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On floods caused by river ice: An overview of mitigation measures

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Summary

In countries where rivers freeze in the winter, severe flooding events along river shorelines can be caused by ice. This happens because the presence of that ice slows down river flow, which then causes the water levels to rise. The rougher the ice's undersurface, the higher the rise in water levels upstream of it. Ice jams have the highest flooding potential because they can form thick rubble piles that constrict the flow. The release of an ice jam can also induce floods downstream of where it formed.

One common risk reduction component is an ice control structure (ICS). These are either *removable*, such as booms, weirs and nets; they can also be *fixed*, such as permanent weirs, piers and floodwalls. Earthworks are a third, more involved option – they include channel modifications, artificial islands, groins and levees. Means to reduce flood risks can also be of a non-structural nature. This is done by favoring the formation of an ice cover with a smooth undersurface or promoting ice cover breakup (with ice breaking, cutting or melting techniques, surface treatment, or warm affluents). The removal of ice jams is yet another way to minimize flood risks.

The resilience of a site against ice-induced floods can be assessed. It begins with an overall understanding of the river at that site and its ability to withstand rises in water levels. What is currently in place or can be readily implemented to anticipate floods? This assessment can be done for the short term (days to weeks), and long-term, i.e., to assess the impact of climate change over future decades.

Table of Contents

List of Figures

1. Introduction

1.1. Context

In countries where rivers freeze in the winter, severe flooding events (hereafter referred to as 'floods'), along river shorelines can be induced by ice. These scenarios are more complex and less foreseeable than open-water floods (in the warmer seasons). They can also be faster and cause more damage for the same increase in water level than those without ice. Over the last number of decades, our societies have developed an ability to counteract these events. Floods caused by ice still occur, however, namely where no measures have been implemented or where they could be improved.

One main risk reduction component is an engineered structure, referred to as an ice control structure (ICS). Some are seasonal – they are deployed in autumn and removed in the spring; others are permanent. Examples include dams, weirs and booms. There are numerous such structures being used across Canada, the U.S., Europe and elsewhere. They alleviate floods and may even prevent them. They do so in three ways (some may perform more than one function):

- By promoting the formation of a flat, stable ice cover. This is important because the alternative, i.e., a thick, rough ice cover, is the main contributing factor to higher water levels.
- By retaining the broken ice that is drifting downstream.
- By minimizing the amount of water spilling out of the river channel.

Means to reduce flood risks can also be of a non-structural nature – e.g., using ice-breaking, cutting or melting techniques or controlling the amount of water through a hydroelectric dam. They imply lower capital costs but involve a considerable level of operation, maintenance and other forms of human resources. While they may not be as effective as ICSs, they are used in many places to complement the effectiveness of those structures.

Flooding of river shorelines is a natural process that has taken place over much of the geological timescale. From an ecological and environmental perspective, therefore, these events are part of what is supposed to happen, irrespective of human presence. However, it is also known that human activities are responsible for changes in climate patterns that have been altering our environment, including ice dynamics. It is then also our responsibility to objectively assess the impact of these changes on shoreline communities and infrastructure.

1.2. Objectives

This report has three objectives:

- To succinctly go over ice processes that lead to floods of river shorelines.
- To summarize what has been documented in the scientific and engineering literature on existing and prospective measures to address shoreline floods caused by river ice.
- To outline the implications of climate change.

1.3. Methods, scope and target audience

Literature searches were conducted on NRC's in-house ice engineering database as well as on Scopus[1] and via Internet search engines (Google, Bing). The documentation that was reviewed spans the last five decades. That material was sorted out, examined and distilled into the present document. No considerations are given to the design, construction and maintenance of the various structures discussed herein or to the assessment of their efficiencies or financial aspects thereof. These topics lie outside the

[1] Scopus is a subscription-based bibliographic platform produced by the academic publisher Elsevier. It gives access to a large number of journals, books and conference proceedings.

scope of this report. ICSs that accommodate the requirements of navigational infrastructures [e.g., 1, 2] are not specifically addressed either.

The report was written for an audience with little or no expertise in river ice. It is meant to raise a general awareness of what is done to control river ice dynamics and what the salient considerations are to mitigate flood risks. In-line references and recommended sources (section 9) point to additional information that could be of interest to the reader.

2. Why and how river ice causes floods

Flooding events along river shorelines are a year-round phenomenon. The location and time of year where they happen depend on many factors, mostly related to climate (precipitation, temperature, etc.) and channel setting (configuration, geomorphology, etc.). Any given area prone to flooding has to be dealt with on a case-by-case basis. '*Hydrological* models', which simulate processes such as precipitation, run-off, evaporation, infiltration and groundwater circulation, convert that information into a 'discharge', which is a volume of water per unit of time that flows down the river canal. By definition, flooding occurs when the discharge results in water levels that exceed the elevations of the riverbanks, causing water to spill outside the defined river channel.

For flooding scenarios in icy conditions (in the winter), in addition to the hydrological models, '*hydraulic* models' are required to capture the influence of river ice on water levels (Figure 1).

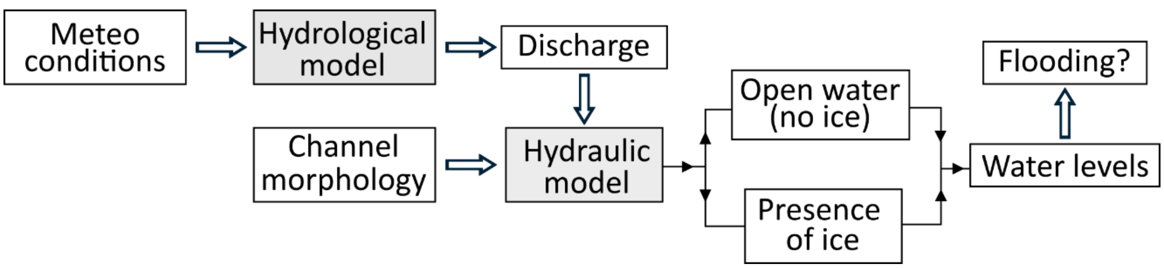


Figure 1: Anticipating flooding extent at a given location along a river begins with a hydrological modeling exercise that generates a water discharge. That discharge, along with the channel morphology, is fed into a hydraulic model, which then determines water levels.

2.1. Water level rise in open water conditions

Under open water conditions (when there is no ice), flooding occurs in places where the river channel is unable to accommodate a higher-than-normal volume of water. This frequently happens after heavy rains. The flooded areas, sometimes known as 'flood plains', are often flat and low-lying. In regions with high-density populations, those areas often are prime real estate.

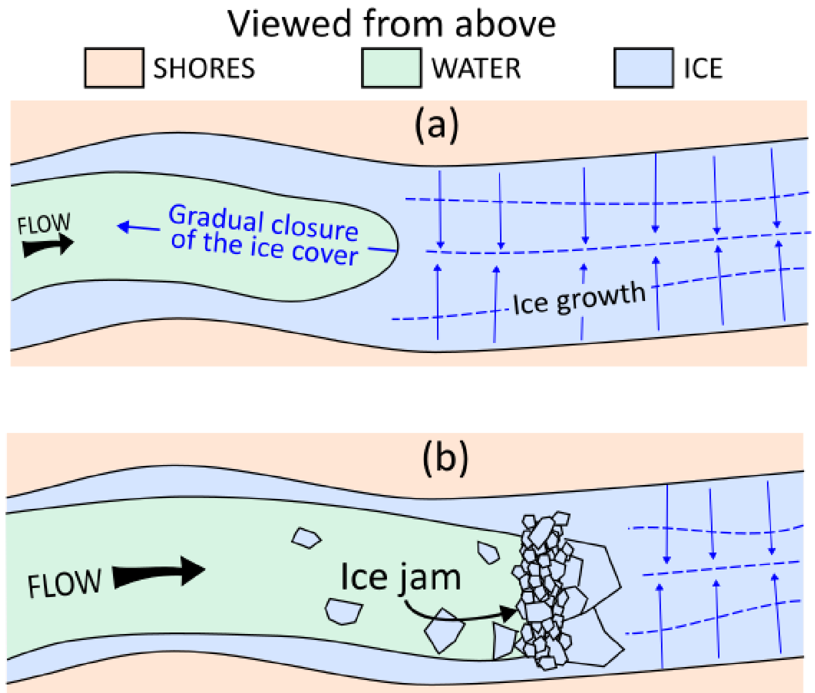
2.2. Water level rise due to the presence of ice

In the winter, the presence of ice complicates the situation. The main reason is that, where there is an ice cover, the interface between the water and the ice's undersurface represents a new and important source of friction for water flow (i.e., in addition to the friction along the river bed and shorelines). The *rougher* the interface, such as would be the case if it consists of ice blocks, the *higher* the friction. As a result, the water slows down, which causes an increase in the level upstream, referred to as 'backwater' in the engineering literature. When the backwater increases above the channel capacity, it causes a flood. Note that, for a given discharge, the ice-affected water levels are much higher than those under open water conditions.

