CHAPTER 3
Ice Control for Flood Damage Reduction and Hydropower Operation

Section I
Nonstructural Ice Control

3-1. Introduction

a. Nonstructural ice control encompasses methods for reducing the frequency and severity of damages from ice jams without use of a structure placed in the river. These were the first measures employed to prevent and breakup ice jams. For example, as early as 1758, blasting was used in Germany to remove ice jams (Van der Kley 1965), and icebreaking vessels were used to break river ice starting in the 1880s (Bolsenga 1968). Nonstructural ice control methods are attractive because they are generally inexpensive and can be applied using readily available equipment and supplies (e.g., chainsaws, trenchers, crop dusters, etc.). Also, these methods are popular because of the perception that they can be applied on short notice; of course, the best results are obtained with advance planning, because obtaining the necessary permits and equipment, and training of personnel, requires a considerable amount of time. Furthermore, the basic concept of not placing a structure into the river has appeal, as it does not create an obstacle for navigation, restrict recreational activity, or change stream habitat. Most of the work that has been done in this area has concentrated on weakening or destroying the ice cover in advance of ice jam formation. However, some nonstructural methods have been used to breach ice jams.

b. At locations that frequently experience ice jam flooding, measures can be applied in advance to reduce or eliminate the risk of ice jam formation. Most often these methods are targeted at weakening, breaking, or eliminating the ice in the problem reach. For example, at a river confluence, stable ice that has formed in the main stem may block ice released from the tributary, thereby initiating an ice jam at the confluence. In this case weakening or removing the ice in the main stem may reduce the likelihood of a jam forming at the confluence. There are three basic mechanisms that have been used for weakening or destroying ice: mechanical, thermal, and chemical. These may be used separately or in concert to provide the desired result.

3-2. Mechanical Measures to Reduce the Risk of Ice Jam Formation. Generally, mechanical measures weaken or remove the ice cover through machining or fracturing the ice so that the remaining cover has little or no structural integrity. Subsequently, the ice may be left in place to melt, removed by natural river flow, or conveyed out of the river via another mechanical system. Below is a summary of the various mechanical measures used.

a. Ice Cutting. It is unclear when the cutting of river ice to reduce ice jam threat first started. The earliest efforts employed the same equipment that was used originally for harvesting ice for refrigeration. More recently, the blocks were cut using gas-engine-driven circular saws (Deugo 1973). The intent of ice cutting is to hasten the release of ice in jam-prone river reaches, such as bends, slope changes, or confluences. An approach frequently used is to cut the ice free from the banks and cut crossing patterns in the ice so that it breaks into pieces that are half the river width or less (Jolicoeur et al. 1984). The efficiency and efficacy of cutting ice have improved with the advent of modern mining and ditch digging equipment. The details of cutter design are beyond the scope of this work. The focus will therefore be on the performance of available cutting machinery, such as cutting rates, and the effectiveness of various ice cutting strategies for preventing or mitigating ice jam formation.

(1) Aleinikov et al. (1974) explored cutting ice to stop an ice jam from forming at the confluence of a river and the reservoir of a hydroelectric dam in Siberia. The river width in this reach was 180–230 meters (590–755 feet). The cutting operation was started about 1 month prior to normal breakup. First, a 7-kilometer (4.3-mile) slot was cut in the 1- to 1.2-meter (3- to 4-foot) thick ice at the center line of the channel, starting from the upstream end of the backwater and proceeding downstream to within 500 meters (1640 feet) of the downstream edge of the reservoir ice cover. Then, transverse slots were cut almost bank to bank at a spacing of 30–60 meters (100–200 feet). Finally, discontinuous slots were cut along both banks. This pattern yielded rectangular ice pieces that were about half of the river width long and about a quarter or less of the river width wide. The transverse slots did not connect to the slots along the bank, which prevented the ice from moving during the cutting operation. About 10 days after the cutting operation was completed, the water in the reservoir was drawn down 1 meter (3 feet) to break up the remaining tendons of ice. Then, just before a forecasted ice breakup event, the reservoir level was returned to the normal pool elevation. This operation successfully caused the ice in the problem reach to release 1–2 days before breakup of the upstream ice. Consequently, the upstream ice was deposited into an ice-free reservoir, rather than jamming at the head of the backwater. In 1972 the ice released 15 hours prior to the spring ice run, while in 1973 it released 2 days prior.

