}\right] \quad \text{Beltaos (2008)} \quad (5.7)$$

Here, q is the discharge per unit width, g is acceleration due to gravity, S_o is the open water surface slope, and B is the channel width as taken under the ice jam (~ distance between resultant shear walls upon ice-jam release). The dimensionless parameters ξ and η are defined in Figure 5.2.

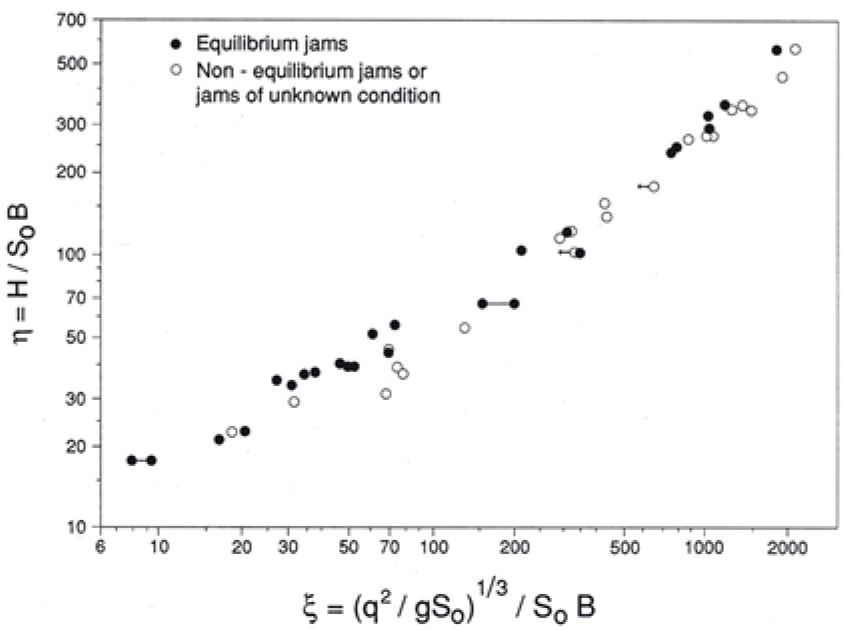

Figure 5.2. Dimensionless depth versus dimensionless discharge relationship for breakup ice jams. After Beltaos (1983) with changes.

The assumption of steady flow is an approximation, especially at breakup, owing to the rising runoff-generated or "carrier" flow. This rise, however, occurs gradually, and temporal gradients do not significantly affect the equilibrium condition. Highly dynamic flow conditions that prevail during ice-jam releases and ice runs will certainly influence water levels during the formation of a new ice jam, but the available evidence suggest that they do not have a large influence on the final, equilibrium, stage of the jam. A detailed discussion of this issue is provided in Appendix A of Beltaos (2012).

In reaches of complex geometry and variable gradient, ice-jam-induced water levels can be simulated using one of several river-ice models that have been (or that are being) developed. Such models can be either steady-state or dynamic and are increasingly used by cold regions river engineers. They include: HEC-RAS (US corps of Engineers), River 1D and River 2D (University of Alberta), RIVJAM (Environment Canada), MIKE 11 (LaSalle Consulting Group, now GCL-NHC), ICESIM (Hatch Energy), RIVICE (consortium of hydropower companies and Environment Canada), DYNARICE and CRISSP 1D and 2D (Manitoba Hydro and Clarkson University). While the ice-jam routine of most models is based on similar differential equations, some models are more user-intuitive while others are more complex, and some of them are of the public domain while others are owned by the private sector. A review by Carson et al. (2011) compares the performance of some existing models for documented ice jams (for both calibrated and blind modes). Under highly unsteady flow conditions, use of sophisticated dynamic models may be more appropriate (She et al. 2009, Nolin et al. 2009)

Input data to river-ice models normally include the bathymetry of the channel and topography of the floodplain, the location and extent of the ice jam, a range of simulated discharges, realistic boundary conditions, channel bed and bank roughness, and historical water levels used for model calibration. The total amount of ice within the simulated jam (a quantity calculated by the model) can also be used for validation. The volume of ice in the jam can only be smaller than the volume of ice of the contributing reach (~product of ice thickness, channel width, and reach length), and represents an important information when evaluating ice-jam mitigation measures (e.g., Turcotte and Morse 2013a). The ice-jam routines of the models require the user to specify several parameters that describe hydro-mechanical properties of ice jams. This introduces a degree of subjectivity, especially where limited site-specific calibration data are available.