2.2.1. Formation of a uniform ice cover

Where current velocity is very low, closer to the shorelines and in small bays, the ice will grow from the bank outward, as it does in a small lake – that ice is called 'border ice'. If these calm conditions prevail, border ice from each shoreline may bridge so as to form a continuous, smooth ice cover (Figure 2a). Under these conditions, the ice's undersurface is relatively smooth, and the upstream rise in water level (backwater) is minor (Figure 3).

Figure 2: a) The formation of a uniform ice cover can occur as a result of border ice growing away from the shoreline. b) Stronger currents lead to a broken ice cover that may pile up at a given location along a river, potentially defining a thick ice jam.



2.2.2. Frazil ice

Frazil ice, a particular type of river ice, may also contribute to floods[2]. That ice typically consists of individual mm-sized particles formed under the water's surface. This happens where the river is shallower and where open water conditions exist, even on very cold days, because it is turbulent (usually where rapids are observed). The frazil ice then rises to the surface to form ice pans, which can cover the full surface of the river. That is another way a uniform ice cover can form, although in that case, the undersurface is somewhat rougher than that generated from shoreline growth (Figure 2a).

2.2.3. Formation of an ice jam

When the current is strong enough (the velocity is about 1m/s or above), as is the case at various locations along many rivers, it will confine the border ice to the shoreline and will drive drifting ice pans, including broken border ice, downstream. That ice may bottleneck at a given location, defining an 'ice jam' (Figure 2b), which is here defined as "*a stationary accumulation of fragmented ice or frazil that restricts flow*" [3]. Drifting pieces may then push against each other and shove, thus increasing the ice undersurface roughness and causing the water level to rise upstream of it (more so than does a uniform ice cover) (Figure 3C). If this shoving process is intense, the rubble may accumulate into a thick pile, which may then induce flow constriction below it. Ice jams thus have the highest flooding potential.

[2] Irrespective of flood risks, frazil ice is also a liability for shoreline infrastructure that relies on water intakes for their operations (hydroelectric dams, water purification plants) because it tends to interfere with water flow.

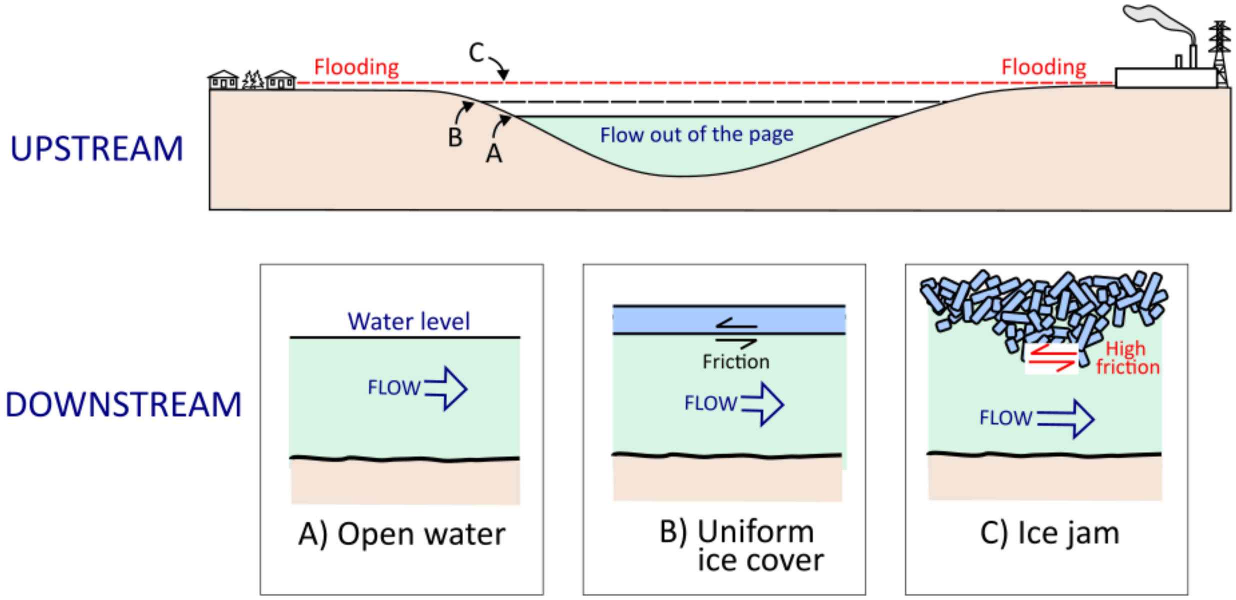


Figure 3: Comparison between the water levels in the following scenarios: A) without ice (open-water season), B) when there is a uniform, smooth ice cover downstream, and C) when broken ice downstream forms an ice jam, which can thicken significantly.

2.3. Water level rise due to ice jam *release*

When an ice jam occurs, as explained above, the water level upstream of it rises (backwater), and a given volume of water gets stored behind the jam. The water volume depends on a number of factors, including the discharge, the roughness of the ice undersurface and the size and strength of the ice accumulation. The ice jam and the ice cover ahead of it may suddenly yield under the pressure that is exerted by that water and the ice upstream of it, as it exceeds the ice's internal strength and the forces that are maintaining it in place. A large amount of water and ice is then released, which travels downstream – this is called an 'ice run'. It can be preceded by a wave, known as a JAm release waVE or 'jave', which, in place, is associated with the largest increase in water level. Traveling speed may be in the order of several meters per second, with a rise in water level several decimeters per minute. The damage may be most severe near the point where the release happens because of minimal warning, and that is where fatalities tend to occur.

An ice run can stop at some point, for example, at a geomorphological feature, such as sharp bends or islands in the channel. This event can also induce the release of jams located further downstream in a domino-like fashion.

Ice runs present a risk to shoreline communities not only because of the large increase in water levels but also for the structural damage to shoreline properties and facilities, which is exacerbated by the presence of large ice blocks carried by the water.