(2) Jolicoeur et al. (1984) examined the use of various trenching patterns in a river meander to prevent ice jam formation, and several patterns were tried that spanned the 36-meter (120-foot) river width (Figure 3-1). The test reach was approximately 600 meters (2000 feet) long. They found that any pattern that crosses from bank to bank was effective, though the herringbone pattern (pattern 1) broke into the smallest ice pieces. In contrast, simply cutting slots parallel to the bank (pattern 6) did not assure breakup of the ice cover. The resulting long, thin ice floes moved intact into the river bend and halted there.

(3) In Finland an extensive ice cutting operation is carried out annually on rivers and lakes to reduce ice jam flooding and damages associated with spring breakup. The cutting operation is done 2–3 weeks prior to the anticipated spring runoff period. Generally, the ice is cut to within 10 centimeters (4 inches) or so of its full thickness, leaving the ice cover semi-intact. This remaining ice melts out and easily breaks up during the subsequent warm weather and rising water. On rivers, slots are cut along each bank. In bends the ice is also cut in a herringbone pattern across the full river width. On lakes, large sections of the ice near the river mouth are cut into herring-bone patterns to allow sections of the lake ice cover to collapse upon arrival of the surge of water and ice from the source river. On one lake inlet, a 300-meter-wide × 10-kilometer-long (1000-foot-wide × 6-mile-long) section of the ice cover was cut to allow storage for ice from the feeding river.

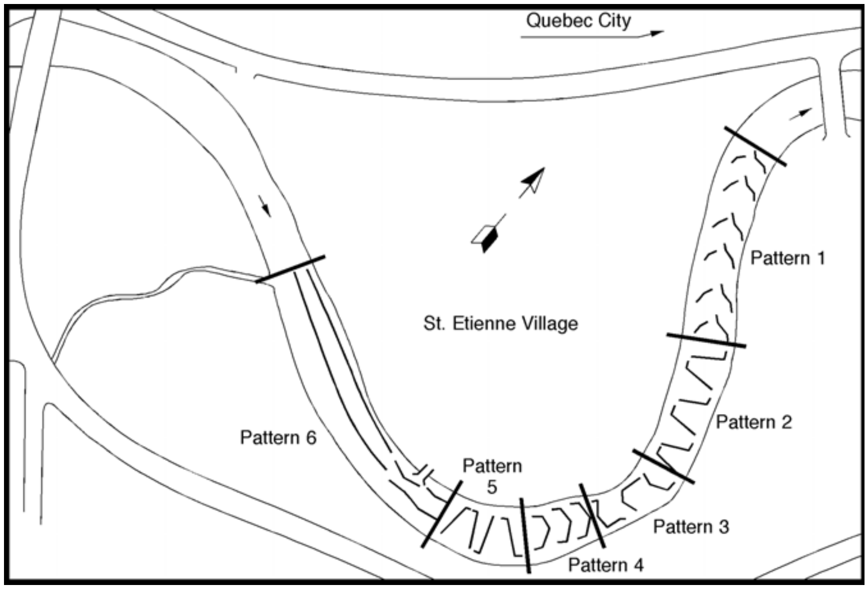


Figure 3-1. Trench patterns cut in the Beaurivarge River, Canada (after Jolicoeur et al. 1984).

(4) Ice cutting requires deployment of personnel and equipment onto the ice cover, so unless amphibious vehicles are used, the trenches need to be cut while the ice is still thick and strong. This usually requires that the operation be carried out about a month prior to the expected ice breakup period, when the probability for ice release is still very low. The width of the slot must be sufficient to prevent freeze back. Usually, widths of 10–15 centimeters (4–6 inches) are adequate.

(5) The type of equipment used to cut ice is a major consideration in such an operation. Some of the types of machinery used to cut ice include trenchers, ice plows, water jet and thermal cutters, and specially designed amphibious cutters.

b. Trenchers.