Though relatively infrequent, there is another type of jam that can cause flooding (e.g. Beltaos et al. 2007a). This is the hanging ice dam, which forms at freeze-up and can attain extreme thickness (e.g. Beltaos and Dean 1981, Michel and Drouin 1981, Shen and Wang 1995). Hanging dams form where a steep river reach is followed by a flat one, such as the approach to a lake or reservoir. Depending on weather conditions, the steep reach may remain open for a sufficiently long time to generate large frazil volumes that accumulate under the sheet ice cover, which forms readily over the flat reach. Hanging dams grow in thickness and length, causing continuous rise in water levels, until the frazil supply ends or the under-ice flow velocities and shear stresses become large enough to prevent deposition of the incoming slush. Computation of the maximum stages caused by hanging dams requires use of a comprehensive river-ice numerical model, such as for example, CRISSP1D, RIVICE, or VARY-ICE (KGS Group 2007). The example in Figure 5.3 pertains to the Kaministiquia River (N. Ontario, Canada) near its mouth at Lake Superior.

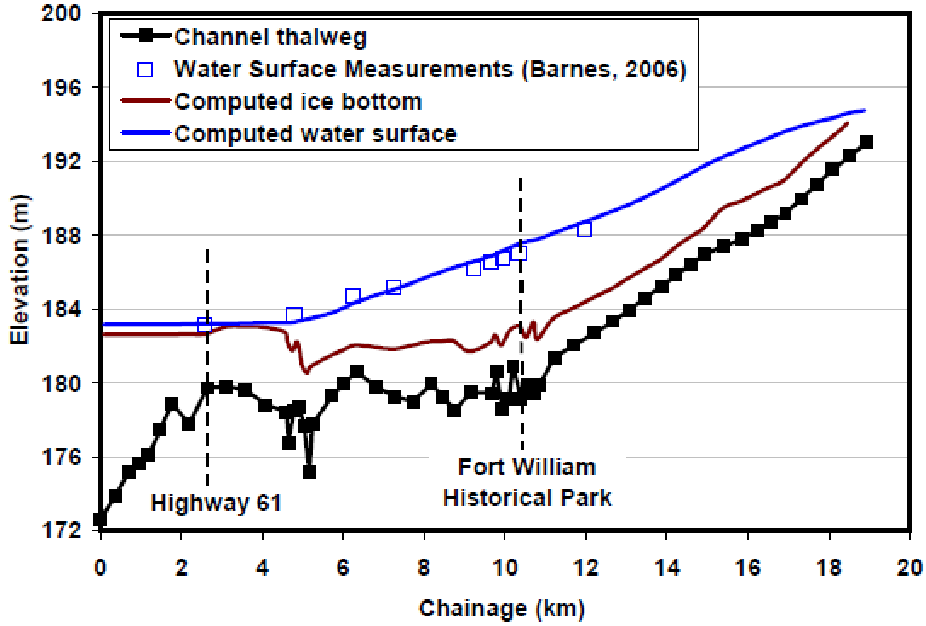

Figure 5.3. Hanging dam configuration as computed by VARY-ICE, a one-dimensional, dynamic model. Reproduced from KGS Group (2007) with the kind permission of R. Carson (KGS group) and P. Boyle (Ontario Ministry of Tourism).

Once the maximum jam stage-discharge relationship is established, either by analytical or numerical modelling means, a probability distribution of breakup discharge can be used to obtain, for a given reach, the frequency distribution of ice-jam-induced water levels as detailed in Section 5.2. There are various limitations associated with the synthetic approach, including uncertainties arising from inadequate field data for model calibration, breakup discharge estimates by hydrometric agencies, occurrence of non-equilibrium jams, as well as channel types and morphologies that do not conform to the wide-channel ice-jam concept of Pariset et al. (1966). Such limitations suggest that the synthetic approach to ice-jam flood risk requires the attention of experienced river engineers who are thoroughly familiar with ice-jamming processes.

