# ICE-JAM EFFECTS ON RED RIVER FLOODING AND POSSIBLE MITIGATION METHODS

Report prepared for the

**International Red River Basin Task Force**

**International Joint Commission**

by

**S. Beltaos, R. Pomerleau and R. A. Halliday**

March 2000

# Table of Contents

## 1. INTRODUCTION

During public meetings on the Red River basin, the International Joint Commission and its International Red River Basin Task Force heard a number of comments concerning the effect of ice on the 1997 flood and on ice mitigation in general. Ice jams have played a role in flooding on the Red River, particularly on some tributaries and several mitigation measures such as dusting and hole drilling have been attempted.

This report describes ice processes with particular emphasis on those occurring in the Red River. It discusses mitigation measures and makes a number of recommendations for future consideration.

## 2. RIVER ICE PROCESSES

The first ice to appear on a river is usually *border* ice, forming over quiescent strips next to the riverbanks. However, it is turbulent flow that largely defines the major river ice types. A slight amount of supercooling (0.01°C to 0.10°C) is sufficient to form tiny discoid crystals called *frazil.* Frazil crystals grow in size and flocculate as they are moved about by turbulence; where turbulence is low relative to the rise velocity of the crystals, a very thin layer called *skim* ice will form on the water surface. In a supercooled environment, frazil is *active*, meaning that it has an extreme capacity to adhere to any object it may come in contact with. It is this property that causes extensive clogging of municipal and industrial water intakes.

Frazil flocs rise to the surface and agglomerate to form porous lumps called frazil *slush*. Freezing of the slush leads to formation of ice *pans*. These are floes comprising a thin layer of solid ice underlain by slush; their rounded shape and elevated edges attest to frequent collisions as they make their way downstream (Fig. 1). Frazil crystals and flocs can also find their way to the river bed and stick to protruding objects, initiating *anchor* ice which can cause water levels to rise or may detach all at once and greatly augment the ice discharge downstream.

As more and more ice is produced, its surface concentration increases, eventually leading to congestion. Usually, the local flow speed is sufficiently low to permit *bridging* or *lodgement* of the incoming ice floes so that a single-layer ice cover is initiated. This is a rudimentary *ice jam*.

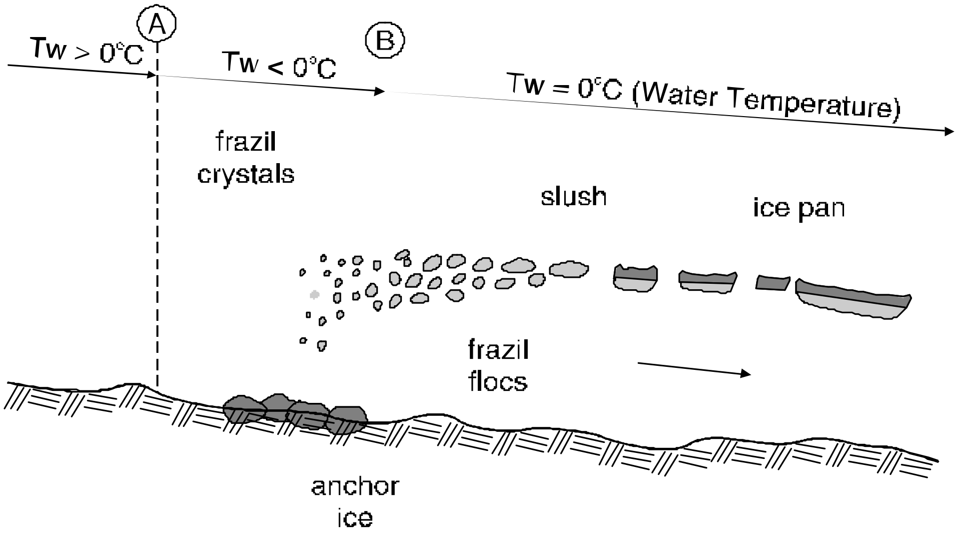

Figure 1. Different river ice forms (after Michel, 1971, with changes)

As the cover propagates upstream, it may encounter higher-velocity reaches where the incoming ice floes submerge and deposit after travelling some distance under the cover, creating a *thickened* jam. [An extreme case is the *hanging dam*, attaining thicknesses of many metres and forming in deep river sections downstream of ice-generating reaches such as rapids]. Increasing cover length often results in collapse and further thickening, known as *shoving* or *telescoping*.

In unregulated reaches, the water level rises to accommodate not only the added resistance caused by the rough jam underside, but also some nine-tenths of the jam thickness that has to be submerged (Fig. 2). Ice jams, whether at freeze-up or at breakup, play a prominent role in the ice regime, being the main cause of flooding and damages in northern rivers, impeding navigation and constraining hydro-power production (Ashton, 1986; Beltaos, 1995a).

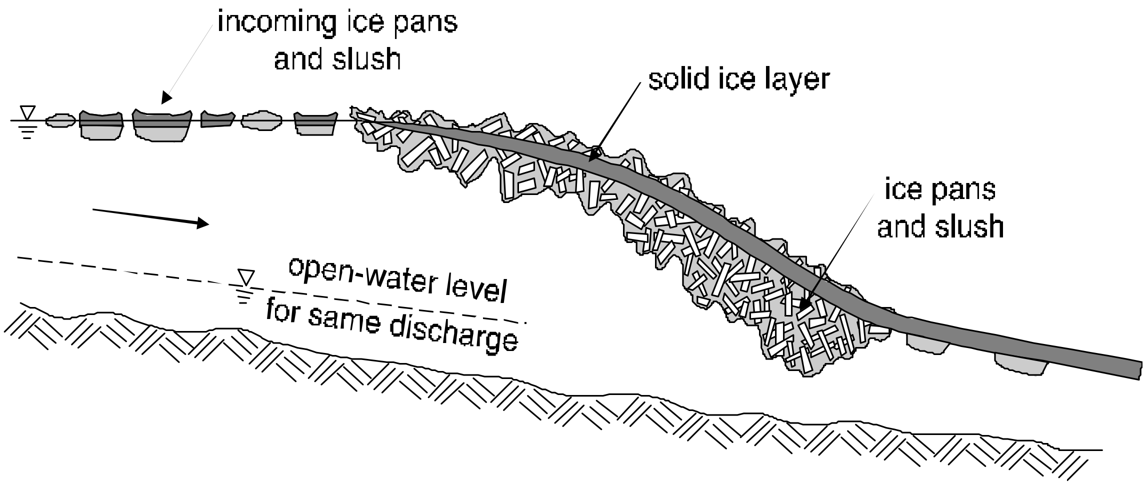

Figure 2. Profile of a freeze-up jam. Note high water levels caused by jam roughness and thickness. The configuration of breakup jams is similar, except for: less or no slush in the voids between ice blocks; no solid ice layer near surface; possibility of grounding near the downstream end, or "toe"; higher water levels due to larger flows during the freshet.