(1) Trenchers are customarily used for digging ditches in soil for laying cable and piping (Figure 3-2). Several types of these have been used without modification. Cutting depths range from 0.6 to 1.2 meters (2 to 4 feet) and trench widths typically vary from 10 to 15 centimeters (4–6 inches). Equipment varies in weight from small walk-behind trenchers (300 kilograms [660 pounds]) to four-wheel-drive and tracked trenchers (2000 to over 10,000 kilograms [4410 to 22,050 pounds]). The choice of the trencher will depend on the thickness and bearing capacity of the ice cover. Jolicoeur et al. (1984) used a Case™ DH4 trencher that weighs about 2600 kilograms (5733 pounds) and has a cutter width of 15 centimeters (6 inches). This four-wheel-drive trencher travels easily on ice that is covered by up to 30 centimeters (6 inches) of snow, and it cut 50 centimeters (20 inches) of ice at a speed of up to 8 m/min (25 ft/min). This trencher took about 8 hours to cut all of the patterns shown in Figure 3-1.

a. Case 750.

b. Ditchwitch 1260 cutting ice in Montpelier, Vermont.

Figure 3-2. Trenching equipment.

(2) During the spring of 1994, a walk-behind, self-propelled Ditchwitch™ 1620 trencher was used at Montpelier, Vermont (Figure 3-2b). This model features a hydraulically actuated cutting boom that reduced the effort to start a cut in the sheet ice and retract the cutting boom from the trench. The cutting boom was fitted with a carbide toothed Shark Chain™, which is designed for cutting hard, rocky, and frosted ground. The 1620 weighs about 600 kilograms (1320 pounds) and has a cutter width of 10 centimeters (4 inches) (kerf width of about 12 centimeters [4.5 inches]). Even with tire chains this trencher could not propel itself through the 15 centimeters (6 inches) of snow on the ice cover, so a path for the trencher was cleared in the snow using a snowblower. This operation required about 12–16 hours to cut approximately 1 lineal kilometer (1/2 mile) of trenches in the ice.

c. Special Design Trenching Equipment. The ice cutting operation on the Siberian reservoir described earlier was accomplished using a specially built trencher developed by Gorki Polytechnic Institute (GPI) (Aleinikov et al. 1974). This 86-kilowatt (115-horsepower), 4300-kilogram (9500-pound) amphibious vehicle was propelled by a twin Archimedean screw drive. The two screws were large, tapered cylindrical pontoons with helixes on the outside. The screws were mounted one on either side of the chassis, giving the vehicle the appearance of a small pontoon boat, with the screws providing flotation if necessary. Forward propulsion was achieved by rotating the screws in unison. Turning was achieved—as with tracked vehicles—using skid steer. The vehicle cut 0.6- to 0.8-centimeter (about 0.3-inch) thick ice at about 0.15–0.21 km/hr (0.9–0.1 mph).

(1) The ICESAW—a 168-kilowatt (225 horsepower), 7.3-tonne (8-ton) tracked amphibious vehicle built by Mobimar Ltd. in Finland (Figure 3-3)—was developed in cooperation with the Finnish government to help reduce ice jam flooding. It was developed to replace more costly methods, such as icebreaking, blasting, and dusting. It has a retractable circular saw that will cut through ice as thick as 1.2 meters (4 feet) in a single pass at speeds of 0.5–1 km/hr (0.3–0.6 mph). There is only one of these in existence, and it has been used extensively in Finland since the early 1990s to relieve ice jam flooding on both rivers and lakes. It is capable of cutting a 300-meter-wide × 10-kilometer-long (1000-foot-wide × 6-mile-long) section of ice at a lake inlet in about 8 hours. In the spring of 1996, it was used to cut over 146 lineal kilometers (90 miles) of trenches on nine rivers in Finland.

Figure 3-3. ICESAW used for cutting river ice (photo courtesy of Mobimar, Ltd.).

(2) The Finnish built Watermaster™ and Canadian built Amphibex™ are similarly designed amphibious excavators that have been used for ice control. They have an ice cutter attachment, a circular saw that bolts to the back, which will cut up to 0.5-meter (1.6-foot) thick ice at a rate 0.37 km/hr (0.2 mph). These amphibious excavators have also be used to break ice (see Figure 3-11) and have been used extensively in Canada on rivers around the St. Lawrence Seaway.

(3) The Aquaglace ice trencher was used to cut ice on the Beaurivage River in 1986 (Belore et al. 1990). This is essentially a conventional walk-behind soil trencher fitted with flotation pontoons to prevent its loss when operating on thinner ice.

d. Channeling Plow.