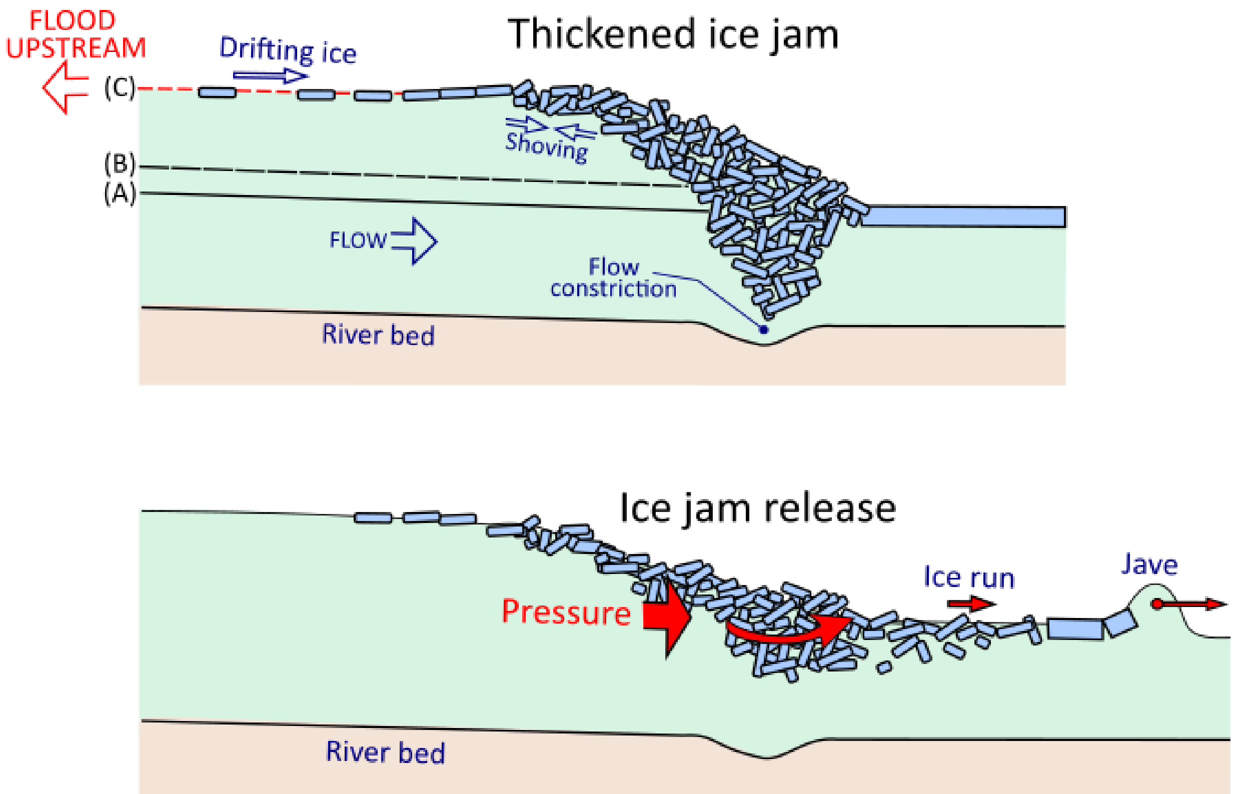


Figure 4: Top) Example of an ice jam, consisting of a thick pile of ice rubble – see Figure 3 for A, B and C. Bottom) Ice jam release, with associated wave (or 'jave') and ice run. Vertical scale exaggerated.

2.4. Timing and type of ice jams

Flooding events caused by ice are mainly associated with ice jams. These jams can occur early in the winter, upon river freezeup (referred to as 'freezeup jams'). These are often the outcome of frazil ice generation. Ice jams also occur in the spring, as the river transitions from icy conditions to open water – these are known as 'breakup jams' and are generally more consequential since the amount of ice formed over the entire winter contributes to the jam formation. Mid-winter jams occur in the winter, between freezeup and breakup. They can be the result of warm spells often accompanied by rain.

2.5. What can be done against floods caused by ice

There are a number of ways to prevent ice jam formation and minimize their impacts when they form. They are categorized as structural (ICSs) and non-structural measures. *Structural* measures include dams, heightening dams, reservoirs, dikes, levees, weirs, ice booms, diversion channels, piers, etc. While the use of structural interventions can prove to be efficient, the expenses associated with designing and implementing them can be substantial; depending on what they are, they can also have notable ramifications for the river ecosystem.

Non-structural measures include mechanical ice-weakening techniques such as ice blasting, ice cutting, ice breaking, and hole drilling. These techniques offer a practical alternative to physical barriers such as dikes. While they are increasingly recognized as valuable tools for ice jam flood risk reduction, a significant knowledge gap persists as to their actual effectiveness. Other non-structural measures include ice jam flood forecasting. All these can be used in conjunction with structural measures.

These are described next.

3. Ice control structures

Ice control structures (ICSs) are meant to mitigate the action of ice against shoreline infrastructure, with floods being the main concern. To address this concern, ICSs serve three main functions:

- *To help establish a stable ice cover with a relatively planar undersurface.* The ICS is located along a river where the ice dynamics would otherwise lead to a rough ice cover that would translate into a significant backwater. This is done, for instance, with floating booms, which will retain the drifting ice. A weir is another type of ICSs, which can raise the water level, thereby reducing current velocities. A higher water level can also drown out open water (i.e., a set of rapids) that would otherwise generate frazil ice.
- *To retain ice runs.* The ICS will promote the formation of an ice jam upstream of the structure. It is located where it will cause the least problems, such as upstream of a community that is known for sustaining these floods. The main concern, in that case, is the ability of that structure to retain broken ice blocks and to withstand the loads exerted by accumulated ice pieces.
- *To protect the shorelines from high water levels.* The structure is built vertically and runs along the shorelines.

This section is an overview of ICSs that have been deployed on various rivers, some as short-term prototypes. Conceptual structures are also included – they were either tested in a laboratory or have only reached the conceptual stage. They are grouped into the following classes:

- Removable structure
- Fixed structures
- Earthworks

3.1. Removable structures

Removable structures are often seasonal, i.e., in general, they are deployed in autumn before freeze-up and removed in the spring after ice breakup, once open water conditions have returned, using standard maritime and land-based equipment – barges, cranes, winches and tugs. Unlike permanent structures, they will not interfere with open water usage, such as recreational and commercial navigation. They are relatively inexpensive. Also, unlike permanent structures, which can induce scouring of the riverbed and foundation settlement), they are more environment-friendly and have a minimal impact on water flow, fish movement and the riverbed.

3.1.1. Booms

Booms refer to floating segments ('boom units') tied end to end with chains or cables [4-7] (Figure 5). They are the most common form of removable structures. The segments have traditionally been made from wood timber and then evolved into sheet metal structures with aspect ratios ranging from about 1:5 to 1:30 – they are sometimes referred to as 'pontoons'. Booms can perform three main functions:

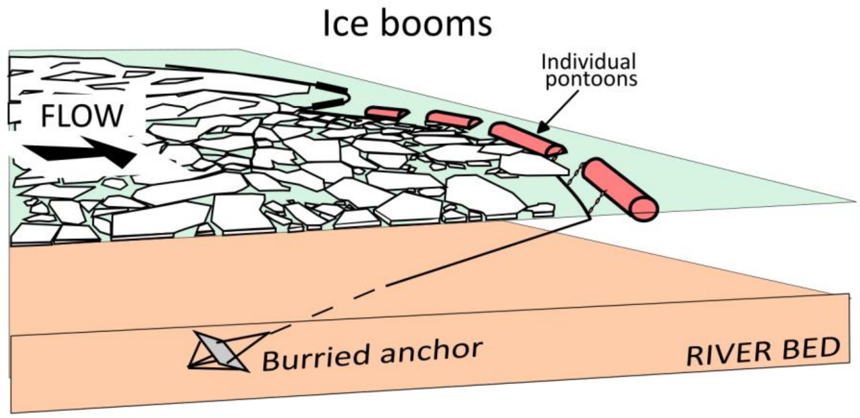
- To keep drifting ice from moving downstream, where they can contribute to ice jams.
- To retain the ice so as to favor the formation of an ice cover upstream during the freeze-up period in autumn. They can also be effective in maintaining that cover during mid-winter thaws.
- To prevent ice from interfering with hydroelectric intakes, navigation and the operation of locks and dams.

Booms are not meant to stop ice runs, although they can be designed to submerge under extreme loads so as to prevent their failure (or 'release'). They are typically deployed in places where the current is not strong enough to drive the ice pans below or above it, which could defeat their purpose [e.g., 8]. Adequate current velocities are in the range of 0.6-1.4 m/s [4]. Some are used alongside another structure whose purpose, as discussed later, is to increase the water level, thereby decreasing current velocity. Their design has to account for water drag below the water line, water surface slope, and wind shear, among other parameters. It also requires a reasonable understanding of the way the ice accumulation upstream will evolve. They can span the full river width or a portion thereof. They can be anchored at the river banks, the riverbed or both. In places, they are attached to fixed structures, such as piers.

Boom releases occur when the design does not meet the conditions to which the structure was exposed [e.g., 9]. Load-measuring instrumentation can be mounted on these structures as an indicator of ice concentration and flow strength.

There are various possibilities for boom unit design, configuration, orientation and sag (the latter is equivalent to a radius of curvature). This is also the case for wire rope and anchoring systems. The eventuality of failure is also factored in. For example, it may be desirable to incorporate fuse links to allow the boom cable to fail before an anchor cable.

Figure 5. A typical deployment of a boom, a linear assembly of cylindrical pontoons. Adapted from Perham [7] and Morse [5].



So-called 'shear booms' or 'deflector booms' allude to units that are used to direct ice, as opposed to stopping it. This would be done in a diversion scenario to guide the ice around dams and their water intakes [1, 10].

3.1.2. Sink-and-float ice boom

A significant drawback in the usage of ice booms is their deployment and removal, which are resource-intensive. Tuthill [11, and earlier writings] refers to a sink-and-float concept for these structures. The pontoons can be filled with water, which causes the boom to sink, and with air, which brings them back to the surface. This concept affords a good deal of flexibility in that the sinking and re-floating process can be conducted on an as-needed basis. This concept has been implemented in Japan [12, 13]. The tear-shaped cross-section of the booms prevents them from being buried by bottom sediments. A similar concept was also tested at some locations along the St. Lawrence River (Prescott and Lac St. Pierre), where it performed well [14].

