RIVER ICE MANAGEMENT IN NORTH AMERICA

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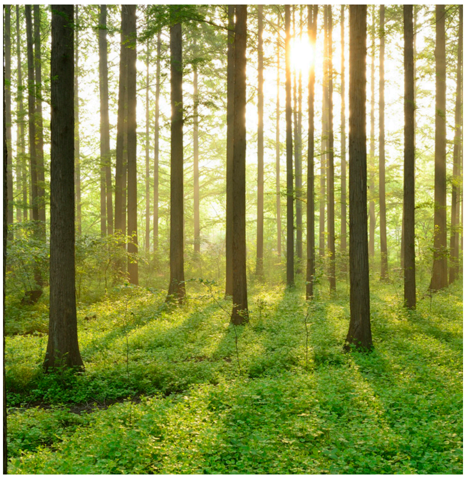

HYDRO POWER

Energiforsk

River ice management in North America

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Foreword

This report describes the most used ice control practices applied to hydroelectric generation in North America, with a special emphasis on practical considerations. The subjects covered include the control of ice cover formation and decay, ice jamming, frazil ice at the water intakes, and their impact on the optimization of power generation and on the riparians.

This report was prepared by Marcel Paul Raymond Energie for the benefit of HUVA - Energiforsk's working group for hydrological development. HUVA incorporates R&D-projects, surveys, education, seminars and standardization. The following are delegates in the HUVA-group:

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Stockholm, November 2015

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Authors´ Foreword

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Summary

This report was prepared by Marcel Paul Raymond Energie for the benefit of Energiforsk's HUVA group.

It describes the most used ice control practices applied to hydroelectric generation in North America, with a special emphasis on practical considerations.

The subjects covered include the control of ice cover formation and decay, ice jamming, frazil ice at the water intakes, and their impact on the optimization of power generation and on the riparians.

A selected number of North American practical cases are documented, as well as a review of numerical models used to assist ice specialists in their decision making process. The variety of such cases shows that the problems and the control methods are very site specific and, therefore, cannot be entirely replicated without the assistance of ice specialists.

The report also shows the importance of including ice control considerations as early as the projects' design phase and thereafter by monitoring the situation throughout the operations phase and by continuously adapting and optimizing the operation strategies with experience.

A review of the literature on ice control methods and cases is also included in this report.

List of content

1 Introduction

In the nordic countries, several hydro power generation operators deal with ice control issues every winter. Unfortunely, most of the valuable practical experience on this subject is rarely disclosed in publications.

In this report sponsored by Energiforsk's HUVA group, the authors, based on their experience in North America and at Hydro-Quebec in particular, assembled a description of the most used ice control methods, with special emphasis on practical considerations.

The subjects discussed include the control of ice cover formation and decay, ice jamming, frazil ice at the water intakes, and their impact on the optimization of power generation and on the riparians. A selected number of North American practical cases are documented, as well as a review of numerical models used to assist ice specialists in their decision making process.

The North American territory faces severe winter conditions every year that request efficient ice management covering several fields, notably:

- Hydroelectric power generation: The hydroelectric power capacity in Canada exceeds 76 000 MW from more than 150 large hydro plants (in excess of 50 MW) and nearly 400 small hydro plants (about 3% of the total capacity). The installed capacity varies from province to province mainly in relation to the sites available. Table 1 gives the territorial distribution. The province of Quebec owns 39 500 MW or 52% of the total capacity.
- Flood control: Numerous problematic sites exist along the rivers, some of which impacting the hydroelectric facilities.
- Commercial navigation: Examples are seen on the St. Lawrence River and on the Great Lakes, impacting the power plant operations at some sites.

These fields are often inter-related and complementary. In the following chapters, representative examples were selected in order to highlight the ice control methods and the ice management challenges faced by hydroelectric generating agencies in North America. Some examples from the international waters of the St. Lawrence River and from the Great Lakes present ice management made in close cooperation between American and Canadian entities. The other examples are mainly on the Canadian territory where ice problems are frequent due to the nature of the climate.

Table 1: Distribution of the hydroelectric installed capacity of Canadian provinces (2014)

Province	Installed capacity (MW)
Quebec	39 500
British Columbia	12 000
Ontario	7 000
Newfoundland and Labrador	6 700
Manitoba	5 200
Saskatchewan	3 300
New Brunswick	950
Alberta	900
Others	550
TOTAL	76 100

The present report contains seven main sections. Chapter 1 is the present introduction. Chapter 2 gives general considerations about ice in hydropower projects. Chapter 3 presents the most used ice control methods. Chapter 4 gives a sampling of eleven ice control application cases combining several ice control methods and describing their operational processes. Chapter 5 discusses ice modelling and its limitations. Chapter 6 presents a short review of literature on ice management and, finally, the conclusion is given in chapter 7. All figures and pictures appear at the end of the document. The pictures are from the authors unless otherwise indicated.

<u>About the authors</u>

Sylvain Robert holds a Master’s degree in civil engineering with a specialty on river ice and has 34 years of practical experience in hydraulics, ice, hydrology and optimization. Until his retirement in 2013, he has been involved in hydraulic design and operations of Hydro-Quebec’s large hydroelectric projects from a 40 000 MW generation system in the province of Quebec, Canada, and has been consulted by various agencies in North America facing river ice management problems. He acted as Hydro-Quebec’s ice expert involved in the critical ice control problems met in the design and operations of Hydro-Quebec’s projects. In particular, he performed the development of an ice model to optimize the ice formation upstream of some power plants, achieving important efficiency gains.

Marcel Paul Raymond holds a Master's degree in Computer Science and Operations Research from the University of Montreal, with a major in mathematical optimization. He has 32 years of experience within Hydro-Québec where he has been actively involved in planning the operations of the utility’s system of generation assets. From 1998 to 2000, Mr. Raymond was the CEO of HydroSoft Energie inc., a subsidiary of

Hydro-Quebec that was involved in the development and international marketing of river management software. Since his retirement from Hydro-Québec in 2009, Mr. Raymond has become an energy consultant and he is currently a technical advisor for CEATI International's Hydropower Operations and Planning Interest Group (HOPIG).

2 Hydroelectric power projects – general considerations

Several hydroelectric projects were built since the end of the 19th century. The oldest ones were built in the southern part of Canada, close to the electricity demand centers. They gradually moved farther, mainly in the northern territories. Several ice control methods were developed with time and applied in order to maximize the power generation while minimizing the adverse effects on the environment, on the riparians and on the hydropower equipment operations.

The authors' experience shows that the most important characteristic of ice problems is that they are very site specific. Most of them can be addressed in the design step. The projects take into account the main components (dams, spillways, power plant) at the site itself, but also the impacts on the environment, both upstream and downstream of the site. Based on economic optimization, some solutions may be definitive, but in many cases, they combine equipment and operational constraints. For different reasons (unit upgrading, human or aquatic environment evolution, experience with extreme hydrological events, etc.), the restrictions are subject to change with time and consequently must be re-optimized. Any operational constraint could have an impact cost, related to the role of a specific project in the generation and transmission system. This situation justifies regular reassessments of the operating constraints combined with improvements of control equipment. The operating experts are regularly involved in the reassessment studies, particularly in the impacts and associated costs studies.

Studies about hydraulics, ice and environmental concerns are required during the project development phase. Experts in different fields try to pinpoint every potential problem and to address the most accurate and economical solutions. Ideally, problems should be solved completely at the design step. For example:

- Preventing frazil ice clogging problems at the water intake: Constructing the water intake where an ice cover may be formed easily in the forebay (low flow velocity). Making sure that the forebay storage capacity is large enough to store any ice that is eventually generated by the river upstream by taking into account that ice could fill up the reservoir and the deposit could reach the intake. These precautions prevent non-active ice or active frazil ice to reach the water intake and clog it. Clogging is a difficult problem in the winter that impacts the power plant operations and the generation reliability.
- Making sure that the design characteristics such as spillways and dyke levels will not limit the plant operation.
- Preventing or reducing as much as possible any operational environmental constraints which could impact the generation, e. g. restrictions on peaking (i. e. hourly variations during the course of a day), on ponding (such as higher power generation during the week and lower during the weekend), on the minimum or maximum flows during certain periods of the year, or

on flow restrictions not compatible with the best efficiency points of generating units.

Most of the existing projects were built with very few significant operational constraints but, unfortunately, in some cases, this was not possible.

3 Ice control methods

Several methods can be used to control ice problems. This chapter gives a brief description of such methods while specific cases will be presented in chapter 4.

3.1 CONTROL OF THE FLOW

This method consists of adjusting the river flow, mainly to provide adequate hydraulic conditions not only for ice cover formation, but for frazil ice control and ice cover breakup as well. Ice problems may be encountered at a site itself, as well as in the river upstream or downstream from a dam. Flow control is the method which has the most impact on the hydropower operations, however its success is not guaranteed. Flow control may require:

- Coordination with external entities
- Good weather and inflow forecasts
- Expertise in ice management for the operations, short term and mid-term strategies
- Access to remote measurements of several parameters in real time to be archived for analysis (water levels, water temperatures, weather parameters, video cameras)
- Optimized operational guidelines, subject to adjustment according to the real conditions
- Computerized tools and alarms
- Field inspections
- Keeping available storage capacity in the reservoirs in order to be able to reduce or increase the flow when necessary
- Limiting the daily flow and, if necessary, the hourly flow variations
- Taking into consideration the load demand forecast
- Providing ice constraints forecasts
- Etc.

3.2 ICE CONTROL DAMS

The Sartigan dam shown on figure 1.1 was built in 1967 on the Chaudiere River in Quebec, Canada. Its building created a 4 km long reservoir used to store large volumes of ice during winter or spring river ice breakup. The river upstream has an average slope of 3 m/km, or 210 m over a distance of 70 km. It is a cascade of rapid and flat sections whose ice breakup is very severe. The Sartigan dam storage capacity significantly reduces the severity of flooding of several towns downstream. Water is spilled over the sill and a steel fence installed in the upper section of each gate prevents the ice from going downstream of the control work. The presence of the Sartigan dam doesn't totally eliminate the flood problems but it reduces its effects significantly.

The Larocque dam in Bromptonville, Quebec, shown in figure 1.2 was designed to clean the ice from its forebay. At the beginning of the spring breakup, a large gate is opened and closed several times to break the ice cover and force it to pass above the adjacent long weir. This forced breakup prevents ice jamming and flooding along the river upstream.

The Iroquois Dam (see section 4.3) is an example of a dam built notably to be used temporarily as an ice boom.

The Champlain Bridge ice boom in Montreal (see section 4.5) was built specifically to prevent ice jamming and winter flood control.

Other examples such as the Niagara control dam (see section 4.4) were designed with submerged gates to allow spilling of frequent ice runs at the site.

3.3 FLEXIBLE STRUCTURES – ICE BOOMS

Ice booms are the most frequently used works to control ice movements. They are made of pontoons kept in place by cables fixed to anchorages and they are designed mainly to resist the static global load which is the lowest of the following loads:

The driving forces: which depend on current and wind velocity, directions, ice conditions, water level variation and on the fetch upstream of the structure.

The resistance capacity of the pontoons to submerge themselves under the ice to relieve the pressure.

The design loads for a flexible structure are of an order of magnitude smaller than those measured on fixed structures in rivers.

Figure 2 shows a diagram of the different design steps and a diagram of the different components of a boom. For better results, a good knowledge of the local hydraulics and ice conditions through the winter is recommended. In some complex cases, cameras were installed and time-lapse videos were taken for one or more winters to observe, analyse, test and select the most appropriate solution (see sections 4.4.4 and 4.8).

The boom technology improved with time. In the past, pontoons were frequently constructed with wood timbers or rectangular steel shape. Now they are generally constructed with steel pipes of different diameters. This latter solution is economic and more efficient than the wood timbers. More and more, the safety booms or the trash booms upstream from the dams are made like ice booms and may be kept in the water all year round.

From an operational point of view, the ice booms facilitate ice stability and improve flood control but nonetheless have a limited capability. Although there have been many years of success with the installation of these ice booms on a river, this may have created a false sense of safety to waterfront residents who were possibly unaware or underestimated the flooding risks and consequently invested in their properties unwisely. Exceptional meteorological events do happen (e. g. excessive uncontrollable flow) in which case the boom may become unable to efficiently stop the ice. As a result, the river then recovers its natural state (see section 4.7) and the damages caused may be worse had there never been an ice boom installed.

Ice boom failures can have significant negative impacts. The risk and impact of a boom failure may justify the over-design of some booms. The inspection and maintenance of these structures is very important as well.

3.4 ICE BOOM AND WEIR ARRANGEMENT

In some cases, an ice boom is installed upstream from a weir. The weir reduces the water velocity upstream, up to a point where the boom becomes efficient. Figure 3 shows a boom installed in the Rupert-Sakami river diversion, in the northern part of Quebec. The boom was installed upstream from a weir which controls the forebay water level and the flow through a 2,9 km long transfer tunnel located downstream. That ice boom was installed to prevent debris and ice from entering the tunnel as well as for safety reasons.

3.5 ICEBREAKERS

Icebreakers can play an important role in ice control. Their size varies from very large ships of the Canadian Coast Guard to much smaller equipment at the power dams themselves.

The services of Canadian Coast Guard Icebreaking Services (CCGS) include:

1. Route Assistance: to escort ships separately or in a convoy, to maintain tracks through shore-fast ice and to stand by for escort requests
2. Ice Routing and Information Services: to provide ice information and ice routing advice and to manage ice operations centres
3. Harbour Breakouts: to break out ice from wharf faces and surroundings of the harbour in order to facilitate access to ships
4. Flood Control: to prevent the formation of ice jams and excessive build-up of ice in areas prone to flooding and to facilitate ice flow during spring breakup.

Examples of icebreakers include:

- Large CCGS ship (figure 4.1): This type of ship is used in deep waters (e. g. the St. Lawrence River, Great Lakes, oceans). Section 4.1 shows an example with an impact on hydropower generation: During the ice cover formation in the Beauharnois Canal and before the St. Lawrence Seaway closes for the winter season, large icebreakers are used to keep the commercial navigation trail opened and to escort the commercial ships.
- Hovercraft (figure 4.2): The CCGS Sipu Muin is a powerful and heavy hovercraft which plays an essential role in flood control activities in Eastern Canada by breaking up ice covered rivers and shores along the St. Lawrence River, where conventional icebreakers are unable to operate. Section 4.6 shows an example of the impact on the hydropower generation activities: Before the spring freshet, this type of ship clears the ice over a distance of 18 km downstream from the Riviere-des-Prairies power plant (owned by Hydro-Quebec in Montreal, Quebec) down to the St. Lawrence River. During Hydro-Quebec's icebreaking activities to clear the ice from the power plant's forebay, the ice is easily drained to the river downstream. This prevents ice jamming

just downstream of the power plant and inhibits the risk of flooding the power plant from downstream.

- Power plant icebreakers (figure 4.3): Beauharnois and Riviere-des-Prairies dams use their own icebreakers for their ice control activities (see sections 4.1 and 4.6). These small icebreakers can break 15-20 cm of ice by direct impact. When a trail is first opened, the ice is broken more easily by the waves created by the ship moving at a high speed without even touching the ice.
- On the Niagara River in Ontario, the two power generation entities use 3 icebreakers (figure 4.4) to control ice jamming at their plant's water intakes (see section 4.4.3).
- Figure 4.5 shows a privately owned amphibious hydraulic excavator. This type of machine is frequently used for flood control, for preventively breaking the ice covers or for breaking ice jams on various rivers.
- Figure 17.4 shows a setup of two giant hydraulic excavators installed on a large barge that shows that there is no limit to what can be done when heavy equipment is required (see section 4.7).