(1) Tsykin (1970, 1982) describes an ice channeling plow, used in the former Soviet Union, to cut triangular furrows in an sheet ice. The plow is mounted on a sledge (Figure 3-4a) and drawn by a tractor. The broken ice is cleared from the channel with a small clearing wedge (not shown). Typically, the mode of operation with the plow is to cut a channel about two-thirds the depth of the ice cover. This channel then fills with water, and quite often a skim covering of ice forms on the water surface. The skim ice stops evaporative cooling of the water, yet still allows

solar energy to warm the water. The addition of solar energy causes convection cells to be set up in the channel (Figure 3-4b), which melt the remaining ice at the bottom of the channel. The ice at the bottom of the channel melts out even if there is no skim ice covering the water, but at a slower rate.

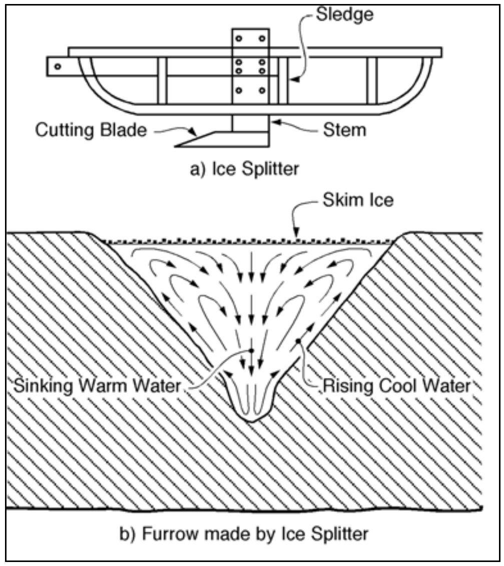


Figure 3-4. Ice channeling plow developed by Tyskin (1970).

(2) The tractive or drawbar force, *P*, required to pull the plow through the ice as a function of cutting depth, *H*, was determined empirically by Tsykin and is

$$P(\text{kg}) = 984 - 105.7\,H + 7.08\,H^2 - 0.071\,H^3 \qquad (3\text{-}1)$$

where *H* is in centimeters. The plow requires about 47 kilonewtons (10,500 pounds) of tractive force to be drawn at its maximum cutting depth of 0.6 meters (2 feet). A 180-kilowatt (250 horsepower) Soviet GT-90 amphibious tractor, weighing about 9000 kg (20,000 pounds), was used to cut channels to a depth of 0.35 meters (1.15 feet) at a rate of 12–15 km/hr (7–9 mph) (Tsykin 1982). Conventional tractors rated at 150–190 kilowatts (200–255 horsepower) can weigh as much as 20,000–26,000 kilograms (45,000–58,000 pounds), which would require an ice thickness of at least 0.6 to 0.7 meters (2 to 2.25 feet) to carry such vehicles. On rivers, where the ice thickness can be highly variable, it would not be advisable to put such heavy equipment on the ice, even if the nominal ice thickness were sufficient to carry the weight. However, in areas where the ice is of uniform thickness, such as lakes and backwater regions, it may be safe to deploy such equipment, provided the ice thickness is sufficient and the operation is carried out early in the spring when average air temperatures are still well below freezing. As an alternative to putting heavy equipment on the ice, the plow could also be drawn by a truck-mounted winch located on the river bank. Tsykin (1982) also describes using shipboard winches and towboats to draw the channeling plow through the ice to weaken the ice cover in advance of icebreakers.

e. Water Jet and Thermal Cutting.

(1) Though water jet and thermal cutting have not been used extensively to cut ice, included is a brief discussion of the technology as it applies to floating ice. Water jet cutting is accomplished by pressurizing water to 100 MPa (14,500 psi) or more and discharging it through a small nozzle. This supersonic water stream can be used to cut rubber, cloth, and food products. With the addition of an aggregate to the water, the jet can be used to cut common metals, such as aluminum and steel. Calkins and Mellor (1976) describe the use of a water jet, without aggregate, to cut both dry and floating ice ("dry ice" in this instance is referring to ice that is not in or floating on water). They were able to cut 0.9-meter-thick (3-foot-thick) dry ice at a rate of 2.3 m/min (7.5 ft/min) for a total of 0.01 m^3/min (0.35 ft^3/min) of ice removed. The ice removal rate for floating ice was about the same as or better than that for dry ice (0.01–0.03 m^3/min) (0.35–1.06 ft^3/min), yet the jet could not cut much deeper than 15–17 centimeters (6–7 inches), because the water quickly disperses the energy of the jet, making full penetration of thick ice on a single pass impossible. Another drawback of using a water jet to cut ice is that it has a kerf width of only 0.5–1 centimeters (0.2–0.4 inches), which quickly freezes back.