3.1.3. Streamwise structures

Floating structures used to control ice are generally laid across the channel, except for shear booms – see above. Calkins [15] describes a concept where standard booms or similar structures would be laid *parallel* to the shorelines and act as a source of ice growth, thereby promoting the formation of a stable (anchored) ice cover earlier in the season (Figure 6). Because they are oriented in a streamwise direction, they could operate at higher current velocities than cross-river structures.

A similar principle is described in Perham [16]. The purpose here again was to promote the development of an ice cover. Arrays of nylon, polypropylene, polyester or metal wire ropes were laid out parallel to the current direction. As the frazil ice accumulated on these wires, causing the rope to float, the entrapped interstitial water freezes. The successful deployment of this system was documented by Sahlberg [17], which was followed up by Liddiard [18], albeit with inconclusive results.

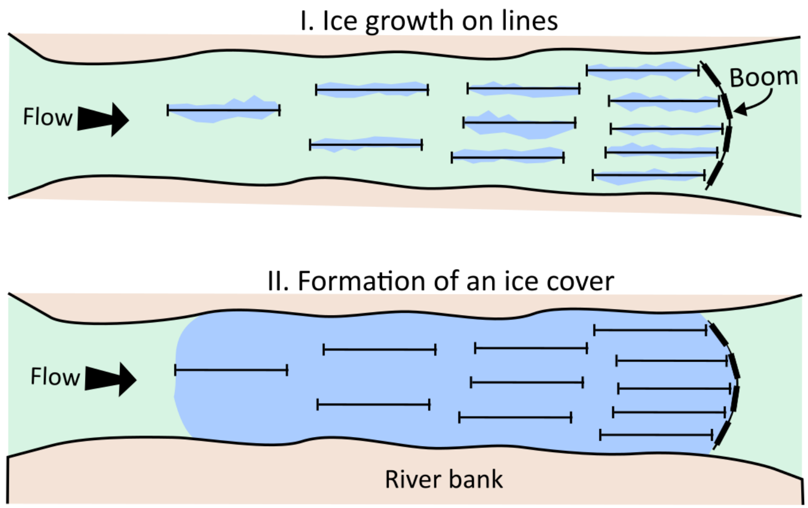


Figure 6. Surface lines deployed in a streamwise direction to induce ice growth and promote the formation of an ice cover at a desired location. Adapted from Calkins [15], who presents this option as a feasible concept.

3.1.4. Seasonal weirs

A 'weir' is a barrier that crosses the width of a river and whose height is slightly higher than the water level. It is commonly used to increase that level so as to decrease the current velocity. While these structures are usually permanent, those mentioned in this section are seasonal. These are also called 'flexible weirs', 'tension weirs' or 'fence booms' [10, 11, 19-21].

An example is the flexible fence first described by Perham [19] (Figure 7). It was tested in the laboratory and in the field. The fence was made up of a series of vertically oriented planks with a space in between, held by steel wires, anchored to the shorelines. The principle behind it is that, under a frazil ice generation regime, that ice would adhere and accumulate onto it and develop into a dam, thereby promoting the development of a pool upstream of it. A uniform ice cover would eventually form. Alternatives to vertical planks are a wire mesh [22] or an impermeable fabric [21, 23], but otherwise very similar in design to that shown in Figure 6. In the latter case, the structure was installed for three winters, during one of which it withstood an ice run without damage.

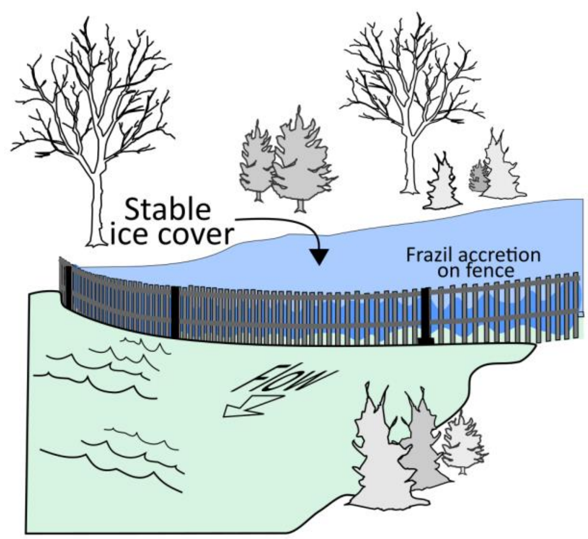


Figure 7: Example of a seasonal weir, adapted from Tuthill [10] – it was tested during two winters. The weir is designed to promote frazil ice accretion and the formation of a dam. After the ice has melted in the spring, the structure can be removed.

3.1.5. Piers and nets

These lighter structures have also been used to contain ice runs [10]. An example is a military submarine net that captured ice pieces and then acted as a pier, with the water flowing around the ice. Another example is a ski lift cable with tires attached to it, laid out every winter across the Lamoille River in Vermont. Morse [24] tested out two concepts in a laboratory (Figure 8). One was with a net attached to a boom that straddled the channel, the other was with the net attached to vertical piers (without the booms).

Figure 8: Two structures were tested in a laboratory. Left) A boom attached to two piers, with a net below it. Right) Nets between piers. Both are meant to retain ice runs. From Morse [24], with permission from the publisher.

3.2. Fixed structures

Fixed structures are permanent works that can effectively address both challenges described earlier. That is, they can promote the formation of a stable ice cover, thereby minimizing the risks of increasing water levels due to ice jams. They can also act as a barrier to ice runs. However, they are expensive. They pose a problem to fish migration and also obstruct the movement of sediments such that periodic dredging operations may be required. They also accumulate debris, which also has to be removed.

3.2.1. Weirs

The main purpose of a weir is to raise the water level upstream of it – that structure can also retain drifting ice while allowing water to flow over it (Figure 9). The increase in level reduces the slope of the upstream water surface and lowers the current velocity, thereby favoring the growth of a stable ice cover and mitigating frazil ice generation. The structure itself and the frozen pool behind it may also be able to absorb ice runs. Weirs are often concrete structures and may also be built from stones or timber. They are sometimes combined with ice booms.

Tuthill [25] documents what is referred to as an 'inflatable dam', a commonly used system for year-long open water conditions (open water conditions), but which has also been adapted to counter ice issues at several locations. It is basically a cylindrical rubber structure installed on top of a weir, which allows water levels to vary by several meters. In the low position, it can permit the passage of flood water and debris and can also facilitate fish migration. Ice that adheres to it breaks off upon inflation. They can withstand ice runs without compromising their integrity. The disadvantages include its relative vulnerability to damage by debris and vandalism. While their main role is to generate power, in some settings, they can also act as an ICS [e.g., 26]. Most often, they are used as a means to manage water levels.

Figure 9: Example of a weir. (Source)

3.2.2. Weirs with columns

Weirs can be combined with columnar structures, as shown in Figure 10. Another such example – Figure 11 – incorporates a grate upstream of the columns. In both cases, the vertical structures can retain the ice while allowing the water to flow over the weir.

Figure 10: The Sartignan structure in Quebec. (Source)

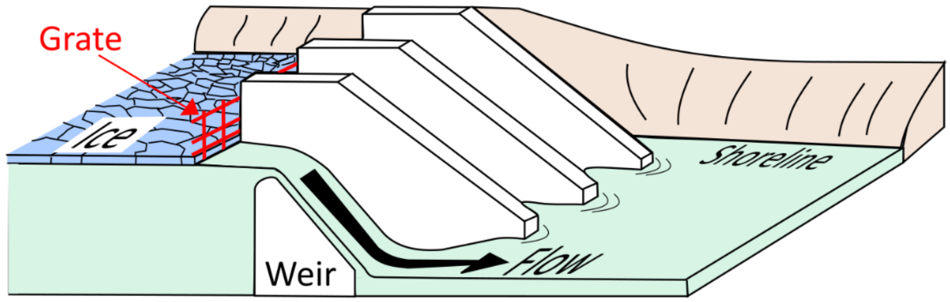


Figure 11: Schematic representation of a weir on the Chaudiere River, Quebec. Adapted from Michel [27] and Perham [16].