Freezing of the interstitial water in the pack results in a sheet of solid ice that grows downward and incorporates any ice fragments or slush that may be under it. (Fig. 2). As winter progresses, freezing in cavities and melting of protrusions at the cover's lower boundary cause a gradual smoothing and water levels drop.

Where water is constantly exposed to the atmosphere, usually due to overflow seepage, extreme ice thicknesses are attained during the winter. Such formations are commonly encountered in braided shallow streams and are alternatively called *icings, aufeis,* or *naleds* (Schohl and Ettema, 1986). By filling a channel or a culvert with ice, they can cause significant flooding in the spring.

With the approach of spring, thermal processes cause deterioration of the ice cover, while increasing runoff results in higher water levels. The weakened cover detaches from the shores and fractures into large slabs and sheets. These are set in motion by the current when enough room for movement is created on the water surface by the rising water levels. Some reaches "go" first, others retain a cover much longer. Moving ice sheets quickly break down into small blocks that are arrested by still-intact ice, initiating ice jams. Increasing flow and advancing thermal deterioration dislodge intact ice cover segments, thus releasing upstream ice jams and producing *ice runs*. Moving ice rubble may be arrested again by intact ice cover, forming new (but now fewer) jams, and the process is repeated until a reach is completely cleared of ice, save stranded ice blocks and remnants of ice jams near the river banks or other shallow areas. This process has led to the concept of *ice clearing discharge* (Beltaos, 1995b; 1997b), which is a threshold value beyond which ice jams can not exist in a given reach. The ice clearing discharge varies with channel morphology and hydraulics, as well as with the degree of thermal decay to which the ice is subjected before being dislodged. An obvious upper bound for the ice clearing flow is that which applies to highly dynamic breakup events that allow little time for thermal decay (see also later discussion).

Because of the relatively high flow, breakup jams are thicker, rougher, and cause much higher water levels than freeze-up ones. Moreover, they tend to release abruptly, producing violent *surges* of ice and water. Erosion, damage to structures, and dislocation of aquatic life can result. Breakup jams are not all bad, however. Often, the regular flooding that they cause in the spring revitalizes nearby lakes and ponds that are haven for many wildlife species. Good examples are the deltas of major Canadian rivers (Marsh and Hey, 1989).

## 3. TYPES OF BREAKUP EVENTS

Depending on hydro-meteorological conditions, the severity of a breakup event can vary between two extremes, those of the *thermal* or *overmature* breakup and the *premature* breakup (see also Beltaos, 1995b, for a comprehensive discussion of breakup processes and associated forecasting and predictive capabilities). The former type occurs when mild weather is accompanied by low runoff, due to lack of rain and slow melt. The ice cover deteriorates in place and eventually disintegrates under the limited forces applied by the modest current. Ice jamming is minimal, if any, and water levels remain low. Premature breakup on the other hand, is associated with rapid runoff, usually due to a combination of rapid melt and heavy rain. The hydrodynamic forces are sufficient to lift and break segments of the ice cover before significant thermal deterioration can occur. Ice jams are now the most persistent because they are held in place by sheet ice that retains almost all of its strength and thickness. This is aggravated by the high river flows caused by the intense runoff, rendering premature events the most severe in terms of flooding and damages. Usually, a breakup event falls somewhere between these two extremes, and involves a combination of thermal effects and mechanical fracture of the ice. Herein, the term *mechanical* breakup will be used to denote all non-thermal events because they are at least partly governed by the mechanical properties of the ice cover.

In the colder parts of Canada such as the Prairies or Territories, we are most familiar with a single event, the *spring breakup,* largely triggered by snowmelt. Because melt-driven runoff is relatively slow, breakup is preceded by a number of warm days. Together with solar radiation, the mild weather results in significant thermal deterioration of the ice cover. Therefore, premature breakup events in such regions are rare, if not altogether unknown.

In more temperate regions, however, such as parts of Atlantic Canada, Quebec, Ontario and British Columbia, events called *winter thaws* are common. Usually occurring in January and February, they consist of a few days of mild weather and typically come with significant rainfall. River flows may rise very rapidly and sufficiently to trigger breakup on many local rivers. This is the *winter breakup*, which can be more severe than a spring event, not only because of its premature nature. Dealing with the aftermath of flooding is hampered by the cold weather that resumes in a few days, while many jams do not release but freeze in place, posing an additional threat during subsequent runoff events.

As will be discussed in more detail later, ice jams in the Red River basin in the continental Great Plains are associated with spring breakup.  Premature breakup events do occur, however, particularly on the tributaries in the United States portion of the basin.

## 4. ICE JAM PROCESSES

The main cause of breakup-jam formation is the obstruction of the downstream movement of ice blocks by segments of still intact ice cover. A jam can therefore form anywhere in a river; however, there are certain geomorphic or anthropogenic features that are highly conducive to jamming. These include sharp bends and abrupt reductions in slope or flow velocity (e.g. a reservoir entrance, a river mouth, or a channel constriction). Reaches with islands, and man-made obstructions to the flux of broken ice are also candidates. The maximum water depth that can be caused by an ice jam at any given location is the so-called *equilibrium depth*, a parameter that can be calculated theoretically with reasonable confidence. It primarily depends on channel width and slope (both being aspects of channel morphology) and flow, a hydrological parameter that is determined by weather conditions as well as runoff characteristics of a watershed. The actual water depth caused by an ice jam can be equal to, or less than, the equilibrium value, depending on the volume of broken ice that is available to form the jam. This volume is limited by upstream river conditions and by the pre-breakup thickness of the ice cover, thus being a function of stream morphology and weather conditions. This aspect is not addressed in the simple equilibrium theory, but can be investigated using a numerical ice-jam model (e.g. see Beltaos, 1997).

The capacity of ice jams to raise water levels is well known (e.g. see Fig. 2). It derives from: (a) the very rough configuration of the jam underside and the attendant resistance to flow; and (b) the near-equality of ice and water densities which dictates that some nine-tenths of the jam thickness, amounting to several metres, must be submerged to achieve floatation of the cover. Consequently, an ice jam can cause widespread flooding, which is usually aggravated by great quantities of ice floes spilling onto the floodplain.