(2) Bojun and Si (1990) developed a specially designed steam jet (designated BRQ10-2) for cutting sheet ice in front of dam piers and gates. The BRQ10-2 produces dry, saturated steam, which is delivered at 0.5 to 0.6 MPa (72.5 to 87.0 psi) through a handheld wand. The wand is fitted with either a single nozzle, or a manifold with as many as 34 nozzles. This design is capable of cutting a 15- to 20-centimeter-wide (6- to 8-inch-wide) slot in the ice with an ice removal rate of about 0.002 to 0.003 m^3/min (0.07 to 0.10 ft^3/min). It is interesting to note that the specific energy (amount of energy required to remove a unit ice volume) of this operation is about 34 MJ/m^3 (915.0 Btu/ft^3). By comparison, simple melting of the ice requires about 300 MJ/m^3 (8190.0 Btu/ft^3). This nine-fold increase in cutting efficiency of the BRQ10-2 suggests that the steam jet is not melting the ice, but is eroding the ice from the jet velocity.

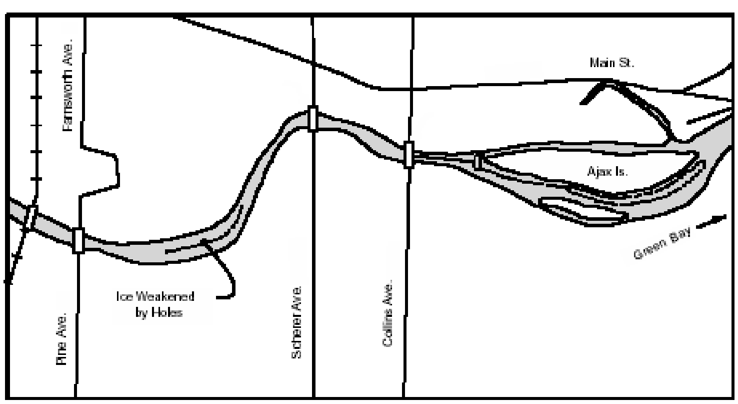
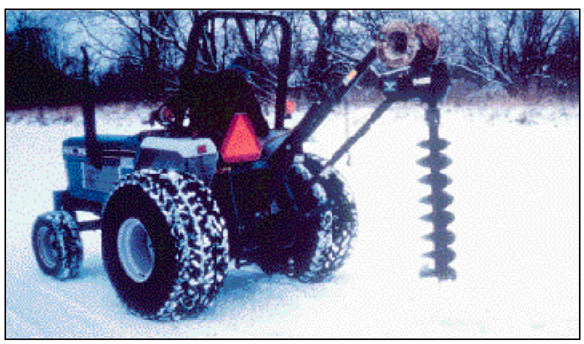


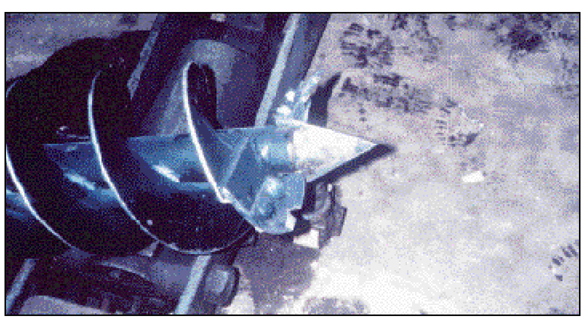
Figure 3-5. Hole drilling operations on the Oconto River at Oconto, Wisconsin.

f. Hole Cutting. Holes cut in the ice cover can be used to reduce the integrity of the cover and curtail ice jam formation. Holes can be created by a variety of methods, such as ice augers, posthole diggers, thermal drilling equipment, and explosives. Typically, the holes are cut about 1 month prior to the ice-out date. Holes on the order of 20 centimeters (8 inches) or more in diameter appear to be sufficient to prevent freeze-back during early spring.