3.6 AIR BUBBLER SYSTEMS

Air bubbler systems consist of an air diffusion line in which pressured air is fed through. The air bubbles rise to the surface and induce a water movement that prevents ice formation. The system is more efficient in melting the ice when the water temperature is a few tenths of a degree above 0 ^{o}C, which could have interesting results as long as the system works continuously to prevent the ice from thickening. When a thin ice plate is formed, the air trapped under the ice insulates it from the water surface. Figure 5 shows four such applications. In figure 5.2, for example, the water temperature was below 0,10 ^{o}C most of the time.

3.7 MUNICIPAL OR INDUSTRIAL WATER INTAKES IN FRAZIL AREAS

Figure 6 shows a diagram of the municipal water intake of the town of Beauharnois. It is located on the right bank 50 m upstream from the Beauharnois power plant. The perforated intake pipes are placed amongst a pile of rocks and porous medium. The water from the Beauharnois Canal feeds the well by percolation. It works well in spite of frazil and active frazil ice at this site. A backup emergency water intake should normally be installed in case of blockage of the main intake.

3.8 ACTIVE FRAZIL ICE CONTROL AT THE POWER PLANT'S WATER INTAKES

Frazil ice is one of the main concerns in the ice management field. The following subsections describe the origin of water supercooling and give examples of the effects while subsection 3.8.4 presents control methods.

3.8.1 Water supercooling notions

By definition, ice melting temperature is 0 ^{o}C. Water freezing is a complex phenomenon (figure 8). In liquid water, the molecules do not have any particular order. In absence of ice, to change from a liquid to a solid phase, the water temperature must drop well below 0 ^{o}C (supercooled water). When the water is supercooled, ice embryos are formed and destroyed continuously in the water. If the water is not cold enough, the embryos are too small and return to a liquid phase. In an ice embryo, there are attraction forces at the surface and repulsion forces between the water molecules. A minimum number of H_2O molecules must be put together in a perfect crystal ice network before the global attraction forces become greater than the repulsion forces. Theoretically, in pure water, it is possible to produce the first stable ice embryo at -40 ^oC. From this point, the embryo grows as ice crystal. The growing of the embryo generates heat (333,5 J/g of ice) and the temperature of the water mass around the ice crystals increases gradually to 0 ^oC.

In the atmosphere, the water is never so pure. The rain droplets may supercool typically at -15 to -20 ^oC before snowflakes are formed (figure 8.2). Freezing rain is due to water supercooling when a warm cloud passes above a cold layer of air. If it rains, the water droplets passing through the cold air supercool, but not enough to freeze. When that supercooled water reaches the ground or different objects, the ice begins to thicken, thus forming what is known as freezing rain.

Water supercooling in a river follows a similar pattern. During a cold period, heat losses at the water surface result in the cooling of the body of water. Ice particles are always present in the water, but often there is not a sufficient quantity to generate enough energy when they grow to prevent the water to supercool. Figure 8.3 shows a typical pattern of water temperature versus time during water cooling in a laboratory. Because of heat losses at the water surface, the water temperature cools with time. At 0 ^oC, the water temperature continues to lower until such a point where the ice embryos are large enough to be inoculated by the small ice crystals which are present in the water. This describes the secondary nucleation process.

Afterwards, thousands of small disks of ice appear in the water. They grow and produce frazil flakes. Flakes agglomerate and settle to the water surface. Finally, they produce frazil ice pans drifting over the river. The heat generated by freezing warms the water, which gravitates towards 0 ^oC. Depending on the river ice coverage, residual supercooling may persist. In the laboratory test results of figure 8.3, the secondary nucleation temperature was -0,1 ^oC. This minimum depends on the water quality and on the rate of water cooling, which was rapid in this case. In river environments, the secondary nucleation temperature is rarely lower than -0,04 to -0,06 ^oC.

3.8.2 Active frazil or anchor ice

Active frazil ice is frazil formed in supercooled water. It sticks easily to submerged objects. The ice crystals grow on the objects, forming anchor ice. Ice crystals also often grow without frazil ice formation, when the water temperature is under 0 ^oC but did not cool enough to reach the secondary nucleation point. A large quantity of anchor ice is frequently observed at the bottom of a river without any visible frazil in the water. This anchor ice may also be formed underneath the ice cover, increasing the cover thickness and roughness near the front edge of the cover. Water supercooling is inhibited by a completed ice cover and by frazil ice runs or by moving thin ice plates covering most of the water surface.

3.8.3 Examples of active frazil ice and anchor ice

Figure 9 shows anchor ice being observed while conducting tests inside one of the Riviere-des-Prairies generating units. At this site, the trash racks are generally removed during winter. Tests were performed during the winters of 1982-1983 and 1983-1984. These winters were relatively warm and it was then possible to remove the ice cover upstream from the plant over several kilometers of river. More than 20 frazil events were monitored.

When frazil events occurred during these tests, they usually began around midnight, causing the generation of the units to drop gradually. When the generation loss became too significant, the operators broke the ice deposits near the stay ring by using quick closing-opening movements of the wicket gates. The units were stopped when the generation was at 30% of its initial value. Normally, the maximum power was resumed at noon the next day with the sun effect. At this site, worse conditions occurred during the night only, at around -10 ^{o}C. For colder conditions, thin ice plates covered the water surface and inhibited the supercooling and, consequently, stopped the ice growth in the units.

The water velocities in the units at full load are 1,5 m/s at the intake gates, 2,8 m/s upstream from the wicket gates and 8,0 m/s on the turbine runner with the units under full load, as seen in the following pictures:

- Figure 9.1 shows ice deposit on a stay vane blade, formed in spite of velocities well above 2 m/s. On the floor, one can see anchor ice blocks of 20 cm thick that had fallen from the ceiling.
- Figure 9.2 shows the ice deposit on a trash rack that had been partly submerged in the water during a test. The rack was completely blocked. The upper picture is a zoom of ice crystals formed on a steel bar of the rack. Large crystals grew like rose petals facing the flow. This suggests more supercooling and less frazil transported in the water.
- Figure 9.3 shows ice on the blades for another occurrence, with a zoom on the second picture. The ice crystals were smaller and more compact but again very solid on the bar. This suggests more frazil (or snow) in the water and less supercooling.
- In all observed cases, the porous deposits were mainly crystals of different sizes that developed on the surface because of supercooling. Such deposits generally have a very resistant structure.
- Figure 9.4 shows a 2-meter diameter piece of anchor ice previously formed in rapids, but adrift on the water.

3.8.4 Control of the frazil (or anchor) ice in the water intakes

The main cause of active frazil or anchor ice is the water supercooling. Some ways to control the frazil or anchor ice are:

- Detection: The phenomenon is easily detected by a power reduction of the generating units, or by an abnormal pressure drop in domestic water intakes. The measure of the water temperature (approaching 0 ^{o}C) is useful to predict potential problems.

- Duration: A frazil ice event in a power intake often happens during the night and disappears the following morning. It may also last several days, the duration being very site specific.
- Operational mitigation measures:
    - Forming an ice cover upstream of the water intake, reducing the flow if necessary, in order to inhibit water supercooling and the possibility of active frazil ice.
    - Removing the trash racks in the winter (the upper section for racks with two sections) if the risk for machine failure by trash such as docks, trees, etc. transported in the water is manageable. The designers are usually not huge fans of such a solution but in some cases, such as the ones described in sections 4.1 and 4.6 below, there is no other alternative.
    - During night ice events, reducing the generation of the most affected units and even stopping the units if necessary to prevent complete ice blockage.
    - Breaking the ice on trash racks with a mechanical rake (see section 4.8). The crane normally used to remove the debris in the trash racks is sometimes used as a rake with up and down movements on the rack to break the frazil ice growing on the bars. This is useful for temporary events.
    - Waiting if it is believed that the clogging could disappear the next day with the sun warming effect.
- Mitigation measures on equipment:
    - Heating of the trash rack bars, consisting in heating the bars just enough to warm them 0,05 ^{o}C above the water temperature: The Shawinigan 2 power plant in Shawinigan, Quebec, has had a bar heating system for several decades. Such heating is required for a few problematic days each year, mainly during the ice cover formation. A high current-low voltage is applied to the steel bars with satisfactory results.
    - Having a larger distance between the bars of the trash racks: A normal distance is between 6 and 10 cm. At Les Cedres power plant in Quebec (see section 4.1) the distance between the bars is 30 cm. The racks are kept in place all year round. These racks reduce the risk of unit damaging. They stop trees, large wood pieces, docks and other debris drifting on the river. Widely distanced bars may tolerate moderate frazil ice events with minimal generation losses.
    - Heating the water by 0,05 ^{o}C with a heating source (used in municipal or industrial water intakes with low flow, when a heat source is available).
    - Surface coating on rack bars or plastic bars: These may be useful, but are normally not sufficient alone. In these cases, the racks are easier to clean, but must be cleaned just the same. Different coatings exist to

reduce the ice adhesion but they are not very resistant for heavy uses like trash racks.

3.9 WINTER OPERATION OF SPILLWAY GATES

To keep the gates usable in winter, it is important to provide heaters for the embedded parts of the gate and for the gate skin plates in order to allow an adequate selection of gates for the winter operations. The hoist must be designed to overcome the increased ice loads. A steam generation is required for ice melting during emergencies, in the cases where the fixed heaters fail or are not sufficient.

3.10 WINTER OPERATION OF STOP LOGS

Stop log dams still exist on several old sites and are operated during winter. Figure 7 shows the example of a large dam called Ring Dam (1910) located on the Ottawa River near Ottawa, Ontario. This dam diverts the inflow to 4 small hydro plants with the excess being spilled. The winter inflow generally exceeds the capacity of the plants. Therefore, all winter long, timber wood logs are placed or removed almost every day. The practices of operations are:

- Leaving a curtain of water to overflow the logs at all times on a selected number of weirs to prevent them from freezing.
- Using steam to remove the ice.
- Regularly cleaning the ice deposits in the embedded parts in order to be able to move the logs at any time (sometimes urgently in the case of prolonged plant shutdown).

3.11 ICE DUSTING BEFORE BREAKUP

This method has been used frequently in the past to weaken the ice before the breakup. It is mentioned in this report even though it is rarely used today:

- The objective is to increase the sun effect on melting ice prior to the breakup by reducing the albedo of the snow or ice.
- The materials used are sand, soil, coal dust, wood ash, etc. and they are applied by truck or by plane.
- This method is efficient for some sites but also limited due to costs, safety and environmental restrictions.

3.12 METHODS TO PREVENT THE FREEZING OF THE SOIL DURING FREEZING SEASONS

During the construction of large earth dams in the north of Quebec, the freezing of the moraine core was not desirable. Two protection methods were widely used:

- When sufficient snow making machines (which are widely used in ski centers) were available, this method of covering the core with a thick layer of snow is the preferred solution.
- For very large dams where the use of snow making machines is not sufficient, the core moraine is used to build water basins on the top of the dam and fill

them with 1 m of water. Water basins can cover part of the dam only and snow making machines can be used for shorter sections to be ready to protect the moraine core at the beginning of the freezing period. The water basins are efficient to protect the moraine core on some sections until they can be covered by the snow making machines.

4 Ice control application cases

In this chapter we present a more detailed description of different cases combining several ice control methods. Most of them involve operational actions and coordination within several entities. Examples are given for a selection of large and small systems.

4.1 BEAUHARNOIS-LES CEDRES COMPLEX

4.1.1 Description and context of operation

The Beauharnois-Les Cedres complex (figure 11) is one of the most complex cases for ice control. This site is located on the St. Lawrence River, 45 km west of Montreal, between St. Francis and St. Louis lakes. The Beauharnois power plant has 36 turbines with a total capacity of 1 906 MW (8 700 m^3/s with a head of 24 m) and is located at the east end of the Beauharnois Canal. This man-made canal is 25 km long, 9 m deep and 1 km wide. Parallel to the canal, is the natural bed of the St. Lawrence River with four compensation dams used to keep the water on the bed. The flow on the natural section is controlled at the outlet of Lake St. Francis by the Coteau dams, which normally allows a minimum flow of 280 m^3/s and a maximum of 6 500 m^3/s. However, the flow at Coteau is significantly restricted to a maximum between 1 500 and 2 800 m^3/s in the winter to prevent flooding in the natural river bed. Downstream, Les Cedres power plant has a flow capacity of 1 000 m^3/s. This complex receives an annual average of 7 200 m^3/s, 96% coming from Lake Ontario whose outflow is controlled at the Moses-Saunders complex on the border of Canada and USA.

The St. Lawrence Seaway has huge ships traveling through the Beauharnois Canal (up to 25 000 tons or 225 m long, 23,8 m wide and 8 m draft). Historically, the first day of ice at Beauharnois varied between December 6th and February 2nd depending on the year, and the formation of the ice cover lasted between 4 days and 4 weeks. The Seaway navigation season ends in early January. Navigation having a legal priority over electric generation, one year out of two, the commercial navigation continues in the canal during the cover formation with up to more than 100 ships on certain years. The breach caused by the ships in the cover has a crucial detrimental effect on the cover stability. Downstream, the Montreal Harbour operates all year round and has its own level expectations.

Lake Ontario, which is on the USA-Canada border, is regulated with an international plan approved by the International Joint Commission (IJC) who represents the Canadian and American governments. The operational arm of the IJC for the St. Lawrence is the International St. Lawrence River Board of Control (ISLRBC). The regulation process follows very strict rules and allows conditional flexibility for ice control. Each flow change at Moses-Saunders must be first recommended to the ISLRBC by the Operation Advisory Group (OAG) formed of representatives from three generating entities (Ontario Power Generation, New York Power Authority and Hydro-Quebec) as well as from three commercial navigation entities. A consensus is required amongst the entities before a flow change is allowed. The ISLRBC normally accepts the recommendations and implements them.

The decisions taken on the local ice management on the Beauharnois Canal and on the natural section are under Hydro-Quebec's jurisdiction while the St. Lawrence River flow is under the jurisdiction of an international group. Because the Beauharnois-Les

Cedres complex has no storage capacity, the ice control based on flow reductions is dependent completely on flow reductions at the outlet of Lake Ontario. Daily exchanges amongst all entities involved and with the national governments are an important part of the ice management process and add to its complexity.

4.1.2 Project development

The Beauharnois power plant was built and commissioned in three phases (1932, 1942 and 1960), each with a capacity of about one third of the total flow. Since the early sixties, several actions were implemented to improve ice control:

- Dredging: The canal was dredged on the right shore from 1963 to 1965 between km 13,5 and km 22,7, adding 650 m² of cross section and providing a uniform 9 km stretch of 9 300 m². Upstream and downstream from this stretch, the river bottom is made of rock formation and, therefore, could not be dredged, resulting in narrower cross sections.
- Ice booms: Ice booms had been tested in the canal in the early 1950s. Between 1961 and 1964, ice booms were installed on 8 sections and this first setup was then optimized with time. Since 1981, a 2,2 km long ice boom at km 0,0 prevents ice runs from Lake St. Francis to enter the canal during the navigation season. An ice boom at km 22,7 is installed from shore to shore to prevent the ice from entering the head pond of the plant. The other booms are installed at six cross sections with the following setup over the 1 km canal width: boom section of 225 m from the south shore, followed by an opening of 225 m, followed by another 225 m boom section and finally a 325 m opened section used by the Seaway. This setup stabilizes the ice cover while leaving open sections for the ice to travel downstream and eventually cover the canal.
- Load detectors at boom 22,7: Since 1971, three load detectors (tensiometers) were installed on three anchorage cables. Data is transmitted in real time to the powerhouse where two alarm signals are sent to the operator at the beginning of cover formation and also when it is time to reduce the flow.
- Trash racks: To prevent the clogging of the water intake by frazil, the upper sections of trash racks (made in two sections) are raised (removed) during the winter only. Impeller shear pins are occasionally broken when ice blocks enter the machines during the ice breaking operations. The racks are lowered during spring as soon as the ice has melted.
- Icebreaker upstream from the power plant: A small icebreaker available at all times in the head race is used periodically during the winter period to remove ice between the plant and the boom situated at km 22,7. The head loss is typically 0,30 m in that section when the forebay is clean, but may increase to 0,80 m with heavy ice deposit. As the canal flow capacity is limited by the minimum level of the forebay, an excess of head losses of 0,50 m may require a reduction of turbine flow and of generation of up to 15%.
- Field observations: Remote cameras are used to observe the ice at some critical points from the control room. Daily inspections are made on the canal by a technician during the cover formation and breakup periods and informative reports are sent at least once a day to the concerned staff.