The release of an ice jam is followed by a surge, characterized by a sharp rise in water levels downstream of the jam, and by a rapid drop upstream (Fig. 3). The *celerity*, or the speed of propagation of the surge front, can be 10 m/s or more; the actual velocity of the flow is always less than the celerity but comparable to, or more than, what is experienced under the

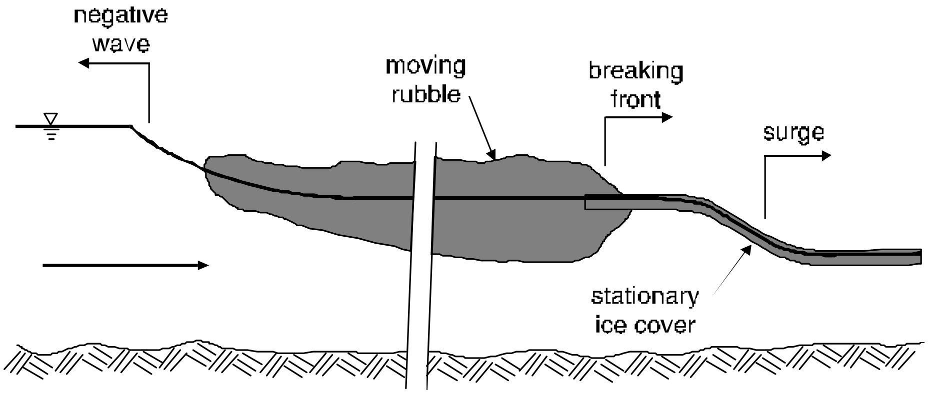

Figure 3. Flow and ice conditions during a surge caused by ice-jam release.

rarest of open-water floods. Values of 5 m/s are not uncommon, imparting enormous kinetic energy to ice floes, with obvious repercussions to river structures. Because hydrodynamic forces are proportional to the square of velocity, they can easily be augmented by an order of magnitude. Surges are thus capable of major bank erosion and bed scour, being a threat to many aquatic organisms or to the stability of bridges by undermining in-stream piers. They can also dislodge downstream ice jams and produce very high concentrations of suspended sediment (Beltaos et al, 1994; Beltaos and Burrell, 1998; Milburn and Prowse, 1996). In cases of over-bank flooding, the swift drop in water levels upstream of the jam can cause extensive fish mortality because it allows little time for the fish to return to the main river (e.g. Thames River below Chatham, February 1984).

The *ice run*, that is, the rubble from the released jam trails the front of the surge whose rate of propagation defines the celerity. When an ice run encounters competent ice cover that has not been dislodged by the surge, a *breaking front* usually forms. This is a sharp transition between rubble and intact ice, that moves downstream as the intact ice edge is broken up and incorporated into the rubble. Breaking fronts may move for very long distances or they may be arrested shortly after formation, thus causing a new jam. Exactly what causes the arrest is not known; shallow river depth, or strong and thick ice cover are two possibilities (Beltaos, 1995b).

Not all the ice in a jam participates in the ice run that follows a release: rubble that is grounded at shallow zones near river banks, islands, or bars, remains in place and forms vertical features called *shear walls.* The height of a shear wall is indicative of the approximate thickness of a jam (e.g. see Beltaos, 1995a).

## 5. ICE PROBLEMS IN THE RED RIVER

River ice can cause property damage, erode stream banks, disrupt transportation and hydropower operations, and make flood forecasting difficult. As of 1999, the U.S. Army’s Cold Regions Research and Engineering Laboratory (CRREL) National Ice Jam Database lists 391 events in the Red River basin within North Dakota in which ice, particularly ice jams, affected river stages. Similarly, 488 events have been catalogued for the Red River basin in Minnesota. Rannie (1999)has catalogued similar data from the Canadian portions of the basin. There has been no effort to produce a basin-wide list of ice jams.

Tributaries generally rise in the upland areas at the extremities of the basin, flowing down somewhat steep gradients to the broad glacial lake plain and the main stem. The Red River main stem channel has a significantly lower stream gradient. The river flows north into colder regions where the ice cover is likely still intact.

Tributaries with relatively significant channel gradients and confined channels are prone to ice jams. Examples include the Sheyenne River from Valley City to upstream of Kindred, North Dakota, Pembina River above Walhalla, North Dakota, and the Red Lake River from Thief River Falls to Crookston, Minnesota. Ice jams in these reaches can cause rapid and sometimes severe stage fluctuations. Shear walls more than six feet high have been measured on the Red Lake River near Red Lake Falls.

As the tributaries reach the wide floodplain, the gradient decreases, and local blockages and backwater from high stages on the main stem of the Red River sometimes cause jams. The tributary floodplain is normally quite wide at these locations and ice blockages cause the rivers, seeking a path of less resistance, to rise and break out over the prairie. Once overland flooding occurs, ice jam events decrease.

Main stem conditions differ from those of tributaries, in that there is usually a broad, wide floodplain and mild stream gradients. During the initial break-up, river levels can fluctuate greatly as the ice jams and flows increase. Once the river starts to overflow its banks, however, the width available for floodwaters increases dramatically and the ice jam potential is reduced. Generally, the ice dissipates before the peak flood stage. However, this is not always the case; during the 1989 spring flood, for example, the ice effects remained until the peak stage (Fig. 4).

Figure 4. Red River breakup, April 13, 1989. Looking north toward Grand Forks, ND; flow is from bottom to top. The ice cover, comprising fractured sheet ice and occasional rubble, is contained in the channel by trees while the water is contained within the levees. Photo taken by Kathleen White, CRREL.

While conducting backwater studies of the 1826 flood peak at Winnipeg, KGS Group (2000) concluded that the peak stage was ice effected.

Most rivers in the basin are highly sinuous. Ice floes exacerbate stream bank erosion as the ice strikes stream banks and cuts into soils. Damage to bridges can occur when ice hits the structures or jams against them; small bridges can be swept away if stages are high enough to dislodge and float the bridge structure downstream. Even if a bridge survives the spring event, the approaches and portions of the roadway may erode due to ice and overland flow.

Ice jams occur infrequently on the Red River and its tributaries in Manitoba with some exceptions such as the Red River at Selkirk and the Assiniboine River. Although not part of the IJC study area, the Assiniboine River situation will be discussed in this report on account of its potential effect on the operation of Winnipeg flood control works.