(1) Hole drilling operations have been carried out since 1989 to alleviate ice jamming and flooding at the confluence of the Oconto River and the Green Bay in the city of Oconto, Wisconsin (Figure 3-5). In 1989 holes were cut around bridge piers, islands, and river bends (indicated by the dashed lines in Figure 3-5) to create shear lines for the ice to fail along. Although this severely weakened the ice along these lines, an ice jam still formed at Ajax Island that had to be removed using blasting. In 1991 a combination of trenching and hole drilling was used to weaken the ice, with the result being that no ice jam occurred that spring. In 1992 the city of Oconto started weakening ice by drilling 22-centimeter-diameter (8.5-inch-diameter) holes in the ice cover from the railroad bridge to the bay, a distance of about 5 kilometers (3 miles) (see Figure 3-5). A posthole digger mounted on the back of a lawn and garden tractor (Figure 3-6a) was used to drill the middle third of the river. Holes were spaced about 2.4–3 meters (8–9 feet) apart (Figure 3-7). Although the unmodified posthole digger was a great improvement over hand-held ice augers, the cutting speed of the auger was improved significantly by replacing the stock auger tip with a spade tip (Figure 3-6b), which allowed cutting 150 to 200 holes per hour in the 35- to 40-centimeter-thick (14- to 16-inch-thick) ice cover. The entire operation takes about 2 weeks and costs about $2000 annually. Since 1991, when the city of Oconto began employing this method, ice jams have not formed on that stretch of the river.



a. Posthole digger mounted on tractor.



b. Close-up of the modified auger tip.

Figure 3-6. Equipment used for drilling holes in the Oconto River.

Figure 3-7. Holes drilled in the Oconto River ice cover at the upstream end of Ajax Island.

(2) Moor and Watson (1971) used small explosive charges to create a line of holes in the ice cover along which the ice would fail. In this case two sticks of ditching powder were packed in 3.8-centimeter-diameter (1.5-inch-diameter) holes. The resulting holes were 1.7 meters (5.5 feet) in diameter. Smaller holes could be cut using shaped charges (Mellor 1986). Hot water drills have been used for cutting holes ranging from 0.1–1 meters (0.3–3 feet) in diameter and can penetrate ice as thick as 2 meters (6.5 feet) or more (Francois 1984, Echert and Kollé 1986).

(3) The holes appear to not only mechanically weaken the ice cover, but can also cause localized melting of the ice cover in the vicinity of the hole. This is shown schematically in Figure 3-8. The initial drilled hole has straight sides, as indicated by profile 1 in Figure 3-8. Over time, the ice below the water line melts back away from the hole, as indicated by profiles 2 and 3. Similar observations were made in the laboratory (Haehnel et al. 1999). Figure 3-9 shows the observed melt pattern around a 2.54-centimeter-diameter (1-inch-diameter) hole drilled through an ice cover floating in the CRREL refrigerated flume. Haehnel et al. (1999) showed that this increased melting around the hole is caused by local modification of the heat transfer in the vicinity of the hole (the local Nusselt number is increased by a factor of 10). Thus, the influence of the holes on weakening the ice cover increases with time, underscoring the advantage realized by cutting the holes several weeks before river breakup. This illustrates an important point about nonstructural measures. Often, there is more than one governing physical process that makes a nonstructural measure successful. In this case, drilling the holes in the ice mechanically weakens the ice cover. Yet further weakening takes place through thermal processes, such as enhanced water–ice heat transfer attributable to the presence of the holes, and warming of the water by direct exposure to sunlight through the holes. This additional thermal degradation may be crucial to the success of the hole drilling operation; thus, the interplay of the various physical processes at work must be considered as part of the overall ice weakening strategy.