6. Needs

6.1 General needs

Although floods in northern countries can be driven by open-water or ice events, most floodplain, flood-hazard and flood-risk mapping considers classic open-water scenarios. The methodologies for obtaining the data for open-water floods are widely accepted as meeting industry standards. On the other hand, how to determine the magnitude of representative ice-jam design floods is a process that is less well defined by industry standard, and is more data intensive. Regardless, considering ice-jam flood impacts is necessary to appropriately capture the inherent flood risks through floodplain, flood-hazard, and flood-risk mapping.

Field observations and measurements are required to better determine and document ice jam and associated flooding extents and impacts. Ice-jam effects on water levels can be very localized, and may not be captured by nearby water level gauges. For example, there are two water level gauges in the Town of Peace River, located approximately 3 km apart. Under normal conditions, water levels between the two locations differ by 0.4 to 0.6 m, depending on the stage. Following a freeze-up ice jam forming between the two gauge sites in January 2015, the difference in water levels between sites was more than 3.5 m. If only one of the gauge records was considered to evaluate freeze-up impacts and flood potential, it would not have been representative of actual conditions. Supplemental information such as locations of the head and toe of the ice jam, backwater extents, high-water mark elevations and ice-jam thicknesses (when possible) help to complete the picture. Field measurements provide valuable calibration and validation information for numerical models of ice process (Hicks 2008). In order to continue to develop understanding of these dynamic processes, continued field measurements (through ground-observation or remote sensing efforts) are required. The development of a centralized database of documented ice-jam floods and associated field data would also be a tremendous asset.

Ice-jam formation and release events are dynamic by definition. Expertise is required to determine the flood risk and frequency of ice-jam-related flood events. A more complete understanding of these processes and appropriate methodologies for floodplain mapping are crucial for both long-term planning in communities prone to ice-jam flooding, as well as for emergency management teams responding to these events.

6.2 Research Needs

6.2.1 Hydrotechnical research

As noted in section 5, the most reliable means for determining the frequencies associated with various ice-influenced stages, is the use of an extensive set of historical data. However, historical data are often unavailable, uncertain, or too few to permit assignment of frequencies to very high stages and identification of rare events such as the 100-year return-period flood. In such instances, the only recourse is the use of a synthetic method.

Synthetic methodology, however, has several limitations arising from uncertainties associated with its hydrotechnical components. A key such component is the calculation of the equilibrium stage of an ice jam as a function of flow discharge. For the very common, wide-channel jam, there is adequate knowledge, but the same cannot be said of the hanging dam which requires improved understanding of under-ice transport and deposition processes of frazil ice (Beltaos 2013).

The concept of ice clearing discharge can be very helpful in the synthetic analysis, ensuring that the resulting stage-frequency relationship will not be unnecessarily conservative. However, there is little guidance on how to determine this discharge. Familiarity with local floodplain morphology and bathymetry are essential but not sufficient, as was found in a documented case study (Beltaos et al. 2007b). A fruitful research option would involve a comprehensive examination and analysis of maximum known stages at selected locations where long-term observations and data are available.

Uncertainty is also involved in breakup flows, which are most often obtained from archives of hydrometric agencies such as the Water Survey of Canada or the US Geological Survey. Once breakup is underway, flow measurement becomes unsafe and the archived data represent mere estimates by agency staff, based on gauge records and ancillary evidence. Such estimates can be in considerable error (e.g. Pelletier 1990) and there is a need to develop guidelines on how to assess this uncertainty and its impact on synthetic stages.