In 1996 a major ice jam formed just downstream of Selkirk causing significant damage in the city. The City takes a responsible approach to floodplain management, so damage tends to affect recreational facilities rather than homes and businesses. The Selkirk Golf and Country Club, the waterfront, and a number of storm water outfalls are vulnerable to ice jam flooding although dikes provide some protection. With the forecast of flooding in 1997 some 12,000 holes were drilled in the river ice near Selkirk to weaken it in advance of the spring break-up. There were no jams in 1997 but it is impossible to state with certainty that the hole-drilling was responsible.

The Assiniboine River Diversion is one of three flood control structures that protect the city of Winnipeg from large floods, the others being Shellmouth Dam in the upper Assiniboine and the Red River Floodway that diverts water around Winnipeg. The Assiniboine River Diversion consists of a control structure that forms a small reservoir near Portage la Prairie, a second structure controlling flows into an excavated and diked channel leading to Lake Manitoba, and three drop structures, including one at the Lake. The design capacity is 25,000 cfs.

The effects of ice runs in the spring breakup period have threatened the diversion project in the past. Ice frequently jams upstream of the diversion and releases suddenly. The rapid inflow of a surge of water and ice has caused the reservoir level to rise uncontrollably, with concern for overtopping of the structures. Greater than desirable volumes of ice and water have been released through the River Control Structure in the past when large inflows could not be totally managed with potentially hazardous results. For example, in 1983, this caused an ice jam downstream that caused a backup of the tailwater to the extent that it threatened overtopping of the reservoir dikes, knocked out the primary power supply and threatened the backup power supply. (KGS Group, 1999)

Raising of the gates at the entrance to the Diversion Channel to prevent the problems in the River downstream can increase the opportunity for ice to pass into the Diversion Channel. This can lead to:

- Damage to the ice boom in the approach channel to the Diversion Structure

- Concern for the potential for damage to the Diversion Structure and gates (although none has yet occurred)
- Minor damage to the drop structures
- Formation of an ice jam at the Outlet Structure at Lake Manitoba
- Severe overtopping of both the overflow section in the channel's west dike (at the downstream end of the diversion channel) and the east dike upstream of the Outlet Structure

Of particular concern is the potential for overtopping of the earthfill structures that retain the reservoir in the Assiniboine River.

The loss of the capability of the project to pond water and to divert it into the Portage Diversion in the weeks that follow the ice run could affect flood conditions in Winnipeg. It could eliminate a flood control capacity of up to 15,000 to 20,000 cfs, depending on the subsequent flood flow of the Assiniboine River. Since the commissioning of the project, flow reductions of up to 5000 cfs have been observed. (Kozera, personal communication 2000)

Release of large flows (up to 10,000 cfs) into the river downstream of the River Control Structure can cause the formation of ice jams. The breakup of the ice cover or of a jam can release a large flow at a time when river levels in Winnipeg are already high. This phenomenon has happened in the past, including the spring of 1997. As well, such ice jams can cause high water levels and subsequent damage to property along the Assiniboine River between Portage la Prairie and Winnipeg.

Ice conditions also play a role in the operation of the Red River Floodway's inlet control structure. During the winter a permanent ice cover forms on the Red River and this cover must be cleared prior to Floodway operations. If ice enters the Floodway channel it could jam against bridges and reduce channel capacity. A two-metre high entrance lip keeps ice out of the channel; gate raises are usually postponed until ice is moving in small pans.

In 1997, ice remained largely stationary or in large pans much longer than in previous floods. To protect property in the city of Winnipeg, the gates were operated before the ice had cleared. Some large pans did move into the Floodway channel, jamming against the St. Mary's road bridge. Fortunately the jam persisted for only eight hours. (Red River Floodway Operations Review Committee, 1999)

## 6. ICE JAM MITIGATION METHODS

There are both structural and non-structural measures that can be taken to prevent the formation of ice jams, or reduce their effects once formed (e.g. see Burrell, 1995). Structural measures are generally more effective and reliable than non-structural ones, but also more costly. They may include dams, ice booms, ice - retention structures, dykes, or various channel modifications. Non-structural measures can be subdivided into prevention and emergency measures. The former include various methods for ice suppression (e.g. bubblers, thermal modification of ice regime, surface treatment) and for mechanical destruction or weakening of the winter ice cover (e.g. ice cutting, drilling, use of icebreakers, blasting). Emergency measures are a last resort, to be used when a jam has already formed and become a serious threat (e.g. blasting, bombing, use of icebreakers where feasible, mechanical ice removal). By that time, a considerable amount of damage may have already been sustained. Consideration of such measures is not within the scope of this report, and thus they will not be discussed explicitly. The same applies to structural measures. Therefore the focus herein is placed on non-structural, preventive measures.

This topic has been recently reviewed by Haehnel (1998) who discusses both old, established methods, and relatively new, often experimental approaches. Typical costs of various types of operations are also presented. It is important to note one of the author's main conclusions, i.e. "*…there is little guidance currently available to predict the reduction in ice jam potential due to the application of any of these measures. All that is clearly known is that the complete removal of ice from the river will eliminate the possibility of ice jam formation*." Of course, the latter option is rather expensive and uneconomical in any but very rare circumstances. An example of such a program is the annual ice management operation in the Rideau River at Ottawa, which commenced in the last century (Reid et al, 1995). It includes ice cutting, blasting, and removal into the Ottawa River in advance of the spring breakup event. Depending on hydroclimatic conditions, the cost varies from $ 200,000 to 400,000 each year, and is justified by the much higher annual cost of ice-jam related damages (approx. $ 2,000,000; Reid et al, 1995).

In general, the practical approach is to: (a) identify ice-jam prone sites within the reach of interest: (b) carry out field observations and review existing data sources in order to obtain a thorough documentation of local ice-jam processes and the driving hydro-climatic conditions; and (c) design a mitigation program that will accelerate thermal decay and/or clearance of the ice cover from the vulnerable areas. When the spring runoff arrives, ice floes moving down the river will encounter open water or greatly weakened cover at these areas, thus being able to maintain their downstream progress. Common methods to achieve this outcome are described next

## 7. NON-STRUCTURAL METHODS

### Mechanical

These are measures designed to reduce the structural integrity of the ice cover by mechanical means, so that its breakup can be effected by lesser hydrodynamic forces than those required to break the natural cover.

#### *Ice cutting*

Slots are cut in different patterns and lengths, promoting early breakup of the cover when the runoff starts. Normally, operations require placement of personnel and equipment onto the ice cover; hence, the work must be done well in advance (usually several weeks) of the breakup event. Safety aspects can also be addressed by the use of amphibious excavating equipment. Re-freezing may inhibit the effectiveness of the slots, however, this can be circumvented by not cutting through the entire ice thickness (e.g. see Haehnel, 1998).