3.2.3. Piers and boulders

Piers, boulders and other structures extending vertically are used in places to retain the ice while allowing the water to make its way around the structure (Figure 12). These can take the form of pillars, pre-shaped stones, rock-filled timber cribs or other fit-for-purpose concrete structures. In some cases, they may be designed to promote grounding behind them, so that the ice load can be transferred to the river bed. They could be dug into the river bed or installed atop a weir. The weir may impound a deep enough pool behind it to allow the formation of a stable ice cover or store the ice, namely frazil, drifting from upstream, while the piers can act as a retention barrier for an ice run.

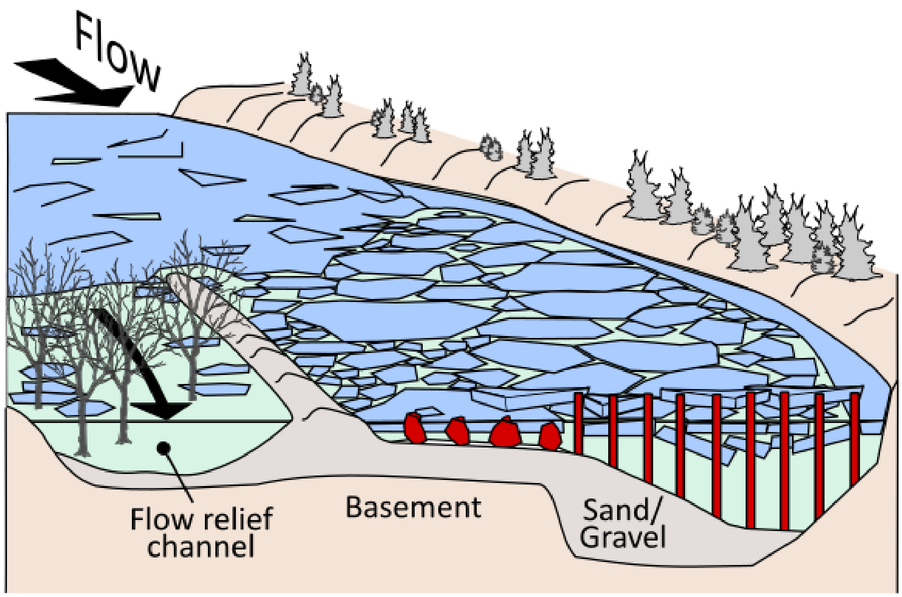


Figure 12: Concrete pier structure and boulders with a channel adjacent to it which allows for water to make its way around and ice jam. Adapted from Tuthill and White [28] and Tuthill and Lever [29].

3.2.4. Floodwalls

Floodwalls are control structures meant to protect shoreline properties against damage caused by floods (Figure 13). Although these structures are usually designed for open water conditions, they can also play a role in protecting shorelines against river ice action. In addition to being able to resist the forces exerted sideways on them by the water, their design also has to account for the impact and scouring of drifting ice and debris. In places, it can make provision for extra room away from the shoreline to accommodate ice accumulation.

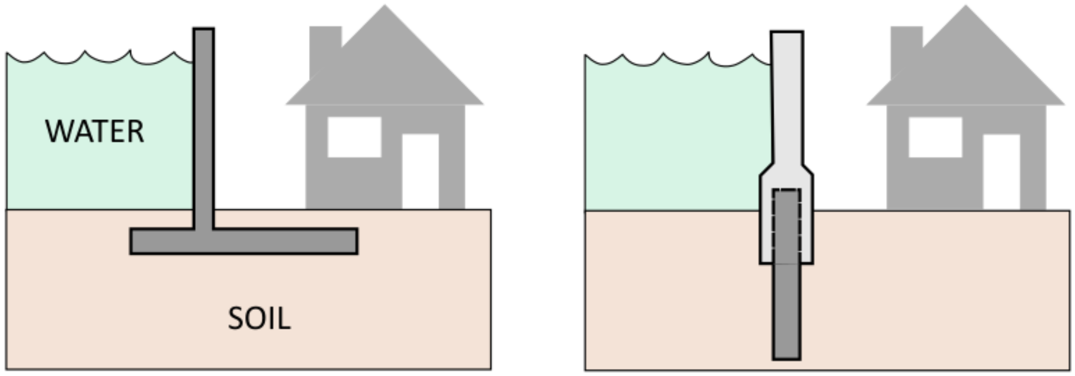


Figure 13: Two general classes of floodwalls: Left) T-type, Right) I-type.

3.3. Earthworks

This class of structures involves machinery and equipment able to move substantial amounts of soil, gravel and rocks.

3.3.1. Channel modifications

Physical modifications of a river channel could be required to improve the flow of ice. Depending on the needs, they could also promote the formation of a stable ice cover if the new configuration allows for slower current velocities and eliminates areas of fast currents. Other desired benefits may be to allow a channel to carry more water or store more ice, and favor the formation of ice jams away from flood-sensitive areas. These modifications could be to deepen the channel, widen the river, straighten out bends (velocity can be higher outside the bend), or stabilize the river banks. The implementation of these measures involves operations such as dredging and excavation. The costs are usually high, and a number of social and environmental factors need to be considered.

River restoration works, such as those required to stabilize the river banks and rectify the negative impact of human intervention over time or improve fish habitat, may change the local flow regime. Planning should give sufficient consideration to the ice dynamics and the way the ice cover forms.

3.3.2. Artificial islands

Shorelines, including those of islands inside a river channel, usually hold a certain amount of ice in place (i.e., border ice)(Figure 14). This helps the development of a stable ice cover. Hence, creating additional shorelines via the construction of islands is seen as another means of controlling ice dynamics. This is primarily because the ice gets anchored along that new interface. Well-known examples of such structures have been documented from the St. Lawrence River upstream and downstream of Montreal, in support of navigation. Protecting them with an armored layer of stone is a way to mitigate erosion, thereby reducing maintenance but increasing initial costs. These structures may require periodic top-offs if they are built on soft sediments and sink into the river bed over time.

3.3.3. Groins

A groin is a linear structure built from stones and extending away from the shoreline (Figure 15). These structures can be used to stabilize the border ice and, if paired (one from opposite shorelines), they may stop large ice pans, which can then bridge across the channel and thus help form a stable ice cover. Also, by constricting the channel, paired groins can reduce water conveyance, thereby raising the water level upstream, thus also helping form a stable ice cover and maintaining it in place. In addition, they can reduce the amount of ice moving downstream. Because a groin does not cross the entire channel width, it has an environmental advantage over weirs and dams in that it does not totally obstruct navigation or impede fish passage.

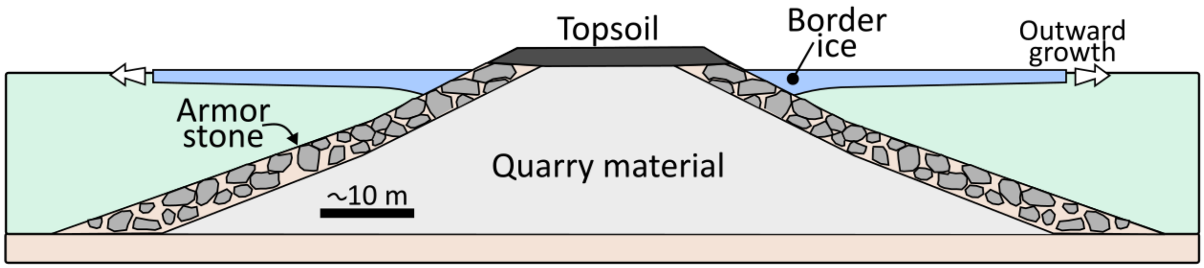


Figure 14: Schematic cross-section of one of three artificial islands built in the St. Lawrence River in 1980. That structure acts as an anchor for the ice growing from it, thereby stabilizing the ice cover as a whole. Adapted from Perham [16].