The changing climatic conditions suggest that a stage-frequency curve that has been developed on the basis of archived stage and/or flow data, may not apply in the future. This limitation is particularly relevant to ice-influenced stages because climate change is known to be more intense in the colder regions of the globe. Research needs on this issue include: (a) comprehensive examinations of how peak ice-influenced stages may have changed in recent decades in order to identify significant trends [e.g. von de Wall (2011), Carr and Vuyovich (2014)] and how such trends may vary among different regions of the world; and (b) investigations of how breakup flows in cold regions rivers may change in the future and the potential for mid-winter breakup becoming the primary event for the year in certain regions (Beltaos 2002).

6.2.2. Mapping and delineation

The estimation of flood level is essential to any flood mapping. As presented in section 5, the estimation of ice-flood levels is challenging. The next task is to take these flood levels to produce flood maps and hazard delineations.

Recent methods for classification of river ice (Turcotte and Morse 2013b) could be developed further to be used as an aid for ice-jam flood mapping. Classification could be used to find the areas were the ice cover will break up first or where ice jams can form. Classification could also be used to estimate the maximum possible volume of ice in an ice jam. When ice-jam flood levels are calculated by hydrodynamic models, the volume of ice in an ice jam is one of the most important parameters affecting calculated water levels and extent of flooding, both in the longitudinal and transverse to river directions. Whether or not there is enough ice volume to produce an ice jam that is long enough to develop an equilibrium section is a key question. This is because the water level is the highest possible for a given discharge in the equilibrium reach.

In open-water flood-delineation mapping, depth and velocity of the overbank flow are important considerations. With ice-jam flooding, there is a third consideration, which is whether or not blocks of ice can flow into overbank areas since large pieces of ice can cause damage to structures. Five factors which determine if ice blocks can flow into overbank areas, and how much damage they can do, are:

1) the height of the water above the banks,
2) the thicknesses of the ice blocks,
3) the presence or absence of obstacles on the bank that can prevent or allow ice blocks to flow onto the floodplain,
4) the velocities of the water on the floodplain which affect the impact forces of the ice blocks on structures, and
5) the size or mass of the ice blocks on the floodplain which also determines the impact forces of the ice blocks on structures.

Given that flow velocity can drive ice blocks to cause damage, it is important to determine the factors that drive floodplain velocity in ice-jam floods. The river water level longitudinal surface slope determines to some extent the water velocity on the floodplain. This is true for open-water and ice-jam floods. In the case of open-water floods the water surface slope is generally constant over a reach of interest unless there are major rapid sections or breaks in river bed slopes. This is not true in the case of ice jams unless the entire reach of interest is in the equilibrium section. The velocity of flow in the overbank areas is determined by the slopes in various parts of the ice-jam profile. In the toe region of the ice jam, the slope is much greater than the prevailing bed slope of the river or open-water floods. Velocities can be extremely high and this is sometimes the location where the floodplain flow is draining back into the river, which is much lower at the downstream end of the ice jam. In the equilibrium section, the floodplain velocities should be similar to the open-water condition. In the upstream transition section they should be less. In the M1 backwater curve upstream of the ice jam, the river surface slope is very flat and floodplain velocities should be correspondingly small. Overbank flow that results from the release of an upstream ice jam could have very high velocity and result in serious damage to structures and property.

Since the water surface slopes in the main channel that drive the floodplain flow can be complex in the case of ice jams, a 2-D model of the floodplain is likely needed to produce an accurate velocity field. A further complication is that ice blocks can increase the time that water takes to get into the floodplain by blocking some of the flow.

Regardless of the method used to define ice-jam flood levels and delineate flood-hazard areas, more observations are needed to continue to develop and verify these methods. If an ice jam occurs in a populated area, there are normally several people watching the fascinating phenomena and taking photos and videos of ice jams. It should be possible to get this observational data for the use in ice-flood delineation and flood mapping. Internet services should be developed for the purpose of collecting this data. The USGS has begun a labelling staff gauges in populated areas with phone numbers to encourage members of the public to text staff. The Alberta government has developed a mobile application that, among other forecasting and river-ice functionality, allows users to submit geo-tagged photos of ice and flood conditions to provincial forecasters. A pilot study allowing members of the public to send photos of the gauge height is also being planned in Alberta. The continued development of online platforms to host and share this information will greatly increase the volume of available ice-jam observational information. Methods should also be developed to collect this data from existing social media sources. People should be encouraged to use the services to upload geolocated information, photos and videos on ice-related phenomena and flooding.