### *Blasting*

Chemical charges have been widely used to clear ice (Van der Kley, 1965; Burrell, 1995), but this method entails both safety hazards and ecological impacts. Where possible, alternative methods should be considered. Explosive action can also be achieved by the less commonly used compressed gas cartridges (Haehnel, 1998). This approach has been very successful in Nebraska when done as soon as a jam forms (White, K. pers. comm., 2000). Blasting can be successful under certain river and ice conditions, provided it is planned well in advance and blasting teams can be deployed on very short notice (White and Kay, 1997b).

### *Icebreaking*

Icebreaking has been used extensively as a jam-prevention or jam-breaching measure, and involves the use of icebreaking vessels (conventional icebreakers, river towboats, ice prows, amphibious tracked and air-cushion vehicles), construction equipment (bulldozers, escavators, dragline buckets, cranes with wrecking balls).

A simple strategy for icebreaking, as well as for blasting, is to severely fracture the cover in a particular reach, and leave the resulting ice floes in the channel, to be flushed out by the prevailing flow or by the freshet. The former possibility is rather remote, because river flow velocities during the winter are generally too low to effect submergence and transport of the ice fragments. It will usually be necessary to wait until the freshet; therefore, re-freezing due to an intervening cold spell may reduce the effectiveness of this technique. In all cases, it is important to ensure that the broken ice has room to move into. Otherwise, it is possible to merely “re-locate the problem” by creating new hazards for downstream residents, infrastructure, and sensitive ecosystems.

A more desirable, and more expensive, approach includes the forced clearance of the broken ice out of the problem reach. This is routinely practiced under the Rideau River Ice Management Program, where the broken ice cover is moved downstream and over Rideau Falls onto the Ottawa River using armoured open boats. It is often necessary to simultaneously augment the river flow by manipulating the outflow an upstream reservoir (Reid et al, 1995).

### *Hole cutting/drilling*

Holes in the ice can reduce the structural integrity of the cover, and promote increasing melt in their vicinity (Fig. 5). Hole diameters of 20 cm or more appear to be sufficient to prevent re-freezing. Drilling, both mechanical and thermal, is an economical method to create holes in an ice cover, but blasting and cutting have also been used. Typically, holes are cut about a month before the natural breakup event (Haehnel, 1998; US Army CRREL, 1996).

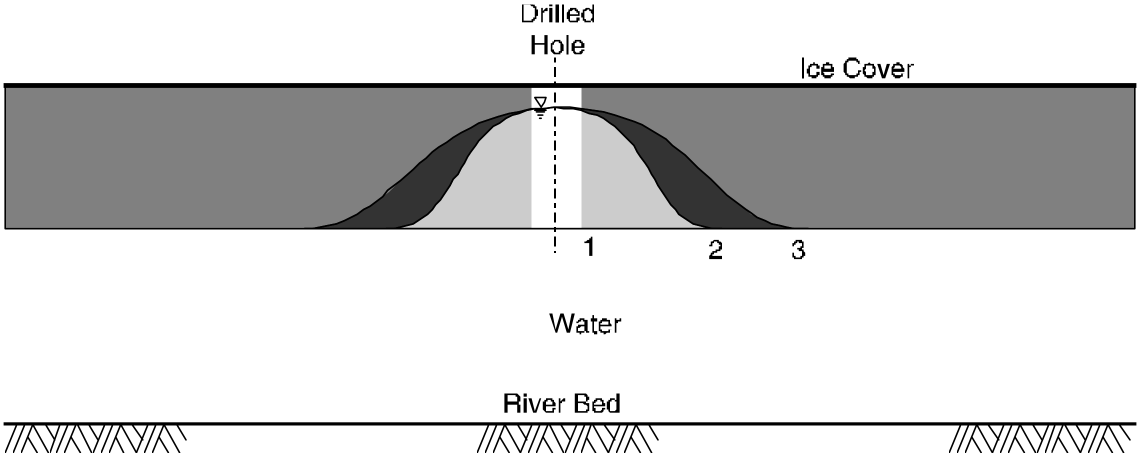

Figure 5. Typical ice profiles observed around a hole at different times. Profile 1: original hole; profiles 2 and 3 show progressive melting of ice in the vicinity of the hole (after US Army CRREL, 1996).

It is noted that the hole profiles shown in Fig. 5 are schematic illustrations and do not represent specific measurements taken at specific times (R. Haehnel, pers. comm., 2000). This question was investigated in a recent laboratory study by Haehnel et al (1999) who concluded that the rate of melting around the hole decreases with time, owing to streamlining of the hole boundaries. With ordinary spacing of the holes (about 3 m apart), the total volume of ice that can be melted in a 0.34 m thick ice cover would be very small relative to the total ice volume in the river. The authors suggest, however, that future work should focus on how the holes reduce the mechanical integrity of the ice cover and increase energy absorption at the ice-air interface. Both of these processes would reduce the ability of the ice cover to resist dislodgment, thus reducing the potential of ice jamming in that part of the river.

This method of weakening an ice cover appears to have been first proposed in an unpublished CRREL report (Zufelt, 1987), with reference to ice problems on the Oconto River at Oconto, Wisconsin. The writers are indebted to K. White (pers. comm. 2000) for pointing this out and providing the corresponding citation.

### Thermal

Thermal methods seek to accelerate the rate of ice decay by enhancing the amount of heat that is absorbed by the ice cover during the pre-breakup period. At the top surface of the ice, thermal fluxes are governed by air temperature, wind speed, humidity, short/long wave radiation, and surface albedo. At the bottom of the cover, the thermal exchange is driven by water temperature and velocity. It is often augmented by taking advantage of available thermal sources, such as power plants, sewage and industrial effluents, etc. Depending on the source temperature and discharge, sizeable river sections downstream can be kept open during the winter. Natural sources of heat include relatively warm water that may be found at the bottom of a lake or a reservoir, and can be utilized to suppress ice growth by means of air bubbler systems or submersible pumps (Ashton, 1986). Such methods are most effective for localized applications, and there is no record of having been extensively used to control river ice jams  (Haehnel, 1998). A successful application is described in a US Dept of the Army pamphlet (1994): 20°C water from the cooling ponds of the Dresden nuclear power plant has been used to melt a nearby hanging dam in the Kankakee River, which obstructs the passage of ice blocks at breakup and can cause damaging ice jams.