- Data acquisition: Measured data is available in real time from remote computers to any personnel involved in the ice management. Measures are stored every 5 minutes for consultation and analysis and they include:
    - Flow at the Beauharnois, Coteau, Les Cedres and Moses-Saunders sites
    - Water level measured at 6 points along the canal
    - Water temperatures at 4 points along the canal and 3 more points up to Lake Ontario
    - Load measured at 3 gauges on boom 22,7.
- Measures adopted to reduce the effect of commercial navigation in the canal during ice cover formation:
    - Daylight navigation only
    - Maximum speed of 5 knots to limit the wave effects
    - Only one direction at the time (no ship meeting) to prevent collisions
    - CCGS icebreakers escort when necessary.

In spite of all the precautions taken and of the generally good collaboration from the Seaway, the ice cover may still collapse in some cases and cause the ice booms to break. Emergency actions such as quick and significant flow reductions may then be necessary. A fast track procedure has been put in place at the Moses-Saunders plant should such an event take place.

4.1.3 Guide of operation

Between the maximum level of Lake St. Francis and the minimum operation level of the Beauharnois head race, the gap is only 1,8 m. Therefore, the head losses in the canal cannot be higher than 1,8 m. When they exceed that value, the power plant generation must be reduced. For example, the difference between a smooth and a rough ice cover could have an impact of up to 200 MW on the winter generating capability. The method used to control the cover formation is to reduce the flow in the canal just enough to form a stable thin and smooth cover with no ice jam. However, excessive reductions could be very costly in terms of generation.

Since 1960, observation reports of the ice cover were produced for each winter at Beauharnois. To produce the guide of operation, each of these annual reports has been analysed. The hydrodynamics of the canal and the weather conditions (snow, wind) were studied carefully in relation with ice events reported. Simple rules were derived as a guide for the day to day operation. This guide defines a maximum flow to be respected for different sections of the canal (between 6 000 and 4 000 m3/s), subject to some positive or negative adjustments depending on weather, navigation or other risks. The guide also highlights the needs for field inspections, namely to monitor the risk of flood downstream of the Coteau dam (figure 11.4).

4.1.4 Day to day operation

At the Beauharnois site, mainly two groups are involved in ice management:

i) Plant operators for:

- Operations
- Field inspections, every site being accessible by road
- Participation in the preparation of the operating strategies
- Internal diffusion of strategies and daily observations reports.

ii) Technical support personnel for:

- Establishing the operating strategies in cooperation with the operators
- Carefully following the operations, inspections, weather forecast and remotely collected data (loads on the ice booms, water temperatures, water levels)
- Identifying any potential problem and making sure that no major point is overlooked
- Taking charge of exchanges with the external entities, namely acting as representative on the Operation Advisory Group (OAG) of the ISLRBC
- Obtaining information on the river flow changes from Lake Ontario which is required by Hydro-Quebec for the ice control at Beauharnois-Les Cedres complex
- Preparing or managing every technical and performance analysis
- Updating the guide of operation when necessary and implementing the changes.

4.2 SHIP RETENTION SYSTEM AT BEAUHARNOIS

Generally, an ice boom is designed to retain ice. The ship retention system is an unusual case that requires a boom that is rather designed to allow ice to go through. In 2013, a new expressway bridge was put into service, 2,1 km upstream of the Beauharnois power plant. For bridge safety reasons, it was necessary to have a system in place in order to prevent a ship adrift to reach the bridge. The retention system had to be capable of stopping a ship of 225 m long, 24 m wide, 8 m draft and with a load of 25 000 tons at a speed of 3 knots. Figure 12.1 gives a global view of the site while figure 12.2 shows a location plan where the highway bridge can be seen to the north (downstream), the km 23 ice boom (100 m upstream of the bridge) and the ship barrier (450 m upstream of the bridge). On the left hand side is the Beauharnois shipping lock entrance.

The power plant owner requested that there be no effect of the barrier on the head losses in the canal, both in winter and in summer. This prohibited any heavy or powerful construction in the water. The effect on the ice movement had to be minimal, i.e. the ice should easily go through the barrier in order to form the ice cover entirely between the km 23 ice boom and the ship retention system.

The final solution retained was a boom (similar to an ice boom) with a judicious pattern of steel and nylon stretching ropes (up to 30-40% stretch) that would apply a continuous extremely high force on a ship to prevent it from reaching the bridge.

The steel pontoons of the ship retention boom (figure 12.3) are designed to remain parallel to the flow so that their shape provides a minimal effect on the ice movement. The pontoons used during the first two winters of operation have proven to be very efficient.

4.3 MOSES-SAUNDERS COMPLEX

The Moses-Saunders power plant is located on the St. Lawrence River, just upstream of Lake St. Francis, 80 km upstream of the Beauharnois power plant (figure 13). At this site, the head and the flow are about the same as those of the Beauharnois-Les Cedres complex. The Moses-Saunders power plant (half USA, half Canada) controls the outflow from Lake Ontario. The flow itself is under the responsibility of the International St. Lawrence River Board of Control, same as for Beauharnois-Les Cedres. The project was completed in 1960 and the new reservoir is used by the St. Lawrence Seaway. Lake Ontario itself is located 160 km upstream of the power plant and an intermediate dam, the Iroquois Dam (figure 13.2), is located 45 km upstream of the plant. The Iroquois Dam is at the head of the rapid which existed naturally before the project when the site was the natural control of Lake Ontario’s outflow. The section between Lake Ontario and the power plant consists of:

- A large reservoir on the first 30 km
- A 15 km river flowing faster and faster from the reservoir to the Iroquois Dam
- A low velocity flow for 6 km upstream of Iroquois, followed by a higher velocity on the 18 km long section between the towns of Cardinal and Prescott and finally followed by a low velocity river.

Ice control

The main objective of the ice management is to minimize the head losses between Lake Ontario and the Moses-Saunders power plant headrace. This results in a better head for power generation and prevents significant potential flow reductions which could be necessary to raise the forebay to prevent its level to drop under the minimum design level. A head race level that would be too low could also impact the water intakes of the towns around the reservoir. Also, excessive outflow reductions at the plant needed to raise the headrace level would impact the winter power generation of the Moses-Saunders and Beauharnois-Les Cedres plants and would also lower the water levels in the Montreal Harbour for navigation and these impacts can be very costly for the entities involved.

To achieve the objective of minimizing the head losses, different measures were taken:

- Ice booms and dredging: Six ice booms were installed and enlargements of channels were dredged between Cardinal and Prescott (2 to 20 km upstream of Iroquois).
- Flow control: The first day of ice happens about one week after it happens at Beauharnois. The ice cover is easily formed on the first 30 km of the reservoir without flow concern. Past this point, the average daily flow is set at 6 200

m³/s. It may then take 1-2 weeks for the cover to reach a point about 4 km downstream of the Iroquois Dam. From this point, the velocities are too high for ice to progress. Then, the flat gates of the Iroquois Dam (figure 13.2), which were wide open until then, are lowered one meter in the water. This stops the ice run and allows the cover to progress upstream. The flow stays low at least until the front edge of the cover is 25 km upstream of the Iroquois Dam. Upstream from this point, the water velocities are lower and the flow may be increased. Peaking generation is allowed at Moses-Saunders with the flow variations being absorbed by the reservoir.

- Regular inspections of the river.
- Data available: Water levels and water temperatures available at different points along the river.

The water management at Moses-Saunders is simpler than at Beauharnois-Les Cedres but extraordinary events may also request special remedial actions. For example, under severe combinations of east winds and very cold weather, ice blockages can happen at the Iroquois Dam (with gates fully opened), before the cover is completed downstream. The Iroquois Dam may then be unblocked by rapidly increasing the flow at the power plant. This method works most of the time, but during the 1992-1993 winter, the Iroquois Dam stayed blocked for most of the winter as the worst scenario described above in the first paragraph of the Ice control section happened. The adverse impacts on several entities were significant, notably at Beauharnois where the flow decrease had negative impacts.

Twice a year, the results of operations and problems are reported to the International Joint Commission who is, ultimately, responsible for the Lake Ontario regulation.

4.4 NIAGARA RIVER ICE CONTROL

4.4.1 Characteristics of the site

The Niagara River extends over 58 km between two Great Lakes, Lake Erie and Lake Ontario. The Canada-USA boundary is situated in the middle of the lakes and of the river. The works and their operations are subject to approval by the International Joint Commission.

The water level drop between the lakes is around 99 m, the Niagara power plants having a head of approximately 90 m and the average river flow being 6 010 m3/s. By international agreement, a minimum flow of 2 830 m3/s is reserved for the Niagara Falls during the summer day-time hours (from April to September), and of 1 415 m3/s for every remaining hour of the year. Any additional water is available for power generation. The site was developed gradually since 1880. Different plants were built, tunnels and canals were dug, weirs were constructed and dredging was carried out. The present setup was essentially completed at the beginning of the 1960s.

Figure 14 shows a general plan of the river with a zoom around the control structure. On the left shore, two water intakes, one for a canal to Beck 1 and one for a tunnel to Beck 2, carry a total of 1 840 m3/s to these Ontario Power Generation (OPG) plants. A new tunnel (not on the plan) to Beck 2 was completed in 2013. On the right shore, a tunnel carries 2 900 m3/s to the New York Authority (NYPA) plant. Downstream of the intakes of the NYPA plant is the Control Dam, 2,6 km upstream of the falls.

The International Niagara Control Dam was completed in 1963. It is used to divert the Niagara River flow to the power generating stations, while maintaining the minimum flow in the falls. The dam raises the river level and maintains it into a fixed range of 0,9 m. The 18 submerged gates of the dam extend over 670 m from the Canadian shore to the American boundary. It distributes the flow across the river, increases the flow in the American falls and spills the drifting ice.

4.4.2 Site development

The following are considerations that guided the site development:

- The dam submerged gates allow the drifting ice to continue its way to the falls.
- Dredging was done to remove anchor points for the ice.
- The submerged lateral water intakes and a wall along the shore on the Canadian side facilitate the ice to travel downstream.
- A long concrete wall between gates 3 and 4 facilitates the acceleration of the surface flow along the shore with gates 1, 2 and 3, as well as ice flushing.

Each winter, NYPA and OPG work together to prevent ice on the upper Niagara River from impeding power production and causing the flooding of shoreline properties.

4.4.3 Icebreakers

When gale winds blow and temperatures drop below zero, three special-duty boats are used to patrol the river, breaking up the ice and leading it over the falls. The NYPA primary icebreaker, the William H. Latham, is a 77-ton vessel that literally glides over the top of the ice, crushing it into manageable chunks. The Breaker, a modified tugboat, assists the Latham. In addition, OPG operates a similar icebreaker called the Niagara Queen II (figure 4.4).

4.4.4 Lake Erie ice boom

A 2,7 km long ice boom at Lake Erie's outlet to the Niagara River is another joint effort from NYPA and OPG.

In the winter, southwest winds are particularly efficient in driving ice flows into the narrowing at the eastern end of Lake Erie. The narrowing of the lake at the outlet restricts the volume of ice that can enter the river, causing an ice arch to be formed across the outlet. The Lake Erie ice boom aids in the formation of the ice arch. Under good (i.e. low wind) conditions, the Niagara River may therefore stay relatively ice-free. Storms, however, can cause destabilization of this natural formation, allowing masses of ice to enter the river when the ice boom becomes submerged, and causing large-scale ice blockages that can cause substantial power losses at the plants on the Niagara River. Some cases of such ice blockages can even cause ice jams and flooding of shoreline properties, leading to serious damage to docks and other shoreline structures.

The ice boom, first installed in 1964, promotes the formation of an ice arch and limits the duration and frequency of lake ice runs. The 22-span boom can be installed when the Lake Erie water temperature at Buffalo, New York, reaches 4 ^{o}C or on December 16th, whichever comes first. Each of the boom's spans consist of a series of floating steel pontoons anchored to the lake bottom at 122 m intervals by 6,4 cm steel cables. The boom is removed on April 1st or when there is less than 645 km2 of ice in the eastern basin of Lake Erie, between Long Point, Ontario and Erie, Pennsylvania.

Reassessment studies were conducted between 1992 and 1996 to evaluate alternatives that would further reduce the release of ice from Lake Erie into the Niagara River. Different measures were taken, namely (Crissman, Abdelnour and Shen, 1995, and Crissman and Lalumiere, 1997):

- Rigorous analysis of the historical performance of the timber ice boom
- Analytical assessment of the performance using limited observations of the lake runs that occurred in the past
- Ice load measurements on the boom
- Analysis of measurements, combined with similar measurements made on the St. Lawrence River at Yamachiche (see section 4.5). Detailed analysis of the forces on different boom components.

The final recommendation was to replace the timber pontoons (41 cm high and 56 cm wide) by 76 cm in diameter steel pipe pontoons. During the 1996-1997 winter season, 5 of the 22 spans were replaced with 76 cm steel pontoons to test the solution. To improve observations, two video cameras were installed on the roof of a Buffalo, New York, 38-story high building. Video images were transferred in real time to the operating staff and images were archived every 5 minutes. The observations confirmed the outstanding performance of the steel booms as compared to the lumber booms. All pontoons were then replaced for the 1997-1998 winter.

Ice booms reduce the occurrence and volume of ice entering the river but in some cases, when a wind storm is too strong, a huge amount of ice still carries over the boom. At the beginning of January 2014, a significant ice jam occurred in the east arm of Grand Island in the upper Niagara River. Two icebreakers worked to maintain the NYPA power plant in operation. Water levels were near the flood stage. A video of the ice breaking operations on January 9th, 2014 can be seen on the following site:

http://globalnews.ca/news/1072555/canadian-u-s-ice-breakers-work-to-clear-ice-jam-in-niagara-river/

4.5 LOWER ST. LAWRENCE RIVER - ICE CONTROL IN THE NAVIGATION CHANNEL

More than fifty years ago, severe ice conditions prevailed on the St. Lawrence River and they caused severe flooding in the city of Montreal along the river due to massive ice jams. Since 1964, icebreakers keep the Montreal Harbour opened to large oceanic ships all year round. The construction of the Expo 67 islands in the river in the 1960s reduced the width of the St. Lawrence River, thus raising the risk of ice jams and flooding. The 2 km long Champlain Bridge control structure (figure 15.1) was built in 1964-1965. It was erected downstream of the Laprairie basin where large quantities of ice are seen every winter. The structure is no longer in service as efficient icebreakers are now used to maintain the navigation channel opened from Montreal to the Atlantic Ocean by draining the ice.