All methods for ice-jam flood mapping and delineation have a lot of uncertainties. There are uncertainties in hydrological observations, ice observations, cross sections, digital elevation models, etc. Research is required to find out how these uncertainties from different sources affect the accuracy of flood maps. Also research should be done on how this uncertainty should be presented on maps and how it should be explained to the end users of the maps. The threat from ice floes affecting the floodplain also needs to be delineated and is another source of uncertainty.

6.2.3 Risk assessment

Development of flood levels and hazard areas estimation is essential for risk assessment. Without knowledge of hazard areas, flood depths, flood probability, and areas that are susceptible to impacts from ice floes, it is not possible to estimate flood damages and flood risk.

The effect of the ice-jam flood rates of rise and the duration of the flood on flood damages should be studied. The floods caused by breakup ice jams often rise quickly and there may not be time for evacuation or mitigation measures. This increases the possibility that the flood is hazardous for people and infrastructure. Rapid water level rise or decrease may also increase erosion of embankments and roads. The durations of breakup ice-jam floods are often relatively short and air temperatures are normally above zero. In the case of freeze-up jams, the flood duration may be longer and the freezing of flooded water may cause extra damages.

There are methods for estimation of direct flood damages typically involving the correlation of historical data of past damages with flood stage (Jasek 1993). This may be more difficult for ice-jam floods as the extent of flooding will be influenced by ice-jam location and extent, and not just discharge. In some cases, indirect tangible flood damages like loss of industrial production, traffic disruption or emergency costs are very important for the estimation of the flood damages. The methods for the estimation of these indirect flood damages should be developed.

6.3 Further development of guidelines

Planners need to consider flood hazards in planning development, while maximizing the benefits of floodplains and treating property owners in a fair and equitable manner. Guidelines for flood–risk mapping should be pragmatic, feasible, and flexible enough to allow alternative means of informing the public and land developers about flood hazards, and alternative means of flood delineation.

Flood damage reduction does not only require hazard identification but engineering solutions. Engineers need new, updated and programmatic design codes and standards taking into account economic and technological feasibility. New methodologies must be practical by taking into consideration data limitations and the possibility of client support for a design engineer’s time and effort.

7. Concluding Remarks

Flood hazard has to be identified in areas of existing and potential development so that measures can be taken to protect public safety. The cause of the flood hazard is less important to the persons affected than the damage caused by floods. In this paper, several examples are given of how damaging ice-related floods can be, often producing much higher water levels than open-water floods. In areas where the more severe flooding can result from ice jams, the delineation of areas of flood hazard must consider ice-related floods. There are several ways of delineating areas subject to ice-jam flooding such as mapping historic events, using biophysical evidence, using a flood-envelope approach, and performing hydrotechnical analyses. These methods enable delineation of the flood hazard based on existing information and are all appropriate means of informing the public about a hazard.

Guidelines for mapping flood hazard areas are still developing. Ideally, guidelines will allow for considerable flexibility while maintaining a standard of due diligence in whatever approach and criteria are chosen. It is the delineation of flood hazard, and the subsequent educating of the public and local authorities about the flood hazard, that is important not the approach or the technology.

Advances in understanding of ice-jamming processes have enabled greater use of the hydrotechnical approach involving hydrology and hydraulics. Whenever possible, waterway structures should be designed for ice-jam floods and ice passage using a detailed hydrotechnical approach based on several years of field observations of river-ice processes. Flood-risk management implies decisions under uncertainty, so the value and effectiveness of detailed risk analyses with limited information have to be considered critically.

To better determine and document ice jam and associated flooding extents and effects along rivers of potential ice-jam flooding, field observations and measurements are required. Regardless of the method used to delineate flood-hazard areas, observations are needed for development and verification. The rates-of-rise of ice-jam floods with respect to public safety and emergency preparedness, and the duration of the flood with respect to flood damages need to be investigated. Qualitative information should not be overlooked.

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