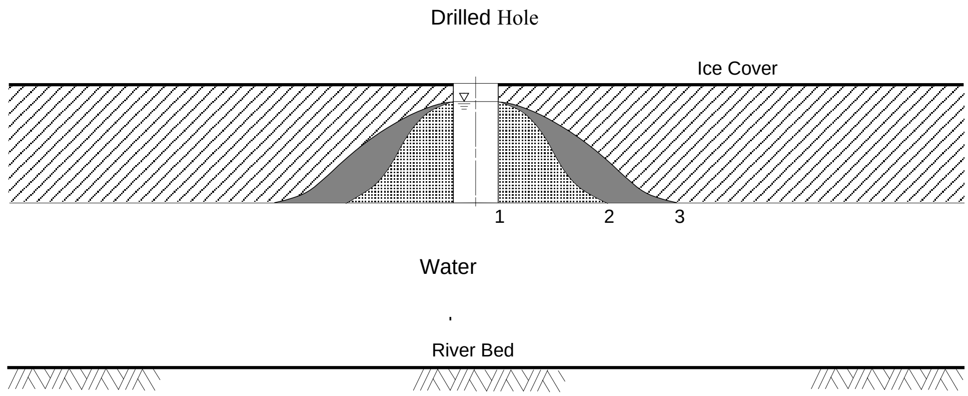


Figure 3-8. Typical observed ice profile around a hole drilled in ice with water flowing by it. The original hole is shown in profile 1. Profiles 2 and 3 show the progressive melting of the ice away from the hole (after Haehnel 1996).

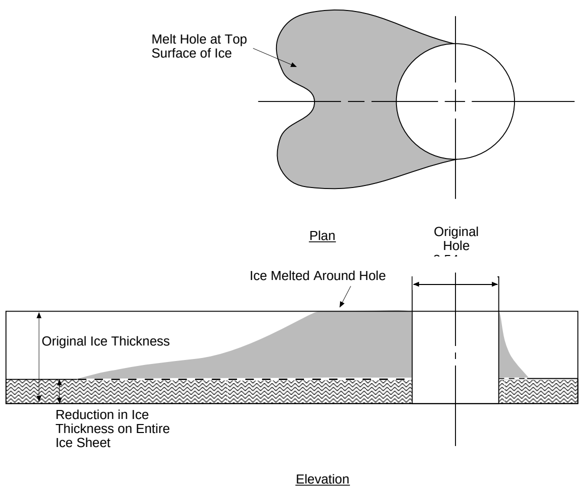


Figure 3-9. Observed melt pattern around a 2.54-centimeter-diameter (1-inch) hole drilled through a floating ice cover in a refrigerated flume.

g. Icebreaking. Icebreaking on rivers and harbor areas has been used extensively in Belgium, Canada, Finland, France, Germany, the Netherlands, the former U.S.S.R., and the United States. Icebreaking may be done as an advance measure to prevent ice jams as well as a countermeasure to break up existing jams. This subparagraph will focus on the use of icebreaking as an advance measure only. One icebreaking technique consists of breaking an entire ice cover early in the spring and leaving the broken ice in the channel. This remaining brash ice cover then is flushed out by the spring freshet, thereby preventing an ice jam. In some locations simply breaking the ice cover is not sufficient, so icebreaking is often accompanied by clearing the ice-out of the problem reach as well. Ice can be cleared by breaking the ice cover, starting at a downstream open water area and progressing upstream into the solid cover, relying on the river flow to carry the ice away. If the pre-freshet flow is not sufficient to clear the ice, it may need to be cleared after it is broken by use of icebreaking ships, towboats, or excavation equipment. In any case, careful consideration of the effects of the loose, broken ice on downstream reaches must be addressed to avoid putting downstream communities at increased risk from the icebreaking operation. This may require establishing a storage location for the broken ice (i.e., pushing the ice into a downstream reservoir) or releasing the ice floes in low concentrations to ensure the ice does not jam before it reaches open waters.

(1) On the Rideau River in Ottawa, Ontario, Canada, the ice has been broken annually since 1897 to prevent ice jam flooding in the city. The Rideau is a shallow, 45-meter-wide (148-foot-wide) river. Starting near the confluence of the Rideau and Ottawa Rivers and progressing up the Rideau, 12 kilometers (7.5 miles) of ice is broken. The ice is flushed into the Ottawa River by regulating the flow out of the Long Island dam, located about 17 kilometers (10.5 miles) upstream of Ottawa on the Rideau River (Deugo 1973). The breaking and flushing operation is timed so that the river reach is clear of ice about 2 weeks prior to the spring freshet. Historically, the ice has been broken using explosives. However, in more recent years the bulk of the ice is broken using the an amphibious excavator. Nevertheless, blasting is still used on sections of the river that are inaccessible to the excavator, such as under low bridges, or on ice that is too thick for the excavator to break. In places where blasting is prohibited (e.g., near sewer lines, water mains, and bridges) slots are cut in the ice that are parallel to the shore. These slots are cut about 15 meters (50 feet) from the shore and extend about 30 meters (100 feet) upstream and downstream of the utility. To ensure the safety of utilities and bridges, 3 lineal kilometers (1.9 miles) of slots need to be cut. Once the slots are completed, the icebreaking and flushing operation commences.