Downstream of Montreal, three long ice booms were built at Lavaltrie, Lanoraie and Yamachiche over a distance of 100 km to facilitate the formation of stable ice covers and prevent them from shifting and blocking the navigation channel. Figure 15.2 shows a plan of the works built on Lake St. Pierre to stabilize the cover. Artificial islands were built and 4 booms were originally installed near the outlet of Lake St. Pierre. Later, the setup was optimized and the 4 booms were replaced by the Yamachiche ice boom. This boom is entirely made of steel pipe pontoons since 1995.

This case is interesting because Yamachiche boom development learnings (laboratory tests, field tests, ice forces measurements) were later applied to other sites, in particular to the Lake Erie ice boom (section 4.4).

4.6 ICE CONTROL AT RIVIERE-DES-PRAIRIES

The Ottawa River has a catchment basin of 146 000 km2. It enters the Montreal archipelago at the Carillon dam, where its flow is divided amongst 3 rivers one of which is the Des-Prairies River which takes about 40% of the Ottawa River flow as it travels between two large cities, Montreal and Laval.

The Riviere-des-Prairies power plant is a dam that was built in 1929 on the Des-Prairies River. Figure 16.1 shows an upstream view of the site, with a 45 MW power plant on the left side and the spillway on the right side. Figure 16.2 shows a global plan of the river. Figure 16.3 represents a long profile of the river. The river is a succession of flat and rapid sections. Up until 1975, the river was subject to major ice jamming on the flat sections, mainly in the first 6 km of the power plant forebay as well as on a section named “A Ma Baie”. During this period before 1975, the ice regime was often detrimental to the power generation. Several remedial measures were taken:

- In 1975, Hydro-Quebec installed two ice booms at the head of the rapid sections, the Cartierville and Ste-Genevieve ice booms.
- An icebreaker is used each winter to maintain a one km long narrow (20 m) canal opened all winter upstream from the spillway. This canal facilitates the ice cover removal activities during spring time. In fact, the canal may freeze, but then the icebreaker removes the ice each time its thickness approaches 20 cm. Before the upper river breakup, a much larger canal free of ice is normally opened in the first 6 km of forebay to allow the evacuation of the upper river ice during the breakup.
- In 1982-1983, a new and much improved Riviere-des-Prairies spillway was built to replace the old one. Its piers and gates are reinforced and they can be struck by thick solid ice blocks without any problem. Each of its 13 gates is equipped with fast hoists. Each gate is heated and may be easily operated during winter and spring. These features allow safe icebreaking activities in the forebay with minimal waste of water.

In general, these control measures are adequate enough to prevent flood damages in the river while maximizing the generation.

4.7 EXCEPTIONAL WINTER FLOOD AT RIVIERE-DES-PRAIRIES DURING THE 2003- 2004 WINTER

The fall of 2003 was exceptionally wet on the Ottawa River system. In December, the reservoirs in the upper part of the system were close to full storage capacity and there was no way to reduce their outflow. Consequently, the flow at the Carillon dam, the first dam upstream of Riviere-des-Prairies, was 160% of its normal value.

At Riviere-des-Prairies itself, the average flow in December was 130% of the maximum flow capacity of the Cartierville ice boom. Consequently, during the cover formation in mid-December, the flow was too high and most of the ice run crossed over the boom. It formed a thick 6 km long ice cover between the power plant and the upstream Sault-aux-Recollets rapid, which was exceptional. Normally, the cover ends about 2 km downstream from this point, in a deeper flow area.

Later, that cover formation period was followed by a warm period up until the beginning of January. On January 4th, the boom had contained the ice run. The water level at the water gauge just upstream of the Bordeaux bridge (between the Cartierville boom and the Riviere-des-Prairies plant) was 18,2 m, 40 cm higher than the normal winter level of 17,8 m. The power plant's operating level is 17,1 m.

At the beginning of January, the weather became extremely cold and the Bordeaux bridge gauge level began to increase abnormally as shown in table 2.

Table 2 ctual and normal water levels at Bordeaux bridge (2004)

Date	Jan 4	Jan 17	Jan 26	Jan 28	Feb 1	Feb 5	Feb 10
Actual 2004 level (m)	18,2	18,9	19,7	19,9	20,0	19,4	18,7
Normal level (m)	17,8	18,0	18,0	18,0	18,0	18,0	18,0
Gap (m)	0,4	0,9	1,7	1,9	2,0	1,4	0,7

Figure 17.1 shows the state of the river cover on Jan 17th when the level was 0,9 m above normal and flooding was already a great concern. The extent of the cover at this date stayed about the same until the end of the month while a 2,5 km long section of river was free of ice.

Field measurements were taken on January 25-26 as river cross sections were made by drilling holes in the ice cover. This way, a longitudinal profile of the river water levels was achieved. A level drop of 1,4 m was observed on the first 15 m of the ice cover, at its front leading edge. Cross sections showed that the ice thickness was generally much more significant in the middle of the river while, along the shores, a large tunnel allowed the passage of significant flows of water. The river flow was then of 900 m3/s.

On January 26th, the water level at the gauge was 1,5 m higher than previously observed on January 4th. The measurements showed a concentrated head loss of 1,4 m in the first 15 m of the cover which indicated that most of the river blockage since the beginning of the month had occurred on a short 15 m long stretch.

The cover had progressed up to a very shallow river section at the foot of the rapids and water supercooled in the upstream open river stretch. This supercooled water generated a thick layer of anchor ice on the river bottom and underneath the cover for a short distance. Ice specialists were confident that the water level would drop if they could remove the ice from the first 15 m of the cover, without sending it in the flow tunnel downstream and risk a blockage. However, such an operation requested powerful equipment and this solution was carried out from the south shore where the access to heavy equipment was easier. A large barge and powerful excavation equipment were rapidly deployed.

Figure 17.2 shows a picture taken from the south shore showing the evidence of a level drop in the order of 1,4 m between the main river course and the level near the shore. Figure 17.3 shows the beginning of ice removing on February 2nd and figure 17.4 shows the heavy equipment being deployed. As soon as a first canal was opened, the level began to drop. Throughout the operation, the canal was widened to about 75 m. On February 10th, the level had dropped by 1,3 m and stayed about the same until the spring melting.

Many lessons were learned from this event: This type of problem was probably more frequent and even worse before the use of the ice booms. On the south shore (the Montreal side), most of the properties along the river were built a long time ago. The riparians and municipalities had experienced flooding in the past and, therefore, knew the risks and took them into consideration. On the north shore (the Laval side), the developments are in general more recent. The ice control measures implemented in 1975 were very efficient but at the same time created a false sense of safety. The ice boom system has proven to be very successful; however, it does have its limits. The very low probability event which occurred in 2004, produced substantial damage even though citizens had installed a considerable amount of sand bags to be protected against the flood. At some accessible sites, snow dikes were built (figure 17.5) to protect against low head flooding. In addition to the damages to the waterfront properties, several hundreds of basements were flooded inland, particularly by sewer back-ups.

Due to the seriousness and costs of this event, several organizations were involved, each playing an important role, namely the Quebec provincial Civil Security, the cities of Montreal and Laval, the Canadian Coast Guard, Hydro-Quebec and consultants.

After the event, the Laval municipality installed several remote water level gauges at key points along the river. They also planned a reassessment of the surface water sewer system to improve the reaction in an eventual future event.

In conclusion, such an event happened only once in the last 40 years, showing that no ice control system is completely full proof. Thus, it is important to document any event for future references by using the lessons learned to improve the reaction to be taken should future rare circumstances occur. Prohibiting construction in flood areas and adapting the municipal and private infrastructures in facing ice events are efficient methods to alleviate future detrimental ice effects.

4.8 ICE CONTROL AT HULL 2

The Hull 2 power plant is a 26 MW hydro plant owned by Hydro-Quebec in Gatineau, Quebec (figure 18). It is located next to the Ring Dam described in section 3.10. This site is prone to active and non-active frazil ice due to an open rapid flow section upstream. The plant is equipped with a mechanical rake (figure 18.2) that can be used to crunch the ice in order to maintain the flow through the trash racks. A rake operating team is required almost full time during winter to achieve this task.

In 1995, a study was initiated to search for ways to reduce the quantity of ice. A video camera was installed on the top of a 14-story building near the river. Time-lapse videos were registered day and night at a rate of one image per second for part of the winter and analysed in order to understand the precise behavior of the river. It was observed that the ice cover in the plant feeder canal was very unstable as it formed and broke several times during the winter. This was due to the water velocity and to the poor quality of the ice. Each breakup caused a substantial amount of ice to enter the intake in addition to de-stabilizing the cover upstream.

A hydraulic study was conducted from these observations and consequently an ice boom was installed in the fall of 1997. Figures 18.1 and 18.3 show the forebay before and after the installation of the ice boom. The boom allows the ice cover to be formed farther upstream and reduces the risk of active frazil at the plant.

The solution significantly reduced the quantity of ice to manage. The mechanical rake is still used however less frequently in order to prevent the emergency situations that could occur at the plant (for ice removal) and at the Ring Dam (for flow spillage) in the event where the ice cover would break in the feeder canal.

4.9 WAKEFIELD ICE BOOM ON THE GATINEAU RIVER

The Gatineau River flows from north to south and reaches the Ottawa River facing the town of Ottawa, Ontario. The river projects include an upstream reservoir with annual regulation and three power plants named Paugan, Chelsea and Rapides-Farmers. The town of Wakefield is located 35 km downstream of the Paugan plant and 20 km upstream of the Chelsea plant. Wakefield is at the upstream end of the Chelsea reservoir. A rapid exists just upstream of Wakefield, followed by a flatter river section. In the past, a hanging ice dam had formed every year along and downstream of the town by the time the ice cover had already formed naturally upstream of the Wakefield Rapid. To prevent flooding at Wakefield, the Chelsea dam pond was lowered by as much as 1 m at certain times. In January 1993, the Wakefield jam was more significant than usual and the lowering of the Chelsea pond was not sufficient enough to avoid a minor flood which occurred at Wakefield and as a result, the peaking capability at the Paugan plant was limited for the remaining of the winter period (Abdelnour, 2001).

This event coincided with the end of authorized log driving on the river and, therefore, numerous wood booms became available for other purposes in the area. During the following 1993-1994 winter, a test was performed using one of the old wood booms that was installed at the head of the rapid. Anchorages were fixed in the rock on each side of the river. Combined with minor flow restrictions at Paugan, the ice cover was easily formed upstream of the Wakefield rapid and the volume of the hanging ice dam was substantially reduced. Moreover, the head pond at Chelsea could be maintained at its maximum level all winter long, providing generation gains. This setup worked well for 6 consecutive winters until the old recycled wood boom was replaced by a new steel pipe boom in November 1999.

4.10 ICE CONTROL ON THE PEACE RIVER

The W.A.C. Bennett dam (Jasek, 2008, and Wigle et al., 1990) was built on the Peace River in British Columbia and commissioned by BC Hydro in 1968. The project includes the dam, the Williston reservoir and the 10-unit Gordon M. Shrum power plant built from 1968 to 1980 with an installed capacity of 2 730 MW (2 800 m3/s) that can supply 20% of the electricity used in the province.

As with every northern project with large reservoirs, the river flow is reduced in the spring and increased in the winter. The Peace River flow has tripled in winter in comparison to its natural flow prior to the project. This completely changed the thermal and ice regimes of the river. As a result, because of warm water (1-4 °C) at the outlet of the Gordon M. Shrum plant and of a significant flow increase, a river section varying between 100 and 200 km depending on climate, now remains free of ice during winter. This situation has a definite impact on the cover formation and decay.

Flow constraints at this project have been applied primarily to avoid flooding at the Town of Peace River (TPR), in Alberta, a community of 7 000 people 400 km downstream of the power plant. The west Peace subdivision of this town is located on the left bank of the Peace River and is subject to flooding. Although the subdivision is protected by a dyke, the alluvial gravels are quite pervious and groundwater levels respond within a week or so to changes in river conditions. There is a flow delay of 2 days between the power plant and the town. The flow restrictions for ice control are the result of exceptional past events.

Wigle et al., 1990, on page 27, shows a good example of lessons learned from an exceptional event described here:

> "Freeze-up on the Peace River at TPR occurred on January 2, 1982. Over the New Year weekend (January 1 to 3, 1982) mean daily flow releases from the upstream G. M. Shrum and Peace Canyon hydroelectric plants were reduced from approximately 1 700 to 1 000 m3/s due to low load demand. This low flow combined with extremely cold weather (mean daily air temperature of -30 to -35 °C) resulted in the rapid upstream advance of the ice front, and by January 7 the ice front was upstream of the town of Dunvegan, approximately 100 km upstream of TPR.
>
> Flow releases at the upstream plant were increased to 1 750 m3/s by January 5, 1982. These plants are more than 370 km upstream and flow travel time from the plants to TPR is approximately 2 days. On January 7 as result of these increased flows, break-up of the ice cover occurred at Dunvegan and a temporary ice jam 15 km downstream was formed. After several hours the jam released and the resulting flow surge estimated at 2 500 m3/s caused the ice cover as far downstream as TPR to break-up. The broken ice debris moved downstream and packed against the upstream edge of the unbroken cover 20 km downstream of TPR. Approximately 155 km of ice cover had broken and consolidated into a distance of 60 km. Water levels on January 8 at TPR increased to El 318.2, 3.5 m above the pre-breakup level on January 7 and only 1,6 m below the top of the dykes protecting the town."

The ice cover that was formed at low flow was too thin and too weak to support the forces applied on the ice cover during the flow increase. Following that event, it was decided to apply a flow restriction during the cover formation period (Ibid., page 28):

> "To avoid a re-occurance of this problem, once the ice front has advanced to within about 15 km of TPR, mean daily releases at the upstream plants are held constant at about 1 500 m3/s until the ice front has advanced well upstream of TPR and the ice cover has had a chance to consolidate. Freeze–up and consolidation

usually takes from 1 to 2 weeks. Although short term flow increases for daily load factoring are usually limited, due to the distance between the plants and TPR minor flow changes throughout the day are almost completely attenuated by the time they reach TPR. Maintaining relatively high river flows during the freeze-up period at TPR, results in the formation of a thick ice cover at a high river stage which is stable under a wide range of river flows. This permits maximum operating flexibility at the upstream plants during the rest of the winter period."

The Peace River is generally steep and wide (about 500 m). During the cover formation, the front cover progress rate is in the order of 15 to 40 km/day depending on the air temperature, the discharge from the upstream plants, the slope and the width of the river. At this rate, the newly formed cover has no time to consolidate and, therefore, it progresses within an ice juxtaposition-shoving process. As a result, the cover is thick and rough. In normal conditions, at 1 600 m3/s, the stage increase at the TPR due to ice is in the order of 2,5 m.

The Peace River hydropower operations during the winter are coordinated through a Joint Task Force that includes BC Hydro, Alberta Environment and the Ministry of Environment of the British Columbia government. They arbitrate between hydropower considerations and ice jam flooding risks. They manage both the freeze up and the breakup periods. This task force was formed after the 1973-1974 severe breakup.

Jasek, 2008, introduced the following current criteria:

1. The control flow consists in maintaining a total flow of 1 600 m3/s at TPR for the control period, the local inflows being between 100 and 200 m3/s.
2. The control flow is implemented 2 days prior to the ice front reaching a point 16 km downstream of TPR.
3. The control flow is lifted 10-14 days after the ice front arrival at Dunvegan (100 km upstream of TPR) or when about 0,4 m of thermal ice is measured at Dunvegan.
4. The target elevation is 315,0 m at TPR. When the level gets over 315,0 m, the situation has to be monitored closely. Furthermore, when the level gets over 315,5 m, the Joint Task Force recommends taking actions to get the level back below 315,0 m.