Enhancing heat absorption at the top of the ice cover is a common ice-jam mitigation strategy, usually involving the reduction of the surface albedo in order to promote penetration of solar radiation into the ice. Unless the exposed top surface is clear “blue” (or “black”) ice, a large part of the incoming solar radiation is reflected off the snow surface or, if the snow has already melted, off the surface of “white” or “snow” ice (Prowse and Demuth, 1992). Blue/black ice are terms used to describe clear columnar ice that forms by downward freezing. In rivers, it usually occurs as a lower ice layer, overlain by “white” (or “snow”) ice, which forms when water floods the snow-covered ice surface through various cracks or leads, forming slush that subsequently freezes solid.

A common means of reducing surface albedo is “dusting”, i.e. the spreading of various low-albedo, particulate materials on the cover, such as coal dust, sand, dry dead leaves, bark dust, or various pigments. Apart from the albedo of a material, various other factors influence the effectiveness of dusting, including particle size, specific gravity, thermal conductivity, and application density (mass per unit cover area). Under favourable weather conditions, dusting weakens the ice first by melting the snow cover, then by promoting crystal-boundary melt as the ice temperature reaches 0°C (Ashton, 1986; Prowse and Demuth, 1992). Moreover, relatively fine particles (~0.5 mm) have been reported to penetrate though the entire ice cover, leaving behind a honeycombed, greatly weakened material (Spetsov, 1965, as quoted by Haehnel, 1998). Practical aspects of dusting operations are discussed by White and Kay (1997b), including planning guidelines, and spreadsheet for estimating operational costs, both developed on the basis of experience in Nebraska streams.

Generally, dusting should take place about a month prior to the anticipated time of breakup. It may not be effective at sites that are subject to sudden thaws, which are typically triggered by rain-on-snow events. But even where sudden thaws are rare, as is the case with the Red River in Manitoba, dusting may be rendered useless by post-application snowfall. Moreover, where the dust has already caused significant melt of the snow cover, much of the benefit may be lost if the meltwater on top of the ice re-freezes as a result of a cold spell. Persistent cloudiness and limited daylight hours will also have an inhibiting effect. Thus, dusting appears to be best suited for relatively northern and cold-climate sites, which are subject to a single breakup event that occurs after late March under conditions of long, clear days, and triggered by gradual snowmelt and runoff. The Red River largely satisfies these conditions, at least within the Manitoba reach. Even so, care must be exercised in selecting the dusting material: negative results in Minnesota and North Dakota applications were partly attributed to the light colour of the sand used for dusting (Haehnel *et al*, 1999a and 1999b).

Of course, the introduction of foreign matter into a river may have detrimental effects on the ecosystem, and the possible environmental impacts of any dusting program should be considered and assessed in advance.

Ice decay can also be promoted by flooding the cover (albedo of water ≈ 15%) to help melt the snow or simply by removing the snow layer, which not only reflects most of the solar radiation but also insulates the ice from warm air temperatures. Weather reversals are again obvious limitations in this case.

### Chemical

For completeness, the use of chemicals to remove ice covers in the former Soviet Union is also mentioned here. Details may be found in Haehnel (1998).

## 8. POTENTIAL RED RIVER APPLICATIONS

The Red River is a low-gradient, low-energy stream, subject to the cold continental climate zone of the Great Plains. Consequently, ice covers are generally smooth, and once formed, they tend to remain in place through the entire winter; break-up jams dominate.

As indicated in a previous section, ice on the Red River and its tributaries is typically present from November to April. Flows are generally low during the winter, while ice growth appears to depend on latitude. Under normal winter conditions, ice thickness ranges from about 46 cm in the southern portion of the basin to about 76 cm near the US-Canada border. Within Manitoba, and closer to Winnipeg, greater thickness can be attained, up to one metre (T. Carpenter, pers. comm. 1999). Breakup is triggered by snowmelt and warmer temperatures, a relatively gradual process that is expected to significantly reduce both ice thickness and ice strength. Though no data specific to the Red River are available to support this expectation, measurements in other streams within the US portion of the basin indicate a 2 to 3 fold reduction in flexural strength by the end of March, with concomitant thickness loss of up to 30 cm (Haehnel et al, 1999a, 1999b). However, early and rapid melt events would tend to inhibit thermal ice deterioration, thus being more conducive to ice jamming. In the Manitoba reach of the river, ice jams are relatively rare, and tend to form near Selkirk as happened in 1996.

An important point to keep in mind while considering the need for ice management on the Red River is that ice jams can only occur when the river flow is less than the “ice-clearing” discharge, as discussed in Section 2 (see also Beltaos, 1995b; 1997b). As mentioned earlier breakup ice jams form when moving ice fragments are arrested by sections of still-intact, stationary ice cover. Increasing discharge and advancing thermal decay will eventually cause such segments to dislodge and release any jams they may be holding in place. The ice-clearing discharge can vary from year to year and from site to site, but remains within definite limits. This expectation is supported by US observations: as described in Section 4, the ice generally goes out before the peak flow is realized, while the jamming potential is reduced once river stages reach bankfull. It is important to remember, however, that ice-jam induced *stages* during the rising limb of the spring flow hydrograph will normally be much higher that those corresponding to the peak flow, which now occurs under open-water conditions. However, this effect may be reversed during rare, very-high-discharge floods such as that of 1997: the high flows and attendant rapid rates of rise would dislodge any jams that might form, at a relatively early phase of the flood. Moreover, the peak flood stage will eventually exceed any local peaks caused by jams.

### Mitigation options and requirements

Based on the preceding discussion, a number of mitigation methods appear to have the potential for beneficial implementation on the Red River. Ice cutting and breaking, hole drilling, and dusting over selected reaches are candidates. However, experience has shown that the success of nonstructural measures depends heavily on local conditions. The selection and design of a mitigation program must be based, therefore, on a thorough understanding of local hydro-climatic parameters and ice processes. In turn, such understanding can be developed from historical records (hydrometric, climatic, ice-jam occurrence), local hydraulics (channel bathymetry, slope, morphology), and most importantly, from field observation and documentation of local ice processes. To facilitate this objective, it would be appropriate to immediately commence field monitoring and data acquisition programs in reaches known to be prone to ice jamming. Such activities should be repeated annually, and eventually be used to build a database, similar to the one that has been developed in the United States (White and Eames, 1999). Though the Red River Basin database would be more limited in scope, it could be more extensive in depth by including detailed hydro-climatic data that are not normally included in the US database.