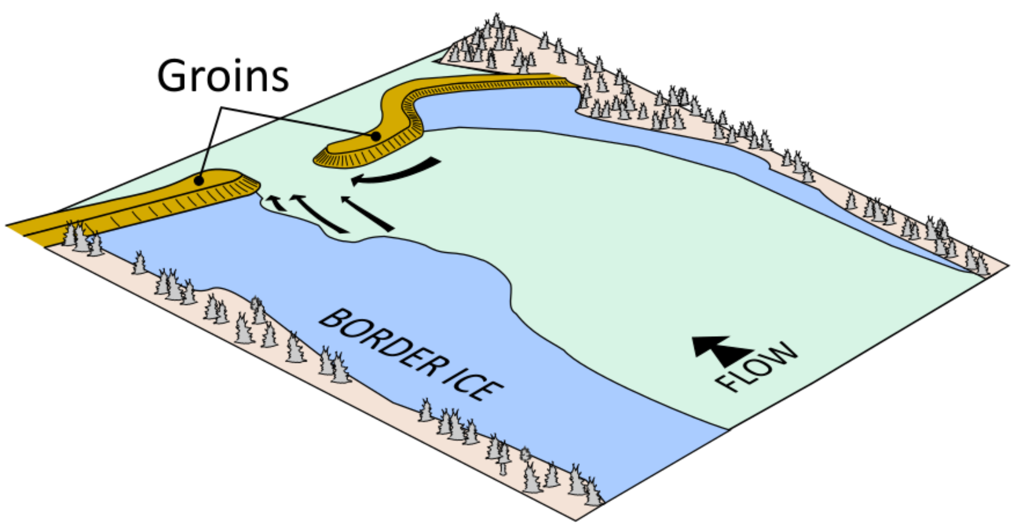


Figure 15: Groins are artificial earthworks that extend outward from the shorelines, sometimes in pairs, as is the case here. Adapted from Burrell [30].

3.3.4. Levees

Levees are sometimes also referred to as 'dikes' and serve a similar purpose as floodwalls, i.e., to keep the water from going where we do not want it to go (Figure 16). They run parallel to the shoreline, sometimes to great distances. They are typically built from soil, sand, gravel and stones. Floodwalls can be mounted on top of a levee so as to increase its height.

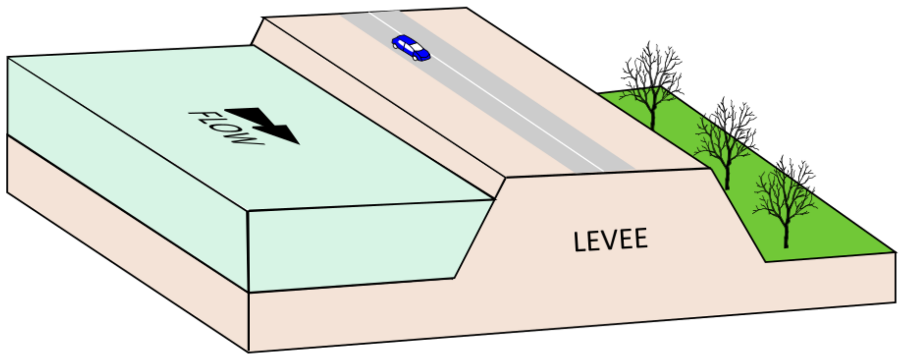


Figure 16: A levee is a raised earthwork that runs alongside a river.

4. Non-structural control

Non-structural control alludes to mitigation methods that are not tied to the construction, deployment and management of physical structures. These methods are less costly and environmentally less intrusive. They have a similar purpose as structures, which is to reduce ice jam potential and mitigate the consequences of an ice jam release. In many instances, they may complement the action of structures. Because these methods may be applied using equipment and supplies that can be readily available, they may be more implementable on short notice. This is conditional on adequate planning, for instance, regarding equipment availability, training in its use, and permits.

That form of control is meant to meet one or more of the following objectives:

1. To control the formation of an ice cover
2. To facilitate ice cover breakup
3. To breach or remove an ice jam

Much of the information provided below is from Haehnel [31] and Simard-Robitaille [32].

4.1. To control the formation of an ice cover

The principle behind this approach is, as before, the acceptance that ice does form in a river but that measures can be undertaken to minimize increases in water levels. This is done by promoting an undersurface that is smooth as opposed to corrugated (Figure 3). This will translate into less resistance to flow. Another advantage in being able to do so is that the establishment of an extensive ice cover, i.e., no open water, prevents the formation of frazil ice.

4.1.1. Controlling water discharge

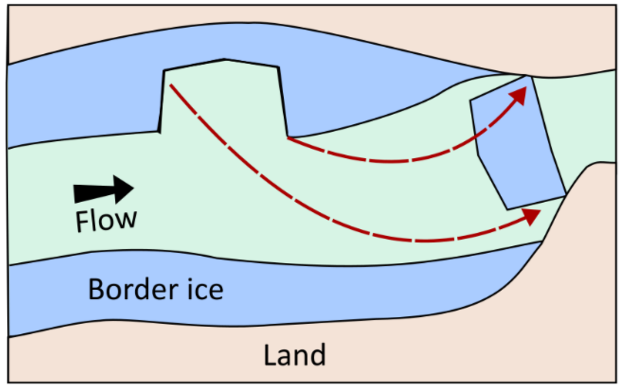
Some rivers are crossed by hydroelectric dams or similar facilities that can control the amount of water flowing down the river channel. In the open water (summer) season, that regime has to be managed so as to meet the energy requirements, i.e., the more water is allowed through, the more electricity that can be generated. This will, in turn, have an impact on water levels upstream and downstream of the facility, which may affect other users (e.g., navigation and shoreline communities). Flow management (often referred to as 'river regulation') must address the requirements of all users all year long.

Winter conditions, however, bring in another consideration: being able to avoid ice jams. For instance, high dam outflows can break up an otherwise stable ice cover downstream, and high currents favor open water surfaces, which favors frazil ice development. To mitigate these circumstances, a typical procedure is to lower the flow at the beginning of the winter until a stable ice cover has formed, then progressively increase it so as to make up for that reduction in energy fed into the power grid. Regulated rivers usually have a pre-defined protocol for dam management, which optimizes energy production while ensuring safety for downstream riverine communities.

4.1.2. Ice bridging

This operation involves removing or cutting off a large enough ice fragment from the border and allowing it to drift downstream so that it 'bridges' the channel (Figure 17). It is analogous to using a boom.

Figure 17: Ice bridging consists of cutting an expanse of border ice and allowing it to drift so that it blocks off the channel. Adapted from Haehnel [31].



4.2. To facilitate ice cover breakup

Near the end of the winter, it can be advantageous to weaken an ice cover while it is stable so as to facilitate breakup and avoid ice jams. Also, if there is an ice run, a weaker cover will yield to it instead of resisting and producing a jam. This matters especially at locations where these events are known to occur. A few approaches can be used for that purpose.

4.2.1. Ice cover weakening

One way to reduce an ice cover's structural integrity is via fragmentation – with smaller fragments better able to flow downstream without jamming. Fragmentation can be achieved in a number of ways and over many kilometers, depending on the requirements and methods.

Excavators

Construction equipment such as mechanical shovels and cranes with wrecking balls can be used to break and excavate an ice cover from the shoreline or a bridge. Floating machinery is also specifically designed to handle these tasks – an example is shown in Figure 18.

Figure 18: An amphibex on the shoreline of the Rideau River in Ottawa. (Photo: NRC)

Ice cutting

Ice cutting is done with various equipment, including self-propelling machines with mechanical saws or trenchers. Particular networks of cuts may be more effective, for instance, a downstream-pointing herringbone pattern. Ice cutting can allow water to make its way to the surface, thereby favoring thermal deterioration. To avoid re-freezing, consideration is also given to the timing and temperature forecasts.

Icebreakers
Icebreakers are ships of various sizes that are designed to navigate through icy waters. They can either ram into the ice cover or ride on top of it, which causes it to break. Hovercrafts are used for a similar purpose.

Vertical loads
A heavy weight, such as a wrecking ball, that is lowered repeatedly onto the ice surface is another way to break up the ice for a narrow river to allow the equipment to work from the shoreline. A load applied, or dropped, from a helicopter has also been attempted.

Perforation
Drilling holes in an ice cover is thought to favor breakup because it also reduces its strength [31-33]. This can be done in various ways, including with augers, mechanical drills and explosives. This method has been used extensively in Quebec [32].

Blasting
Placing explosives below, on or within the ice cover at the right location has been used extensively to break up an ice cover (or to remove an ice jam). They have also been delivered from the air in the form of military ordnance (artillery, warplanes), an approach better suited for remote locations. Ice cover blasting has been considered a last resort because of ecological concerns as well as safety considerations (Figure 19) – this approach is still used, albeit parsimoniously [32, 34].