It is to be noted that the criteria introduced in 2008 for the freezing period are more precise and likely more optimized, but do not differ greatly from the ones established 25 years earlier, after the 1982 event mentionned above. The Joint Task Force also established some criteria for the spring breakup, after the breakup events observed in 1978 (Wigle at al., 1990) and 1992 (Assaf et al., 1995) on the Smooky River, a tributary entering the Peace River upstream from TPR.

The Peace River project was an exceptional proving ground for the improvement of the modeling of thick ice cover stability in large rivers, as well as for the study of surge effects due to ice jam breaks. The CRISSP model and the SWIPS instruments described in section 5.2 below were also used at this site.

4.11 JENPEG GENERATING STATION AND LAKE WINNIPEG REGULATION PROJECT

Manitoba Hydro's Jenpeg generating station, located on the upper arm of the Nelson River 525 km north of Winnipeg, was commissioned in 1979 with an installed capacity of 135 MW and a head of 7,32 m. It is one of the reasons that contributed to the successful development of the hydroelectric potential of northern Manitoba. Jenpeg's powerhouse and spillway structures (figure 19) are used to control and regulate the water outflow from Lake Winnipeg, which in turn is used as a reservoir to store water ensuring that water is continuously available to supply 4 more generating stations on the lower arm of the Nelson River. In the Lake Winnipeg Regulation Project, in addition to the Jenpeg project, three wider and deeper diversion channels were built for a total length of 16 km. The project has led to a regulation that resulted in the decrease of the outflow from Lake Winnipeg in the spring and early summer in order to make it more available for use more extensively in the fall and in winter.

The operation strategy for Jenpeg during the freeze up period aims at monitoring and controlling the ice formation process in the channels upstream of the station. Based on daily observations of flowrate, water temperature, ice conditions and on short term weather forecast, a flow cutback is initiated before any significant frazil production takes place. In doing so, the formation of a stable static ice cover is facilitated and any long term problems, such as the formation of hanging dams or intake blockage at the station, are avoided. A maximum flow of 1 600 m3/s is necessary to achieve these goals, representing an average reduction of 1 000 m3/s (Bijeljanin and Clark, 2011).

The original design included a flow cutback of 1 190 m3/s which was very costly. The cutback was eliminated once in 1977, resulting in a tremendous loss of Lake Winnipeg's winter outflow and of performance at the Jenpeg generating station. In 1983, Jenpeg was shut down completely due to the ice blockage in the intake. In 1984, the Lake Winnipeg Regulation Ice Stabilisation Program (RISP) was implemented and an ice boom was installed upstream to the plant to prevent ice blockage. The RISP includes and takes into consideration (Zbigniewicz, 1997):

- Flow cutback (optimization of the timing and duration depending on weather forecast) to cover the open water sections with ice
- Inspections in the field
- Water temperature
- Water level measurements to follow the head losses in the narrow sections
- Taking into consideration the waterfront residents downstream from Jenpeg by providing them with an information program and by establishing safe ice trails
- Hydraulics and ice modelling (see chapter 5 below).

5 Ice numerical modelling

5.1 GENERAL REMARKS

The new hydropower projects, normally including reservoirs allowing regulation, significantly alter the seasonal flow distribution and the thermal and ice regimes of the reservoirs and rivers. The designers face many issues during the works design including the environmental impacts and mitigations. The first years following the commissioning of a project can be used as a breaking in period to perform more analysis in order to adjust and optimize the operational practices when power generation issues may conflict with ice control needs. Afterwards, regular reassessment of the operational practices or of the equipment may be necessary. For every stage in the life of a project, analyses are required notably with the use of different types of models applied to different needs.

For a new project, different techniques exist to simulate the future thermal regime of reservoirs and rivers, the future ice cover characteristics, the raising of the water level due to the ice, and the dam safety and environmental considerations. Most of the hydraulic aspects are studied with steady-state models calibrated using the experience from other sites and utilized with conservative parameters. As for environmental concerns, the parameters used will generally correspond to average values to reflect average expected conditions in the future.

It is very important to remember that when thermal modules and ice modules are combined with hydrodynamic models, many new equations are added to simulate a large number of phenomena such as the thermal regime, the types of ice (border ice, frazil ice, anchor ice, ice pans, moving thin ice sheets, etc.) and the dynamics ice cover formation and its stability. These equations are usually less accurate than hydraulic equations and are often based on summary theoretical developments and calibrated from clouds of points from a limited number of observed cases. It is nonetheless practical and useful to represent very complex processes by using simpler equations or criteria which, most of the time, lead to a reliable result. A good understanding of the theoretical basis of the model and of the limits of its accuracy may help in adjusting the values of the parameters in order to obtain reliable results or, at least, in explaining why the model does not perform as expected. In other words, in the authors' opinion, using an ice simulation model as a black box only could be ill-advised.

For the existing projects, a model is not adequate enough to solve all problems that may arise, because the river characteristics and ice problems themselves are very site specific and the optimization of operation rules requires experience and precision. The first step to consider is normally to analyse all the relevant information (water levels, water temperatures, pictures, satellite images, video cameras, technical reports, etc.) paying special attention to detrimental events from the past. Each site will have governing parameters and secondary parameters. Even though the solutions to specific problems can be trivial and applied rapidly in certain cases, models may be useful for a detailed analysis of some of the aspects. However, it is to be understood that the models require calibration with the use of measured data. In ice modelling, several different parameters may be needed to adjust one single variable that has an impact on other variables. The parameter adjustments should globally lead to the best answer, in average, for several cases. Models may also be used in some cases for ice cover formation forecast.

5.2 CRISSP MODELS AND SWIPS

The Center for Energy Advancement through Technology Innovation (CEATI International) is a user–driven organization committed to providing technology solutions to its electrical utility participants. This group developed the Comprehensive River Ice Simulation System Project (CRISSP software).

The CEATI website1 provides the following summary description for the product published in 2005:

> "The CRISSP1D program simulates ice processes in natural rivers including water temperature variation, frazil ice and anchor ice evolution, surface ice run, ice cover formation, surface and undercover ice transport and jam, thermal growth and decay of ice, and break up. The hydraulic model is a one-dimensional unsteady flow model, which can be applied to flows with or without ice. The model also takes into consideration of hydraulic structures.
>
> The CRISSP2D program simulates ice processes in natural rivers including water temperature variation, frazil ice and anchor ice evolution, surface ice run, ice cover formation, surface and undercover ice transport and jam, thermal growth and decay of ice, and break up. The hydrodynamic module provides finite-element simulation of two-dimensional unsteady flow model, which can be applied to flows with or without ice. A Lagrangian discrete parcel method with smoothed particle hydrodynamics is used to simulate the ice transport, which include the dynamics of surface ice motion and jamming."

These models are subject to fees and fall under the CEATI licensing, which limits the accessibility to the software as well as the number of its users. It is therefore very difficult to appreciate and understand all of the software's capabilities and using it to its full capacity and allowing it to evolve.

Nevertheless, Dr Hung Tao Shen, a professor since 1976 at Clarkson University who is a well-respected figure in hydraulics, ice research and modeling development, is among the authors of the CRISSP2D User's Manual (2005). His involvement on this project fortifies our confidence in the technical validity of the model.

Fortunately, the authors of this report were given permission by CEATI to access the technical documentation of the 1D and 2D models. It clearly shows that Dr Shen selected a good set of equations to cover a wide range of phenomena. The authors are also confident that the hydrodynamic model interacts correctly with the thermal and ice dynamics equations. But as mentioned above, most of the equations represent the phenomena in an approximate manner and still demand much calibration to better represent reality.

Some uses of the CRISSP programs have been reported in the literature. Bijeljanin and Clark, 2011, report a first step of implementation of CRISSP2D by the University of Manitoba for the section upstream of the Jenpeg plant. The project encompasses an area of 315 km2. Hydrodynamic calibration and verification were conducted on open water for 8 years and showed excellent model performance under all flow conditions. However, the available documentation indicates that only one ice module was tested and verified.

[1] http://www.ceati.com/publication-details?publicationid=5874

On the Peace River, the CRISSP1D model is used for forecasting (Jasek et al., 2011). BC Hydro reported its use for 5 years to support the decisions in changing the flows for ice management. BC Hydro's experience with the model is shared in the paper on page 249:

> "However, it is a challenge to quantify calibration parameters that effect ice production in the model. Thus far, these parameters are calibrated indirectly to match the progression rate of the leading edge of the ice cover, stage and ice thickness. However, a more direct measurement of ice production should provide better calibration coefficients. Direct measurements of ice production have been made on the Peace River with the Shallow Water Ice Profiling Sonar (SWIPS) although until recently these measurements were not easily quantifiable."

The paper discusses actions taken to improve the relationship between the SWIPS derived estimates from sonar data and the calibration of the CRISSP model parameters. The paper concludes that the ice front computed by the CRISSP model is pretty well consistent with the observed values. CRISSP and SWIPS obtained comparable estimates of pan drafts and surface ice concentration. However, this being said, CRISSP's derived value on suspended ice concentration greatly differed from the one derived from SWIPS.

We understand that some of the SWIPS sonar signal interpretations were still not perfect in 2013, but nevertheless SWIPS was a very useful tool on the Peace River. According to Buermans, Fissel and Kanwar, 2011, SWIPS uses the technology of the Ice Profile Sonar (IPS) which has been widely used in polar ocean regions since 1990. A device was developed for shallow rivers (from 2 to 20 m deep) and was introduced in 2004 on the Peace River to observe stationary or moving ice through the sonar field of view. Since that time it has been installed on several rivers. The device is installed at the bottom of the river and measures the pressure (water level), the water temperature, the moving ice thickness, the rate of ice run and the frazil ice concentration in the water. The system can easily identify the arrival and the breakup of the ice cover at the site where SWIPS is installed, this being an important factor for large rivers where access for inspection is difficult. Up until now, several SWIPS systems have been installed on the Peace River.

Other uses of the CRISSP2D model and of its evolution are described by Carson et al., 2007, and by Malenchak, Doering and Shen, 2011.

As per this report authors' opinion, versions 1D and 2D of CRISSP may be useful models, given the correct calibration of the numerous parameters for thermal and ice equations or criteria. They can be used to improve the operation guidelines, or in some cases as decision support tools to guide ice specialists.

SWISP is an interesting ice observation device. For ice control, the most used measurements are the water temperatures, water levels and visual observations from field inspections, cameras and satellite images. The SWIPS system provides water temperatures and water levels, drifting ice thickness and concentration, as well as a confirmation that the ice cover is formed in the water column at the device location. SWIPS gives a spot sample but it cannot replace all of the advantages of global visual observations. To evaluate the interest of using SWIPS at a particular site, its advantages would have to be compared to the costs of equipment, installation, maintenance, data transmission, etc.

5.3 THE MYKE-ICE SOFTWARE

The Myke-Ice software was developed jointly by Hydro-Quebec, the Lasalle Consulting Group and the Danish Hydraulic Institute. This 1D simulation software with pseudo 2D considerations for shore ice formation, has been used within Hydro-Quebec for new project developments and for operation studies for more than 7 years.

Theriault, Saucet and Taha, 2010, shows a summary description, a calibration case and an application of the Myke–Ice software. The model incorporates a large number of physical processes and simulates ice formation on a section of a river throughout the entire winter season. The model was calibrated with a very complete set of data obtained for two winters from the Peribonka power plant project built by Hydro-Quebec on the Peribonka River, in Quebec. The data includes numerous river cross sections, hourly flows, water temperatures and water levels at different points along the river. The extent of the ice cover came from 20 to 30 usable images generated by the NASA Modis satellite for each winter. Warm water flowed through the power plant at the upstream end of the section under study. After calibration, the results obtained for the position of the ice cover's leading edge and the measured water levels were correct. Theriault, 2011, and Theriault and Taha, 2013, present two applications of the Myke-Ice model as well as the calibration process and some of its limits.

Our analysis brings us to conclude that the features of the CRISSP1D and Myke-ICE model are quite similar.

5.4 HEC-RAS MODEL

Beltaos and Tang, 2013, present a brief description of the Hydrologic Engineering Centre's River Analysis System (HEC-RAS) from the US Army Corps of Engineers. This steady-state 1D model can calculate different ice conditions but is better known for its ability to study river ice jams.

6 Literature review

A comprehensive source for literature on the subject of this report is the Committee on River Ice Processes and the Environment (CRIPE) where the ice management community shares its information and findings. CRIPE is a sub-committee of the Hydrology Section of the Canadian Geophysical Union and is comprised of a group of engineers and specialists who all share an interest on river ice.

The CRIPE website[2] provides a list of references in addition to the proceedings from the group's 17 biannual workshops held since 1980.

A selection of these references from CRIPE pertaining to the subjects covered here appear at the end of this report in addition to other publications gathered elsewhere.

[2] http://www.cripe.ca/

7 Conclusion

Coping with river ice management practices is a very broad subject which this report summarized into two main chapters:

i) Ice control methods: Summary of the main methods available

ii) Ice control application cases showing that:

- The problems and the control methods are very site specific.
- The methods can be successful at several sites but also have limits. In operations, the no-risk decisions may be too costly or impossible to implement. Operations have the objective of minimizing the risk of error while taking into account all the uncertainties about the future.
- Knowledge from detrimental events that have occurred in the past contributes to a better understanding of future potential problems and of ice control. Data acquisition and archiving, analysis and documentation are imperative for the continuous improvement of the field.
- Ice control must consider many potentially conflicting objectives such as power generation, project mitigations, environment protection as well as human needs.
- In many cases, a large number of stakeholders are involved in the process and the actions taken may have impacts on several of them, be it in regular or emergency situations. Communication, mutual support and consensus are keys to the success of ice control.
- Numerical models may be very useful as long as they are adapted to each site and that the users are well aware that models are only a simplified representation of reality.
- The development of new technologies, whether numerical or physical, contribute to the improvement of ice control possibilities.

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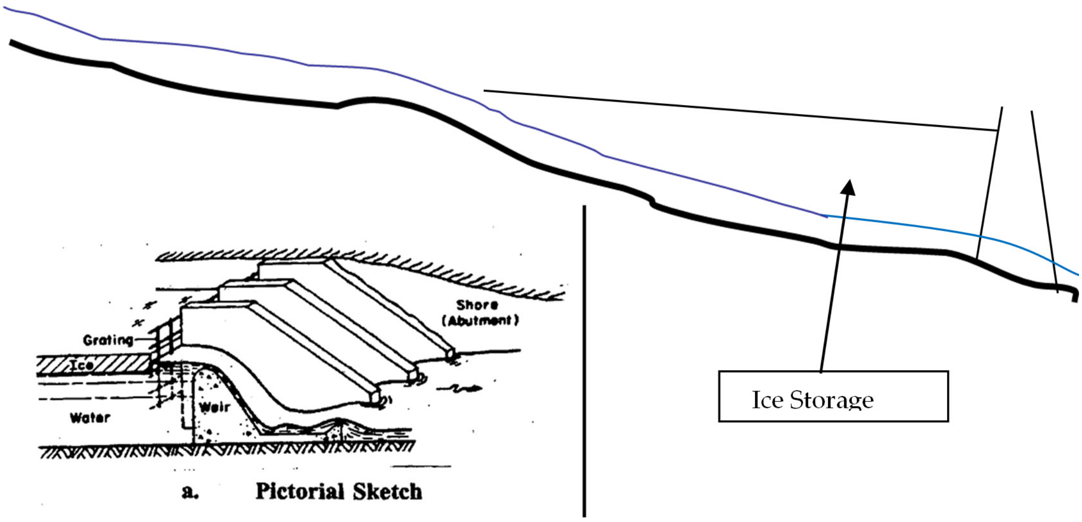
9 Figures

Figure 1

Examples of ice control dams

1.1 Sartigan ice storage structure

From Google Images



1.2 Larocque ice flushing dam

At the beginning of the spring breakup, a large
gate is opened and closed several times to force
the ice to pass over the adjacent long weir.
This prevents flooding along the river upstream.