Prior to the arrival of the 1997 flood peak, a substantial hole-drilling program was implemented near Selkirk, Manitoba, in order to weaken the ice cover and minimize ice-jamming potential. This was prudent, given the fact that a major flood event was anticipated to occur that spring. As it turned out, no jams were reported during the flood, which at first glance may suggest a cause-and-effect link. As discussed earlier, however, it is also possible that the magnitude of the flood was so overwhelming as to render the presence of ice irrelevant. This example again illustrates the importance of building a good understanding of local processes before selecting and implementing long-term ice control programs.

In conclusion, no recommendation is made herein as to which mitigation method may be the most appropriate. A set of non-structural measures have been identified, however, as having potential for further consideration, in conjunction with an understanding of local ice processes and hydro-climatic conditions. Once a method is selected, it would be appropriate to make plans for monitoring its effectiveness and environmental impact, at least during the first few years of application.

### Entire-river ice breaking concept

Before closing this section, an unconventional mitigation concept is examined, in the interests of completeness. It has been suggested by a flood-control advocate during hearings held by the International Joint Commission that if, by means of an ice breaking method, the ice cover were thoroughly fractured prematurely over the entire length of the river, the result would be earlier arrival of reduced flood peaks.  It is not stated why or under what conditions this may be the case.

From hydraulic considerations, the time-of-travel for runoff-generated waves can be determined using the flood peak celerity, C, which is approximately equal to 1.5V, with V = average flow velocity (Henderson, 1966).  *If all the broken ice were to be artificially removed* from the river, a condition of open-water flow would be established. Then, the velocity V and thence, the wave celerity, C, would be greater than the corresponding ice-covered flow values at the same discharge, because the overall resistance to flow would be reduced. It is estimated that this difference would typically amount to 20%. For a three-week time of travel, the flood peak would then arrive 4 days earlier, hardly a major advance. The reduced hydraulic resistance would generally reduce the river stage, not only because of the removal of the upper flow boundary (ice cover), but also because the threat of ice jamming would be completely eliminated.

Be that as it may, this concept appears to have more theoretical than practical value: the removal of the broken ice from the entire river would be a rather difficult undertaking, and if at all feasible, its cost would be enormous. In the event that the ice cover is broken but left in the river, the fragmented cover would actually *retard* the advance of the flood wave, because a broken cover offers a greater resistance to flow than an intact, relatively smooth one. More importantly, the presence of an extensive reach of broken ice at the time when the runoff begins could introduce serious risks of ice jamming at unforeseen locations.

## 9. ICE PROBLEMS IN TRIBUTARIES

It has been noted in Section 5 that relatively steep tributaries with confined channels are prone to ice jams, e.g. Sheyenne River near Kindred, Pembina River above Walhalla, etc. Moreover, tributary streams flatten considerably as they approach the main stem, especially during periods of high Red River stages. This condition is also conducive to jamming, and overland flows have been experienced as a result

The recurrent nature of tributary jams may warrant consideration of structural mitigation measures, such as ice control structures, dyking, or channel modifications. Here, again, selection and design must be based on thorough understanding of local conditions, which must be partly based on field observations and measurements. Moreover, consideration of costly permanent structures should take into account potential modifications to the local ice regime that may result from climate change impacts (e.g. see Environment Canada, 1995; Hengeveld, 1995; Beltaos and Prowse, 1999).

## 10. CLIMATE CHANGE CONSIDERATIONS

Ice breakup and jamming processes are very sensitive to both current and antecedent weather conditions. Consequently, they may be significantly modified as a result of potential changes to local climatic conditions associated with greenhouse gas effects. Therefore, it would be appropriate to consider climate-related scenarios in case long-term structural measures are examined as part of an ice management program, either on the main river or on any one of its tributaries. In the past one hundred years or so, modifications have been detected to the ice regime of Canadian rivers in general (e.g. see Beltaos and Prowse, 1999), and of the Red River in particular (Rannie, 1983). Such changes are consistent with corresponding changes in temperature, representing slight warming trends, except for cooling in parts of Atlantic Canada (Brimley and Freeman, 1997). Very little work has been done on the more complex question of how climate change may influence the frequency and severity of ice jams. This influence is expected to vary from site to site and region to region, and is difficult to predict without detailed hydro-climatic modelling applications. One trend that can be forecast at this time, however, is more frequent winter breakup and jamming occurrences in the middle Canadian latitudes, owing to more frequent rainfall during the winter months. This prediction is based on current understanding of river ice processes and on the results of a recent case study (Beltaos, 1997c; 1999).

## 11. RECOMMENDATIONS

> **Recommendation:** Ice jam information from the entire basin should be incorporated into the CRREL Ice Jam Database so that ice problems in the basin can be analyzed further. Where feasible, historic ice jams from the Canadian portion of the basin should be entered.
>
> **Recommendation:** Channel modifications, ice dusting with chemically benign substances, and ice cutting/drilling are deemed potentially feasible ice management strategies in the Red River basin. Care should be taken to ensure the protection of downstream interests.
>
> **Recommendation:** The selection and design of a mitigation program should be based on a thorough understanding of local hydro-climatic and ice conditions. Such understanding can be developed from historical records (hydrometric, climatic, ice-jam occurrence), local hydraulics (channel bathymetry, slope,

morphology), and most importantly, from field observation and documentation of local ice processes.

**Recommendation:** Climate-related scenarios should be considered in the design of long-term ice-jam mitigation measures if such measures are included in ice management programs, either on the main river or on any one of its tributaries.

## 12. ACKNOWLEDGMENTS

Review comments by Kathleen D. White, Research Hydraulic Engineer, US Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL) are greatly appreciated. Robert Haehnel, Research Mechanical Engineer (also with CRREL), provided valuable information regarding the hole drilling mitigation method. Eugene Kozera, Flood Damage Reduction Engineer, Manitoba Department of Conservation and Rick Carson, Manager of Water Resources Services, KGS Group provided detailed information on ice problems related to the operation of the Portage Diversion. Rick Carson also conducted the analysis of possible ice effects on the 1826 flood peak at Winnipeg.

## 13. REFERENCES

Ashton, G.D. (editor) 1986. River and Lake Ice Engineering. Water Resources Publications, Littleton, Colorado, U.S.A.

Beltaos, S. (Ed). 1995a. River ice jams. Water Resources Publications, Highlands Ranch, Co., USA

Beltaos, S. 1995b. Breakup of river ice. National Water Research Institute Contribution No. 95-125. Prepared for IAHR book *River Ice Processes and Hydraulics*, Chapter 5.