Figure 19: A plaque located near the shoreline of the Rideau River in Ottawa, to the memory of three workers who were killed during ice-blasting operations (Photo: NRC).

4.2.2. Surface treatment

This procedure is meant to weaken the ice cover and accelerate the thermal deterioration of the ice cover. It may be conducted at critical sites in the early stages of ice breakup (spring). Spreading a thin layer of suitable dust allows for a decrease in the reflectivity of the ice, thereby increasing the amount of sun radiation it absorbs. That material has to be dark, e.g., sand, fly ash, dyes, and leaves are examples. Salt has reportedly been used as well because of its propensity to decrease the melting temperature of the ice, just as it does in the streets (i.e., ice in contact with the salt will melt even if it is well below 0^{o}C). For this procedure to be successful, several factors have to be taken into consideration, namely, the availability of suitable material, spreading technique, and climate parameters (air temperature, amount of sunshine and wind conditions). Surface treatment may be objectionable from an environmental standpoint.

4.2.3. Warm affluents

In some cases, the formation of an ice cover at critical sites may be delayed or even prevented by the discharge of warm water into the river upstream of that site. In that context, 'warm' is a few degrees above zero. That water may originate from heating plants, atomic power plants and wastewater treatment plants, or by drawing water from a deep lake or reservoir. This measure relies on the availability of enough warm water at the site of interest, which is uncommon.

4.3. To breach or remove an ice jam

In places, there could be a requirement to remove the ice where it has jammed or at least free up a channel within the river to flush out the excess water behind the jam. This is a reactive measure and may be brought to bear as an emergency to address quickly rising water levels. Because the surface of an ice jam is usually jagged and irregular, accessing it on foot or with machinery may not be safe or feasible. Some of the fragmentation approaches described above may be mobilized, for example, icebreakers and amphibious vehicles equipped with a mechanical shovel. Conventional mechanical shovels working from the shoreline could assume that role for small rivers. The procedures should be done so as to allow the flow to carry the broken ice pieces downstream by starting at the downstream end or by breaking the ice where the flow is faster, e.g., away from the shoreline.

5. Assessing the resilience of a site against ice-induced floods

Assessing risks and optimizing preparedness for a given target site, namely, a river section known to be affected by ice-induced floods, may be divided into these steps:

1. To gather general information about the site.
2. To understand the site's flood resilience.
3. To identify the current means of forecasting, monitoring and warning.
4. To account for climate impact

The information collected during these steps would form an important basis for deciding the way forward, i.e., the adequacy, or lack thereof, of the system in place to protect shoreline communities and infrastructure against the threat of floods caused by river ice, current and future. There are several sources where that information can reside. They include government databases and reports, output documents from engineering consultants, the scientific literature as well as newspapers and other media products, citizen science and crowdsourcing networks.

5.1. General information

An overall understanding of the river is the first step in being able to evaluate the current status of a site. This includes:

- Geomorphology and surrounding landscape – bathymetry, width and channel shape, the topography of the landscape and evolution over time, taking into account factors such as sediment transport and artificial structures crossing the waterline (e.g., bridge piers, earthworks).
- Flow regime in open water conditions, i.e., discharge, currents, turbulence state (rapids versus calm water), and variations in water levels, natural or human-induced.
- River ice hydraulics in the winter, i.e., the ice regime over the winter and year-to-year, for the whole river and its tributaries.
- Animal and plant ecology and environmental aspects such as water quality.
- The perspective of Indigenous communities.
- Usage of the river for navigation (commercial, leisure).
- Infrastructure connected to the river – water purification plants, power generation facilities, water treatment plants – and the nature and usage of that connection (crossings, inlets, outlets, conduits,…).
- Infrastructure in general: industrial and residential developments, hospitals, road systems, parks,…

5.2. Flood resilience

Flood resilience in the context of this report is the ability to withstand the consequences of a flood in areas where ice jams are known to occur.

5.2.1. Historical flooding events

A comprehensive overview of historical flooding events should be conducted. This would include flood extent and damage as well as mitigation measures in place at the time of the floods.

5.2.2. Land management

An understanding of areas that are more at risk should be obtained. This would be based on the information from the foregoing steps as well as on water levels associated with large floods. In icy conditions, it would be the outcome of standard hydraulic modeling and similar exercises. These analyses allow for the establishment of a contour map onto which the flooded zones and their water depth are delineated. An appreciation of risks to current infrastructure would be obtained, and new developments could be restricted or prohibited in the flood hazard zones.

5.2.3. Structural and non-structural controls

This step is a review of the structural and non-structural controls that exist or are used at the site.

5.2.4. Floodproofing

Floodproofing alludes to the local measures to protect individual buildings against water penetration. Permanent measures include the elevation of the building on earth fills, piers or frames. Ad hoc, contingency or emergency measures include plywood, door seals or sandbags to block openings in buildings.

5.3. Flood forecasting

This step addresses the question: What is currently in place, or can be readily implemented, to anticipate floods in the short term (days to weeks), and long-term effects, i.e., those related to climate evolution over future decades?

5.3.1. How does flood forecasting work?

A flood forecast is not unlike a weather forecast. In both cases, they bring together a lot of information and process it through complex computer models.

- *For the weather*, the main factors include air temperature, atmospheric pressure, humidity, wind speed and direction, and sun radiation. These observations are collected from ground instrumentation, weather satellites and aircrafts. Laws of physics are then used to interpret how these factors will evolve over time. Weather forecasts are about *what happens in the atmosphere*.
- *For flooding*, the main factors include precipitation, air temperature, sun radiation and wind. Note that information such as air temperature and precipitation is from weather forecasts. Different laws of physics are used because these are about *what happens in the ground and the river channels*.

5.3.2. Difference between *open water* and *river ice* flood forecasts

Foreseeing *open water* floods depends on weather forecasts, namely precipitations, as well as a hydrological model to process that information. It also assumes that the configuration of the river channels is well known. The hydrological model determines how much water makes its way to the channel. Flooding is forecasted in places where the river channel is unable to accommodate a higher-than-normal volume of water.

In *icy conditions*, the challenge is more complex because, in addition to the above, the forecast also has to consider factors that affect ice (e.g., air temperature, water levels and discharge, and ice cover characteristics). Under those conditions, a hydraulic model is brought to bear (Figure 1), which considers ice production, how that ice interacts with itself and the shorelines, and how it evolves inside the water column. Different models have been used, each one addressing particular aspects of these interactions [35].

5.3.3. Preparedness and warnings

Figure 20 depicts a proposed scheme involving three forecasting levels. They are as follows:

- *Preparedness forecasting*: This forecasting level is a heads-up to the community about what could be expected in terms of event severity. Under some circumstances, the ice cover can melt in place, which does not pose a threat. However, the available evidence may indicate that a jam will either form and induce backwater to a level that needs to be assessed or a jam already exists and may break up. Based on the outcome of the modeling exercise, the community can start thinking of mobilizing material (e.g., sandbags) and heavy equipment, moving furniture up one level, etc.
- *Event forecasting*: Water level rise is in progress, but its nature and extent are being assessed.
- *Evacuation forecasting*: The modeling focuses on the ice jam dynamics to evaluate how it is going to behave – input of data from the previous modeling phase allows an appreciation of what to expect in terms of flood levels.

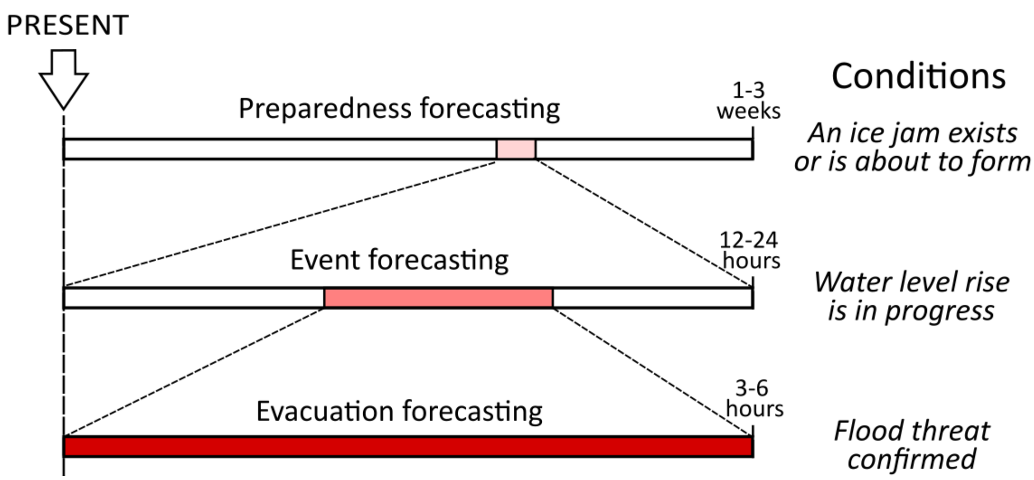


Figure 20: Three levels of forecasting, each one using an appropriate model. Adapted from Hicks [36].