Figure 2

Ice boom design steps and ice boom diagram

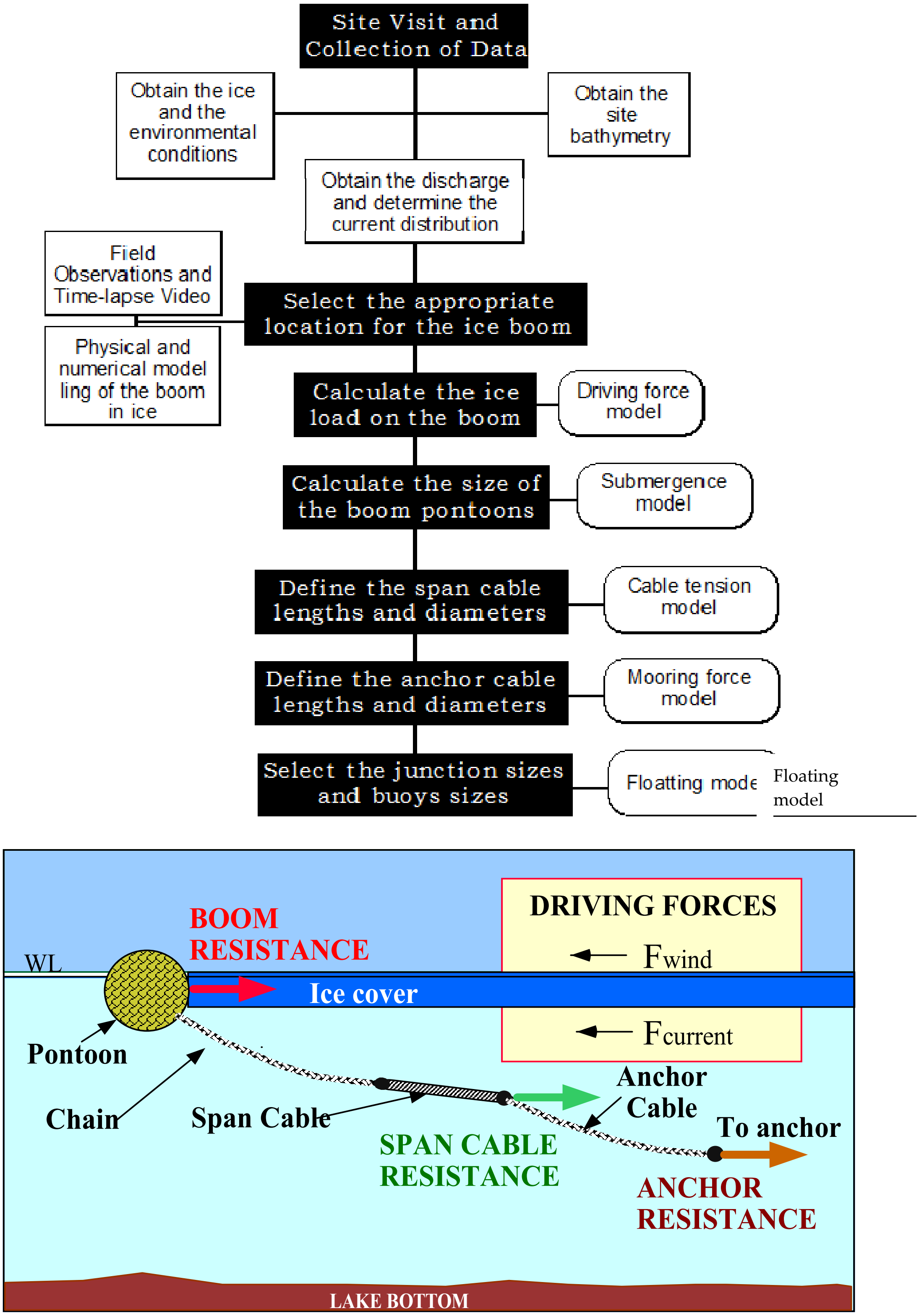


Figure 3

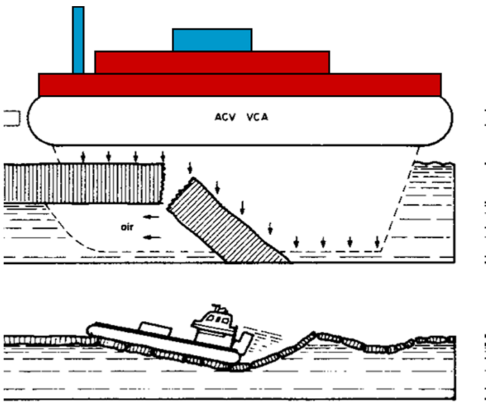
Ice boom upstream of the Rupert Diversion weir and tunnel

Figure 4

Icebreakers

4.1 Large CCGS icebreaker

4.2 CCGS hovercraft



4.3 a. and b. Riviere-des-Prairies dam icebreaker

4.4 OPG icebreaker, Niagara Falls

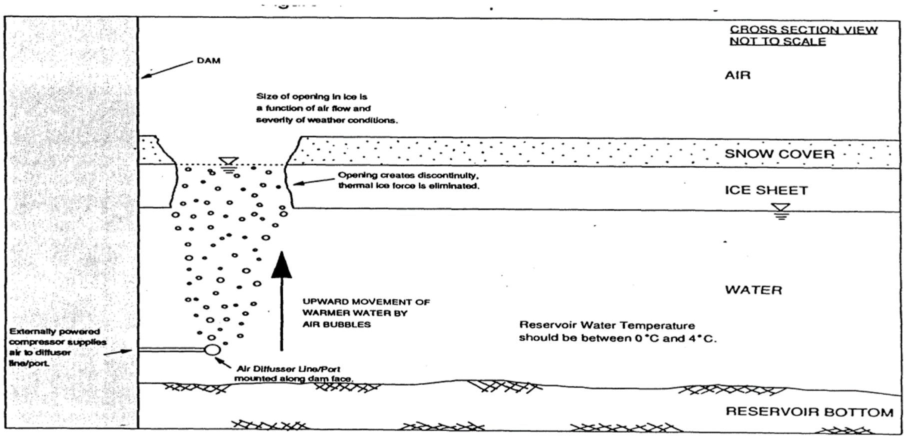
From http://globalnews.ca/news/1072555/canadian-u-s-ice-breakers-work-to-clear-ice-jam-in-niagara-river/

4.5 Amphibious hydraulic excavator

Figure 5

Air bubbler systems

5.1 Diagram of an air bubbler system

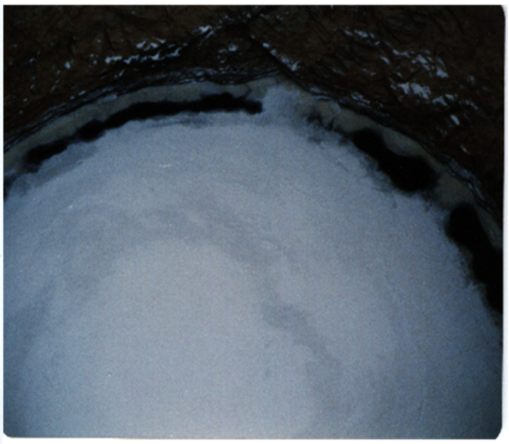


5.2 Bubbler system upstream of the Hemmings dam (Drummondville, Québec)

Bubbler system used to inhibit the static ice forces on a wall built on the top of the weir of Hemmings dam for the winter.

5.3 Chute-des Passes (Mont-Valin, Québec) air bubbler system

Bubbler system used along the walls of Chute-des-Passes surge tank to prevent the ice cover to seal the water surface and harm the operation of the surge tank



5.4 Anprior (Ontario) air bubbler system

Bubbler system integrated in Anprior gates to prevent ice formation upstream of the gate and prevent the static ice forces to push on the gate.

Figure 6

Device for municipal or industrial water intakes in frazil ice area

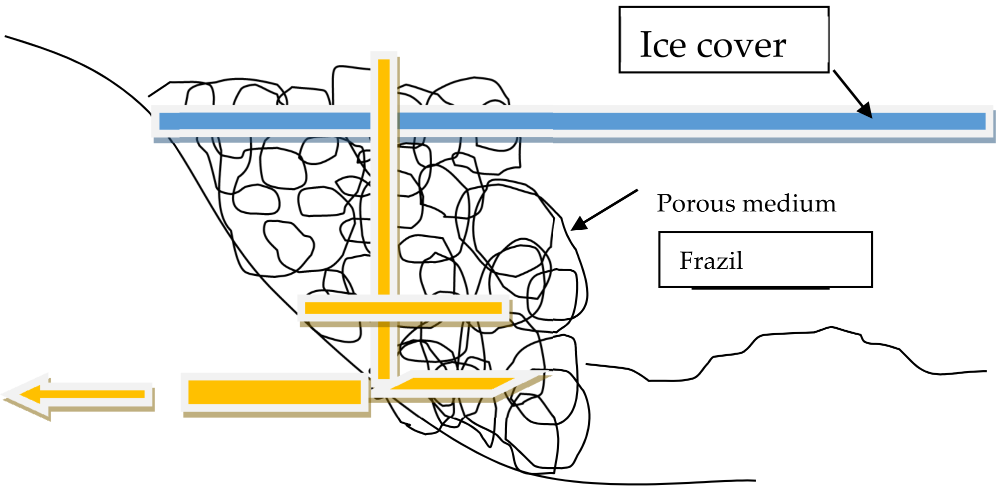


Figure 7

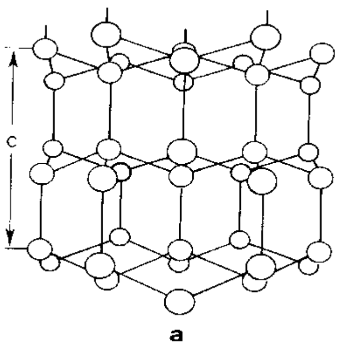
Winter operation of stop logs

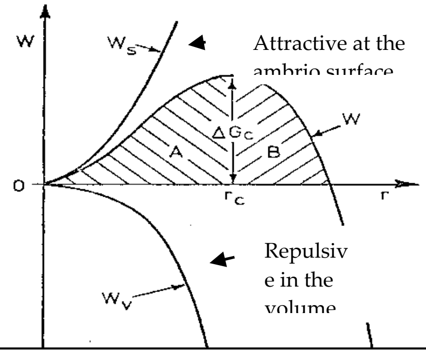
Example of the Ring Dam (Ottawa, Ontario)

Figure 8

Water supercooling - Technical aspects

8.1 Water supercooling and ice nucleation – how to form an ice crystal



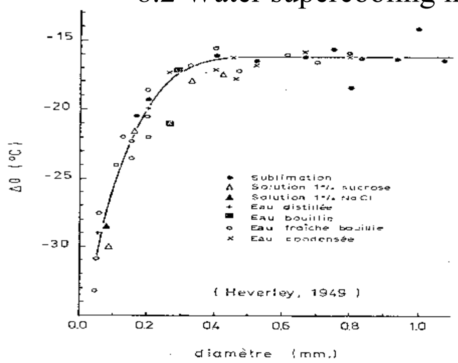


Ice crystal structure

To form an ice crystal, a random distribution of H_2O molecules must be transformed to a perfect tetrahedral molecules network.

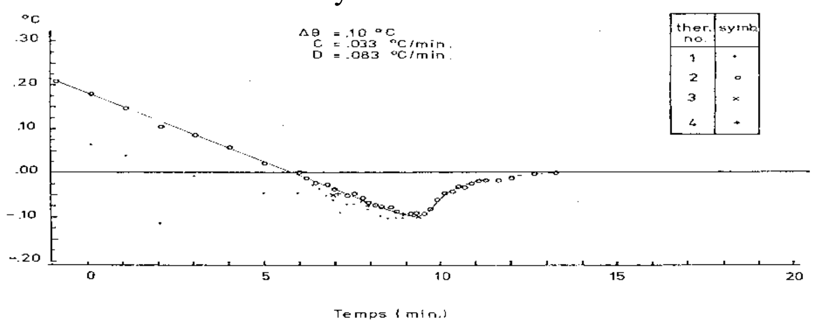
When a stable ice embryo is formed in the water mass, the attraction energy of the group of the H_2O molecules must be higher than the repulsion energy. In pure water, a stable embryo is obtained theoretically at -40 °C.

8.2 Water supercooling in the atmosphere



In the atmosphere, the water is never so pure. Impurities attract the H_2O molecules. Smaller diameter droplets have fewer impurities and have a greater tendency to cool.

8.3 Secondary ice nucleation in rivers



In rivers, the supercooling is only a few hundredths of °C. This is due to the fact that there are always ice particles in the water, coming from the cold air from the shores, for example. This ice inoculates the unstable ice embryos present in the water mass. This is the secondary nucleation process. At a given temperature, thousands of frazil disks appear and grow in the water mass and consequently the water warms. On this laboratory test, it happened at -0,1 °C. The water is clean and the rate of water cooling is fast. In rivers, the minimum temperature is rather around -0,04 to -0,06 °C.

Figure 9

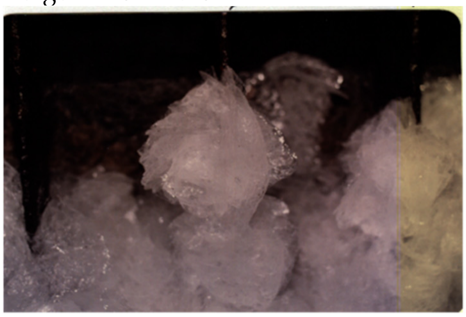
Active frazil ice and anchor ice examples

9.1 Ice deposit inside a power unit, on a stay vane blade

Ice deposit inside a power unit, on a stay vane blade.