Beltaos, S. 1997a. User's manual for the RIVJAM model. National Water Research Institute Contribution No. 97-18, Burlington, Canada, 43 p.

Beltaos, S. 1997b. Onset of river ice breakup. Cold Regions Science and Technology, Vol. 25, No. 3, 183-196.

Beltaos, S. 1997c. Effects of Climate on River Ice Jams. Proceedings, 9th Workshop on River Ice, Fredericton, NB, Canada, 225-244.

Beltaos, S. 1999. Climatic effects on the changing ice-breakup regime of the Saint John River. Proceedings, 10th Workshop on River Ice, Winnipeg, 251-264.

Beltaos, S. and Burrell, B.C. 1998. Transport of Metals on Sediment during the Spring Breakup of River Ice. Proc., 14th International Ice Symposium, July 1998, Potsdam, NY, USA, Vol. 2 (in press).

Beltaos, S. and Prowse, T.D. 1999. Climate impacts on extreme ice jam events in Canadian rivers. (Report to the Canadian National Committee for the International Hydrological Program (CNC/IHP), prepared at their request, as part of a contribution to UNESCO/IHP summarizing Canadian expertise in Hydrological Sciences).

Beltaos, S., Burrell, B.C. And Ismail, S. 1994. Ice and sedimentation processes in the Saint John River, Canada. Proc. IAHR International Ice Symposium, Trondheim, Norway, August, Vol. 1, 11-21.

Brimley, W. and Freeman, C. 1997. Trends in river ice cover in Atlantic Canada. *Proceedings, 9th Workshop on River Ice*, Fredericton, New Brunswick, 335-349.

Burrell, B.C. 1995. Chapter 7: Mitigation; "River Ice Jams" (S. Beltaos, ed.), Water Resources Publications, Highlands Ranch, Co., USA.

Environment Canada. 1995. The state of Canada's climate: monitoring variability and change. SOE Report No. 95-1. Ottawa, Ont., 52 p.

Haehnel, R.B. 1998. Nonstructural ice control. US Army CRREL Special Report 98-14, 36 pp., Hanover, NH, USA.

Haehnel, R.B., Clark, H.C. and Daly, S.F. 1999. The effects of holes drilled in a river ice cover on the heat transfer at the ice water interface. ASCE Proceedings of the Tenth International Conference on Cold Regions Engineering: *Putting Research into Practice*, Edited by J.E. Zufelt, Lincoln, NH, 641-652

Haehnel, R.B., Zabilansky, L.J. and Clark, H.C. 1999a. Evaluation of the use of dusting for prevention of ice jams in Minnesota. US Army CRREL Contract Report CON128, 13 pp. plus Figures and Appendices, Hanover, NH, USA.

Haehnel, R.B., Zabilansky, L.J. and Clark, H.C. 1999b. Evaluation of the use of dusting for prevention of ice jams in North Dakota. US Army CRREL Contract Report CON128, 13 pp. plus Figures and Appendices, Hanover, NH, USA.

Henderson, F.M. 1966. Open channel flow. The Macmillan Company New York.

Hengeveld, H. 1995. Understanding atmospheric change. State of the Environment Report No. 95-2, Environment Canada, Ottawa, Canada.

KGS Group 1999. Flood Protection for Winnipeg, Report on Part I - Vulnerabilities and Part II - Mitigation Measures. Report to the International Joint Commission

KGS Group 2000. Flood Protection for Winnipeg, Report on Part III - Pre-feasibility Studies. Report to the International Joint Commission.

Marsh, P. and Hey, M. 1989. The flooding hydrology of Mackenzie delta lakes near Inuvik, N.W.T. Canada. Arctic, Vol. 42, No. 1, 41-49.

Michel, B. 1971. Winter regime of rivers and lakes. US CRREL Monograph III-B1a, Hanover, NH, 131 p.

Milburn, D. and Prowse, T.D. 1996. The effects of river ice breakup on suspended sediment and select trace-element fluxes. Nordic Hydrology, 27: 69-84.

Pomerleau, Richard 1999. Ice Problems in the Red River of the North Basin. US Army Corps of Engineers, St. Paul District 4 p.

Prowse, T.D. and Demuth, M.N. 1992. Spatial and temporal variability of river ice-cover strength. Proc., 9th Int'l Northern Research basins Symposium/Workshop, NHRI Symposium No. 10, Canada, 405-421.

Rannie, W.F. 1983. Breakup and freeze-up of the Red River at Winnipeg, Manitoba, Canada, in the 19th century and some climatic implications. *Climatic Change*, 5, 283-296.

Rannie, W.F. 1999. *Hydroclimate, Flooding, and Runoff in the Red River Basin Prior to 1870*. Geological Survey of Canada Open File 3705, 189 p.

Red River Floodway Operations Review Committee 1999. *A review of the Red River Floodway Operating Rules.* Manitoba Department of Conservation, 64 p.

Reid, B.A., Torrens, L.W. and Hodgins, D.B. 1995. Proceedings, 8th Workshop on the Hydraulics of Ice Covered Rivers, Kamloops, BC, edited by D.D. Andres, 121-142.

Schohl, G.A. and Ettema, R. 1986. Experiments on naled ice growth. Proc. IAHR International Ice Symposium, Iowa City, USA., Vol. I, 507-520.

US Army CRREL. 1996. Drilling holes in ice to reduce ice jam potential. US Army corps of Engineers Cold Regions Research and Engineering Laboratory, IERD newsletter No. 14 March 1996.

US Department of the Army. 1994. Ice jam flooding: causes and possible solutions. Engineering and Design Pamphlet 1110-2-11, Washington, DC.

Van der Kley, I.J. 1965. The use of explosives for clearing ice. Rijkswaterstaat Communications, No. 7, The Hague, Netherlands.

White, K.D. and Eames, H.J. 1999. CRREL ice jam data base. US Army CRREL Report 99-2, 17 pp., Hanover, NH, USA.

White, K.D. and Kay, R.L. 1997a. Dusting procedures for advance ice-jam mitigation measures. ASCE Journal of Cold Regions Engineering, 11(2): 131-145.

White, K.D. and Kay, R.L. 1997b. Is blasting of ice jams an effective mitigation strategy. *Practioner's Forum*, ASCE Journal of Cold Regions Engineering, 11(3): 171-179.

Zufelt, J. E. 1987. Trip report: ice jamming 1987, Oconto, WI. Unpublished report, US Army CRREL, Hanover, NH.