5.4. Climate considerations

Global warming is a term used to designate the temperature increase of the Earth's atmospheric system since the pre-industrial age in the mid-19th century. Since then, the burning of fossil fuels has increased the amount of greenhouse gases in the atmosphere, with CO_2 being the most abundant (alongside others, such as methane and nitrous oxide). These raised the overall temperature of the Earth's atmosphere by about 1°C. While this appears to be negligible, it has important consequences on the temperature distribution over the planet's surface, air circulation, precipitations, and a number of other phenomena, all of which are collectively referred to as 'climate change'[3] [37].

One of the outcomes is an increase in the frequency, intensity, and duration of climate and weather extremes. These changes are highly inhomogeneous and location-dependent. Powerful computer models, known as Global Climate Models (GCM), are downscaled to Regional Climate Models (RCM), which are used to assess these phenomena at a local scale. Changes in weather patterns, temperature fluctuations, and shifts in seasons are expected, which may affect the timing, thickness, and extent of ice formation on rivers and other water bodies.

[3] This term is defined as *"[a] persistent, long-term change in the state of the climate, measured by changes in the mean state and/or its variability."*

5.4.1. Impact on river ice

Being able to predict how river ice will evolve in the future at a given location relies on our ability to simulate many variables at that location decades ahead. Air temperature is the most influential one; others include precipitations (rain or snow), solar radiation, and cloud coverage. A changing climate will affect these hydro-climatic conditions, which will, in turn, have an impact on river flow and river ice dynamics. The following is currently believed to be the salient consequences:

- With time, the ice may become intermittent or not form at all, or the ice covers will be thinner.
- Breakups may occur on rivers that have had a stable ice cover.
- There is a general consensus pointing to a reduction in ice season length, with later freezeups and earlier breakups.
- The number of mid-winter breakups is also expected to increase.
- Frazil ice events may be expected to increase in any given year.
- Extreme jamming events may occur more or less frequently at different locations.
- The unpredictability of these events may be heightened.

5.4.2. Implications for ice control measures

In general, warmer winters and irregular freeze-thaw cycles can result in less foreseeable ice conditions, thus raising the likelihood of ice jams, which means a higher chance of flooding. These regimes could make the traditional ice control methods less effective. To counter these circumstances, it might be necessary to adapt existing ice control structures (like ice booms or pier-type ice barriers) so they can handle more variable and extreme conditions. Ice control measures thus need to be adjusted to fit the specific climate characteristics of each region. Locations that are getting warmest may need different strategies compared to others. This calls for the periodic reevaluation of ICSs for their effectiveness in controlling ice jam floods based on the ever-changing ice processes in the vicinity of the structure [38].

Most ICSs were built between the 1950s and the 1980s. Shorter winters and the increased likelihood of mid-winter breakups mean that many existing ICSs are now facing different conditions than what they were designed for. For example, the spacing between piers was optimized to hold bigger and thicker ice blocks that had been formed over the entire winter. If the ice cover becomes thinner and less able to resist flow drag, smaller ice blocks would form during breakup. These smaller blocks will more likely pass through the ICS, i.e., that structure will have limited holding capacity. Climate variations could change how effective non-structural operations are – these may have to become more adaptable on a deployment-per-deployment basis. Real-time monitoring and quick-response strategies may have to be enhanced to deal with sudden changes in ice conditions.

6. Conclusion

Effective and sustainable control measures can protect infrastructure and communities against ice-induced floods – the purpose of this report was to provide an overview of what they are. Each one is custom-designed to address the particular river scenarios at a given target site. It should be borne in mind, however, that river ice behavior at any site can vary considerably on a year-to-year basis. It is thus important to understand that behavior before implementing any new measure or assessing the effectiveness of the existing ones. For climate adaptation strategies – i.e., in the long term – an understanding of local climate trends and how they affect ice dynamics is necessary.

7. Acknowledgements

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54. Jasek, M. and S. Beltaos, *Ice-jam release: Javes, ice runs and breaking fronts*, in *River ice breakup*, S. Beltaos, Editor. 2008, Water Resources Publications: Highland Ranch, CO. p. 247-303.
55. Jasek, M. and J. Evans, *Predicted effects of climate change on hydropower operations for freeze-up ice jam flooding mitigation*, in *Proceedings of the 26th International Symposium on Ice*. 2022, International Association for Hydro-Environment Engineering and Research (IAHR): Montreal.

9. For more information

This section provides a listing of sources meant to complement the material included in this report. Many of these sources are documents whose target readership is typically people in academia or the private sector with a background in civil engineering, and with some understanding of water hydraulics.

9.1. River ice

River ice and the challenges it poses to shoreline infrastructure is a topic that has been researched extensively in the last several decades. Two introductory textbooks on river ice are recommended (and described below): Hicks [36] and Lindenschmidt [39]. Historical sources, which are still often cited in the recent literature, include Michel [27], Ashton [40] and Beltaos [41].

9.2. Ice control measures

The report draws from several previous writings that document earlier classifications and descriptions of ice control measures, including Williams [42], Michel [27], Perham [16], Belore [43], Tuthill [10], Burrell [30], White and Kay [44], Haehnel [31], Hopper [45], Morse [24], Abdelnour [6], Tuthill and Lever [29], Tuthill [11], Hicks [36], Simard-Robitaille [32] and Lindenschmidt [39].

9.3. Climate impact

Sources of information relating river ice to climate change's impact on hydraulic processes include Beltaos and Prowse [46], Turcotte [47], Beltaos [48] and Burrell [49]. For readers interested in the details of the data gathered to produce information on climate impact, examples are Chen and She [50] for Canada, Agafonova and Vasilenko [51] for Russia, Newton and Mullan [52] and Fukś [53] for the North in general.

9.4. Key sources

F. Hicks [36]. ***An introduction to river ice engineering for civil engineers and geoscientists*.** This monograph provides an overall perspective of river ice and includes some basic notions in hydraulics and thermodynamics. It is a good source of visual information (photographs and diagrams) on river ice in general.

K.-E. Lindenschmidt [39]. ***River ice processes and ice flood forecasting - A guide for practitioners and students***. This monograph is another good source of introductory information on river ice, more advanced than [36]. It begins with some background material on river ice and then describes a hydraulic model designed to determine water levels due to the presence of ice. That model is one among several other models to simulate river ice dynamics [35].

S. Beltaos [48]. *Assessing the frequency of floods in ice-covered rivers under a changing climate: Review of methodology*. An instructive discussion on the relationship between water levels and discharge in the presence of ice.

M. Jasek and S. Beltaos [54]. *Ice-jam release: Javes, ice runs and breaking fronts*, in *River ice breakup*, edited by S. Beltaos. A description of what happens when an ice jam breaks up, i.e., the production of a wave, mechanisms leading to that release and its consequences.

A.M. Tuthill and J.H. Lever [29]. *Design of breakup ice control structures*. This is a good introduction to ICSs as well as to engineering design guidelines.

J. E. Zufelt, J. A. Earickson and L. Cunningham [26]*. Ice jam analysis at Idaho Falls, Snake River, Idaho*. This report investigates one particular site – it is a nice example of the various considerations when assessing options to mitigate floods cause by river ice.

R. B. Haehnel [31]. *Nonstructural control*. A comprehensive yet concise review of non-structural controls.

B.C. Burrell, S. Beltaos and B. Turcotte [49]*. Effects of climate change on river-ice processes and ice jams.* This is an instructive perspective of river ice in general, how the various parameters (temperature, precipitations, etc.) are expected to vary as a result of climate change, and the outcome on river ice dynamics.

M. Jasek and J. Evans [55]. *Predicted effects of climate change on hydropower operations for freeze-up ice jam flooding mitigation*. This is a recent example of a modeling exercise used to predict future river ice dynamics.