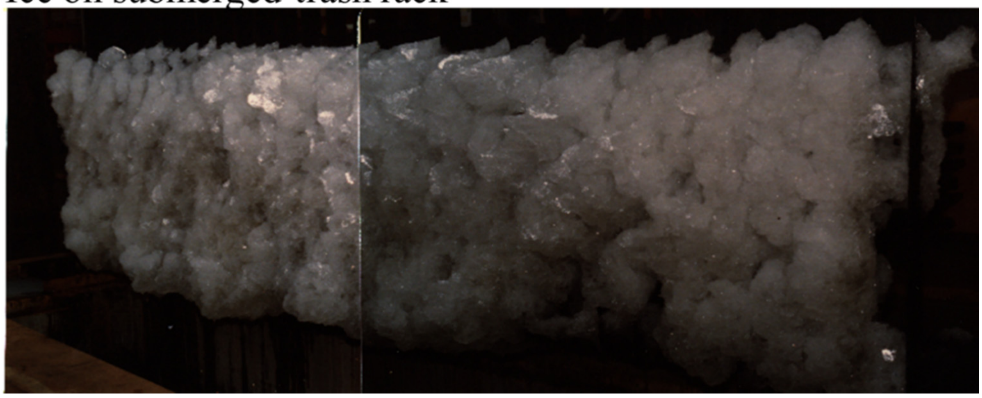
When the power produced by the unit drops, the operator opens and closes the wicket gates several times to break the ice and improve the machine production

9.2 Ice on bars and on submerged trash racks

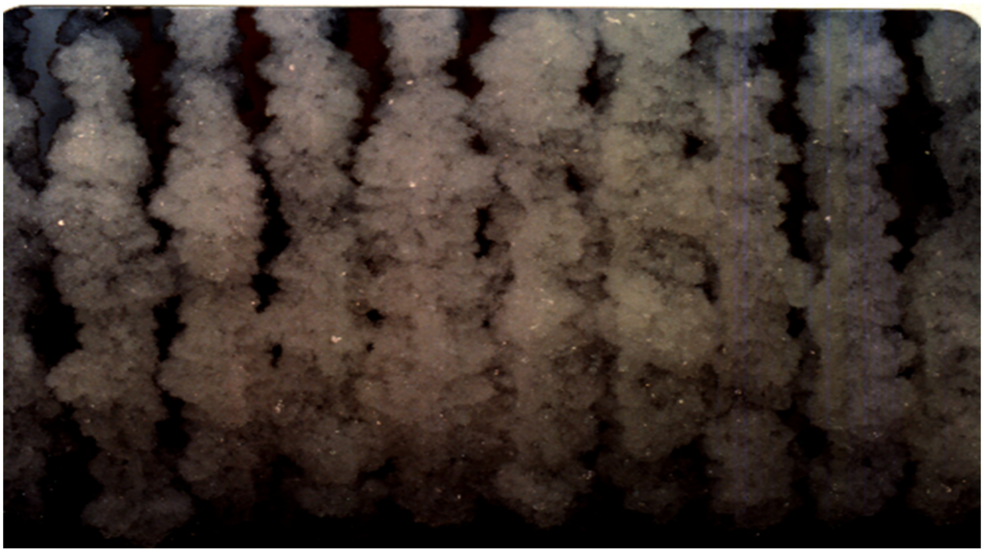


Ice on bars

Ice on submerged trash rack



9.3 a. and b. Ice formed on trash rack bars and zoom on a steel bar

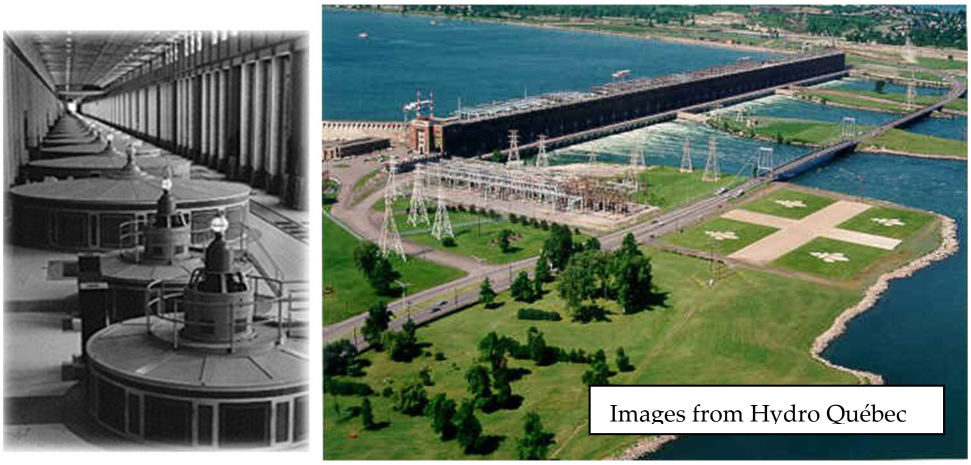


9.4 Anchor ice previously formed on the river bed rapids came adrift in the river flow.

Figure 10

Beauharnois-Les Cedres

10.1 Beauharnois power plant



Images from Hydro Québec

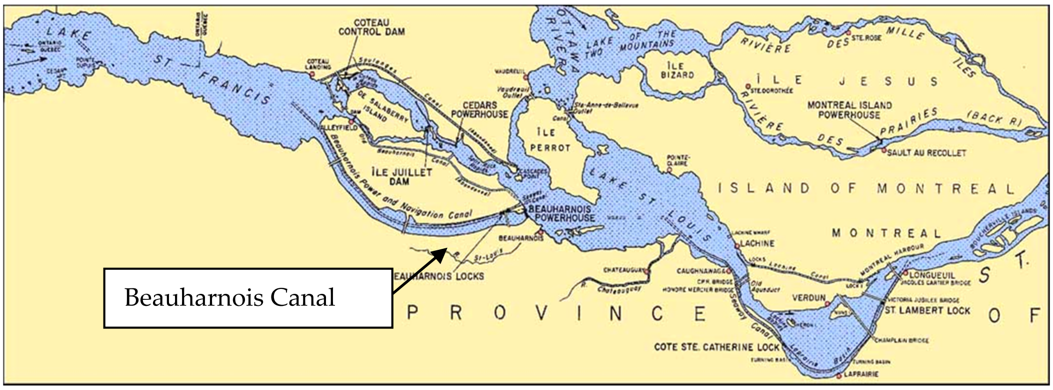
10.2 Les Cedres power plant

Image from Hydro Quebec

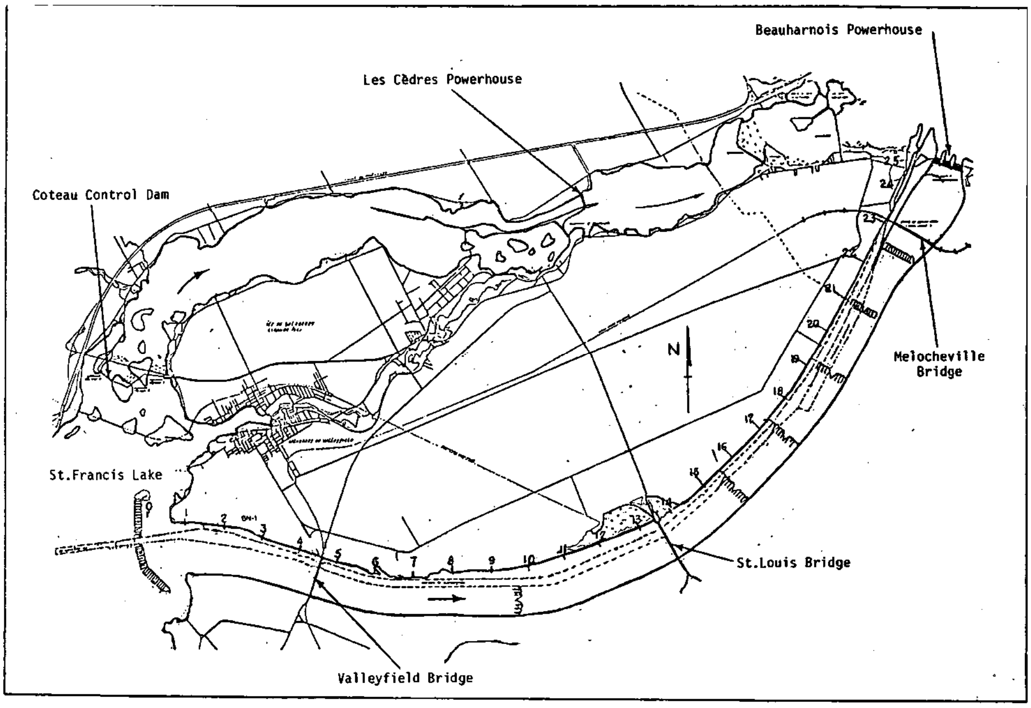
Figure 11

Location plan of the Beauharnois-Les Cedres complex

11.1 From Lake St. Francis to the Montreal Harbour



11.2 Beauharnois canal (south) and natural water course (north)



11.3 Ice entering the Beauharnois canal from Lake St. Francis

11.4 Damages to properties downstream of the Coteau dam

Images from Hydro Quebec

Figure 12

Ship retention boom upstream of the Beauharnois power plant

12.1 View of the expressway bridge upstream of the Beauharnois power plant

Image from the St. Lawrence Seaway

12.2 Location plan of the highway bridge (downstream), the km 23 ice boom (100 m upstream) and the ship barrier (450 m upstream of the bridge). On the right hand side, the Beauharnois shipping lock.

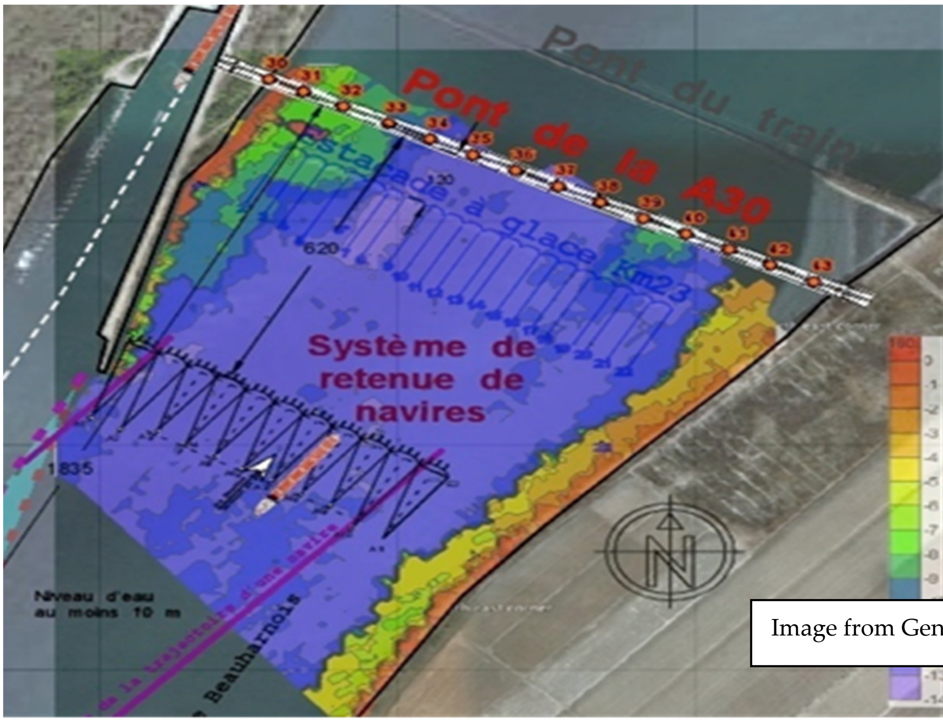


Image from Geniglace

12.3 Pontoons of the ship retention boom – summer and winter

Image from Geniglace

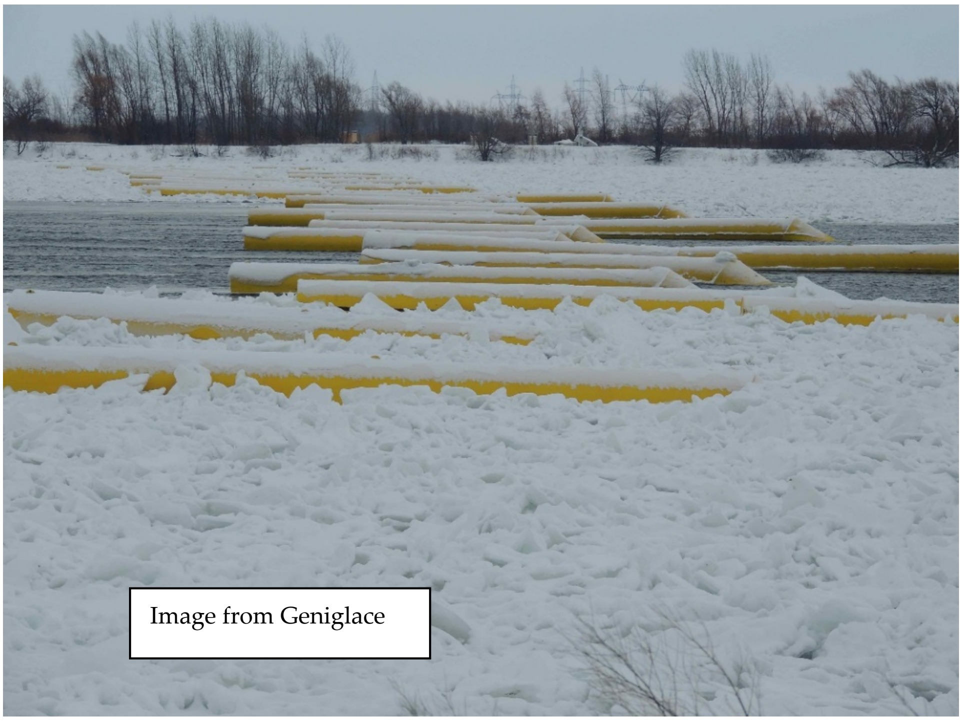


Image from Geniglace

Figure 13

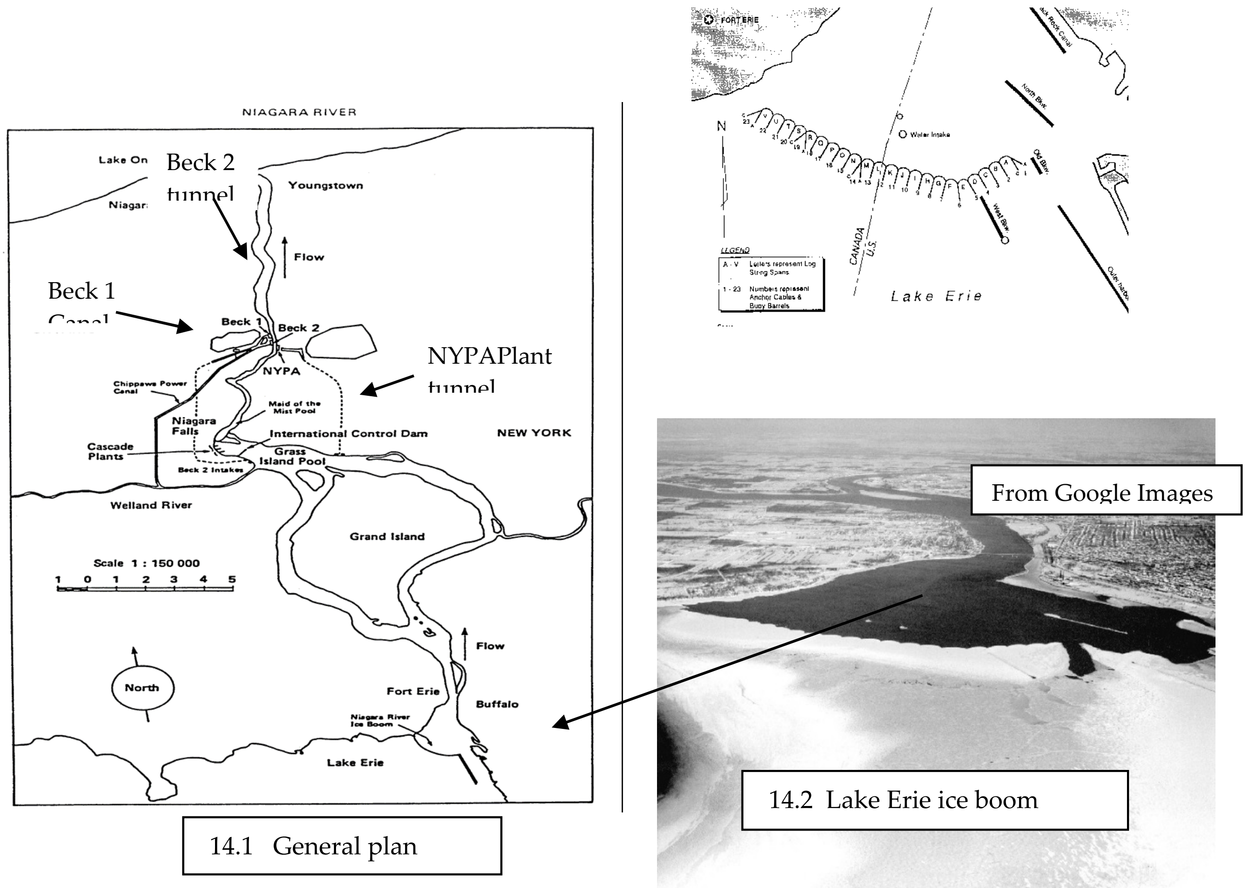
Moses-Saunders power plant and Iroquois Dam

13.1 Moses-Saunders power plant

13.2 Iroquois Dam

Figure 14

Ice control in the Niagara River system



14.1 General plan

14.2 Lake Erie ice boom

14.3 Control Dam with submerged gates that allow ice passing.

On the left side, 3 gates drain the passing ice along the submerged water intakes. Downstream of the intakes, tunnels and canals get the water to the generating plants downstream of the Niagara Falls.

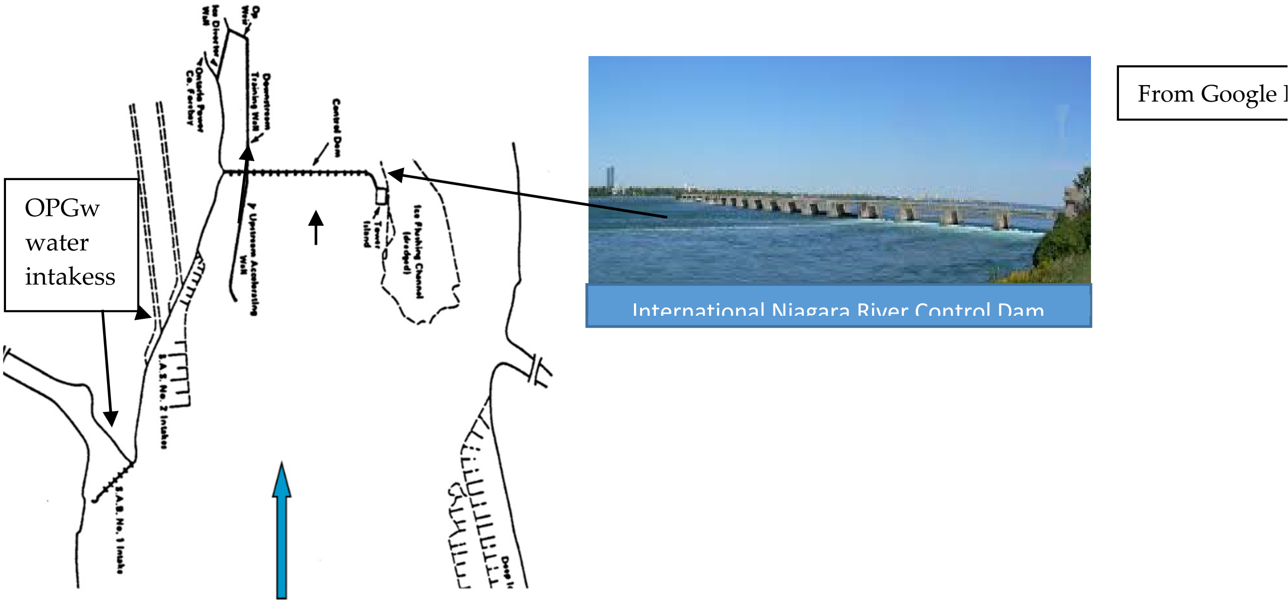


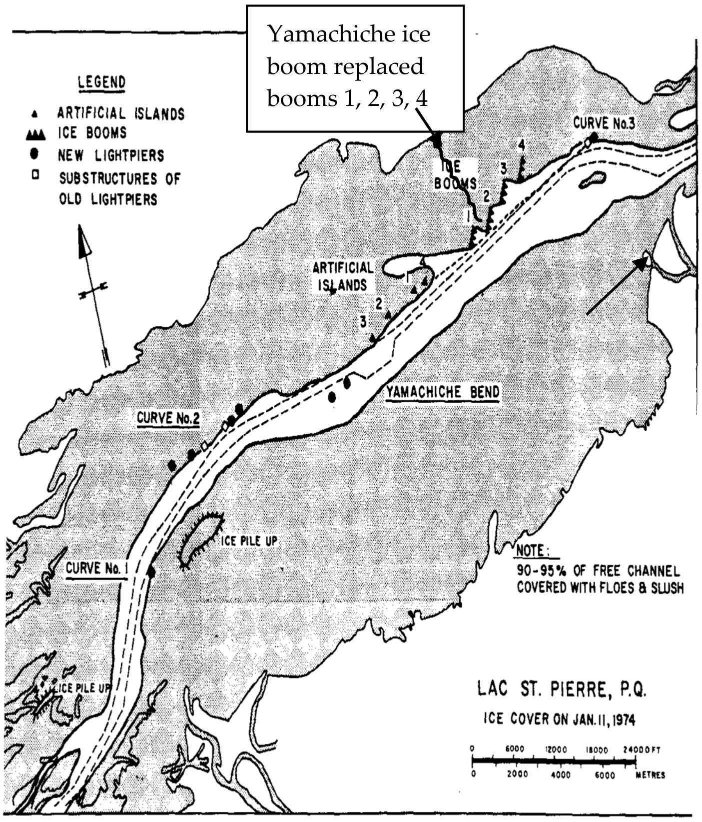
Figure 15

Ice control on the lower St. Lawrence River, between Montreal

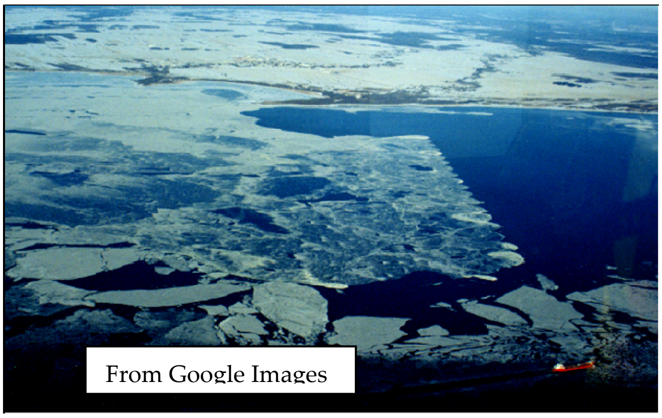
and Lake St. Pierre

15.1 Fixed ice boom upstream of Champlain Bridge, Montreal

15.2 General plan of the ice control works on Lake St. Pierre



15.3 Yamachiche ice boom



15.4 Plans of artificial islands

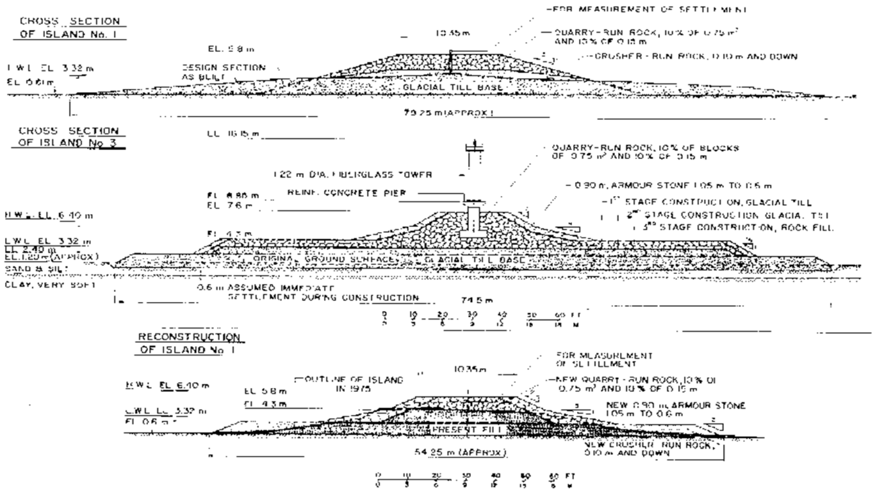
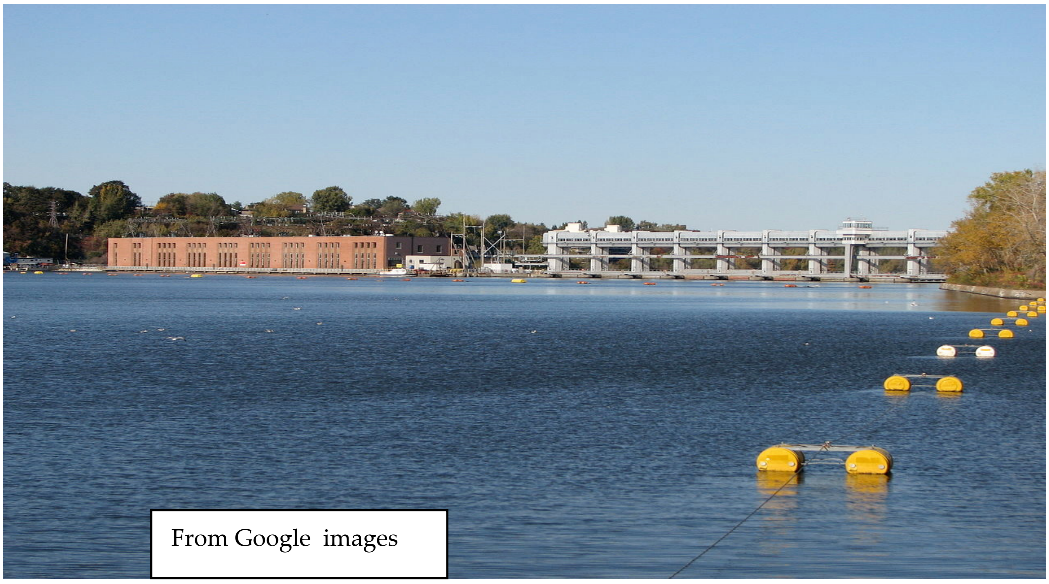


Fig. 10 Cross sections of artificial islands: island 1 "as designed" and "as built", island 3 as designed and built, island 1 redesigned for reconstruction.

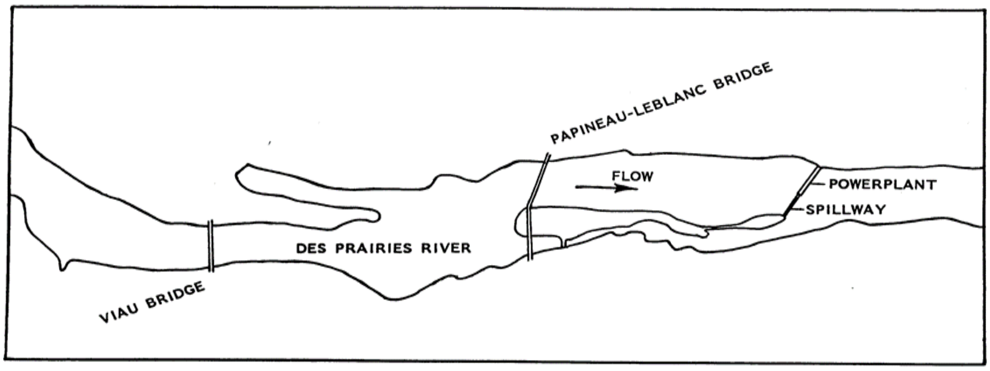
Figure 16

Ice Control at Riviere-des-Prairies (Montreal, Quebec)

16.1 Upstream view



16.2 Plan view of the forebay



16.3 River profile

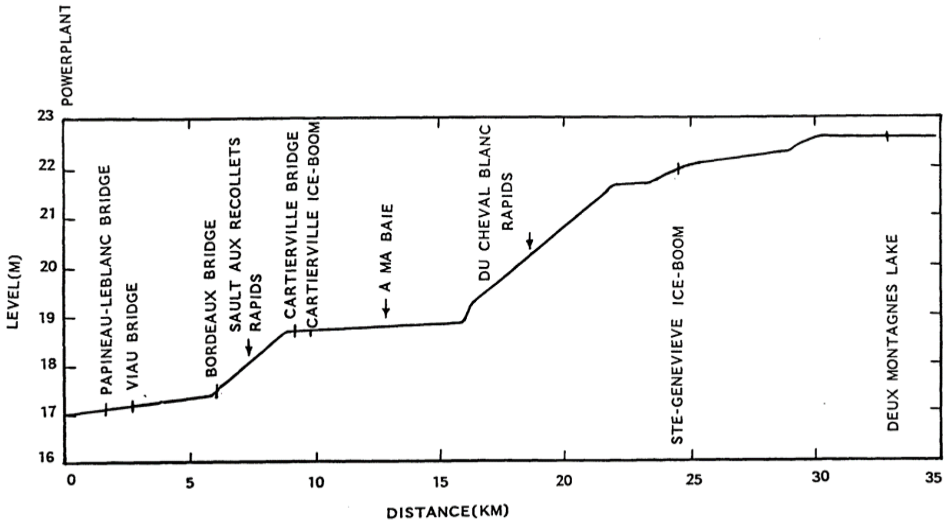


Figure 17

Rivière-des-Prairies - Exceptional flood of 2003-2004 winter

17.1 Global view of the river ice jam, the rapid free water surface section and the ice cover upstream on January 17th, 2004

17.2 Evidence of a water level drop of 1,5 m over a distance of 15 m, seen from the south shore on January 28th, 2004

17.3 Front leading edge of the ice jam channel being made in the ice near the right shore on February 2nd, 2004

17.4 Two large power shovels on a barge to make a channel in the ice on February 2nd, 2004

17.5 Snow dyke made to prevent the river water to flood the road; the snow was transported and compacted with a snow blower; February 2nd, 2014

Figure 18

Ice control at Hull 2 power plant

18.1 Forebay before the ice boom installation

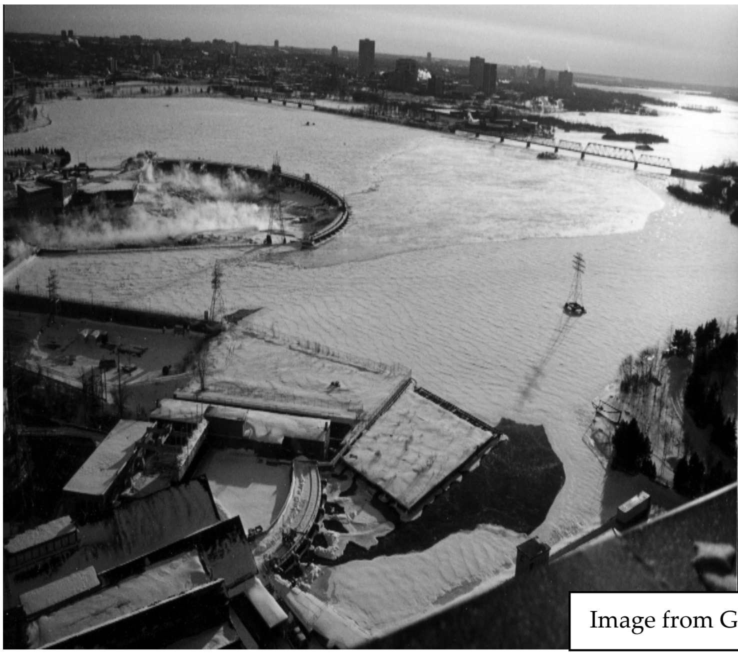


Image from Geniglace

18.2 Mechanical rake to break the frazil and clean the trash racks

18.3 Forebay after the ice boom installation

18.4 Steel pipe pontoons

Figure 19

Jenpeg power plant and Lake Winnipeg Regulation project

19.1 Jenpeg power plant and control dam

19.2 Lake Winnipeg Regulation project map

From Google Images

RIVER ICE MANAGEMENT IN NORTH AMERICA

This report describes the most used ice control practices applied to hydroelectric generation in North America, with a special emphasis on practical considerations.

The subjects covered include the control of ice cover formation and decay, ice jamming, frazil ice at the water intakes, and their impact on the optimization of power generation and on the riparians.

A selected number of North American practical cases are documented.