(2) The icebreaking is carried out in concert with reservoir releases, and proceeds upstream from the confluence. First, the reservoir is ponded at the Long Island dam to collect additional water for the flushing operation. The ponded water is then released, bringing the flow in the Rideau up to 35 m^3/s (1236 cfs), and icebreaking commences (Deugo 1973). When the flow drops below 35 m^3/s (1236 cfs), icebreaking is halted until the reservoir is again filled and a flow of 35 m^3/s (1236 cfs) can be reestablished. Experience has shown that it is not necessary to remove the entire ice cover, but rather to concentrate on removing the ice over the main channel. The remaining shore-fast ice that extends 6 to 15 meters (20 to 50 feet) into the channel usually just melts in place and does not cause a problem.

(3) Icebreaking has been accomplished using a variety of methods, ranging from conventional icebreaking ships to excavation equipment and blasting. In a typical icebreaking operation, two or more icebreaking vessels may work together in echelon, breaking ice starting at the downstream edge of the ice cover and advancing upstream into the unbroken cover. The ice is broken into pieces that are less than a quarter of the river width. Given sufficient water velocity, the water current carries the broken ice pieces downstream. Often additional vessels will need to be used to clear the broken ice and move it downstream, as well as to monitor drifting ice pieces to ensure that they do not jam in downstream reaches. When the broken ice begins to arch across the river, these vessels are used to break up the arch and maintain clear passage of the ice to open waters. When the ice begins to run, icebreakers may also be deployed to assure the safe passage of the drifting ice (Bolsenga 1968).

(4) The thickness of ice that can be broken by an icebreaker can be extended by cutting or weakening the ice in advance of the icebreaker. Tsykin (1982) describes making a single furrow

in the ice in front of the stem of the advancing icebreaker using the channeling plow. Tsykin reports this operation allowed the icebreaker to break a channel at 2–2.5 times faster or break ice up to twice its design thickness. Also, the U.S. Coast Guard tested a hull design that had three ice cutters, one at the stem and one on each side of the beam that cut the ice in front of the icebreaker. This design was shown to cut the power requirements for breaking level ice by 30% (Lewis et al. 1973).

h. Construction Equipment. Icebreaking has also been accomplished using various types of construction equipment, including bulldozers, excavators, dragline buckets, and cranes with wrecking balls. The bulldozers are useful only in shallow rivers and can cause considerable damage to the bed and associated habitat. On narrow rivers excavators working from the shore and bridges can break ice without having to work in the river. Bucket dredges (Figure 3-10) and cranes have considerably longer reach and, working from the bank, can be used to clear ice on rivers that are 50 to 100 meters (165 to 325 feet) wide. All of these methods require easy access to river along much of the length where the ice is to be broken.

i. Blasting. Use of blasting to clear ice dates back over 200 years, with the first successful attempt being noted in Germany in 1758 (Van der Kley 1965). There are two types of explosive devices that have been used to break up ice, chemical explosives and compressed gas cartridges. As it turns out, there is very little difference in the performance of these two methods. Because chemical explosives are the most widely used, their performance will be discussed first. Following this, the different use and performance between chemical and compressed gas explosives will be identified.

(1) *Chemical Charges.* Extensive experimental work studying the ability of explosive chemical charges to break up level ice were carried out by Van der Kley (1965), Kurtz et al. (1966), and others. Mellor (1986) compiled the available field data and developed basic guidance on use of explosives to break up a level ice cover. Those results are summarized here. For a given charge size, the maximum crater diameter is realized with the charge placed just under the ice cover. The optimum charge size, W_{opt}, for a given ice cover thickness, t, is given by

$$W_{opt} = 21t^3 \qquad (3\text{-}2)$$

where t is the ice thickness in meters, and W_{opt} is in kilograms. For English units the charge size is

$$W_{opt} = 1.4t^3 \qquad (3\text{-}3)$$

with t in inches and W_{opt} in pounds. The resulting crater diameter, D, is

$$D = 15t. \qquad (3\text{-}4)$$

Figure 3-10. Using a bucket dredge to break ice in a river.

(*a*) Because there is little radial cracking beyond the crater, the effective damage is no greater than 15*t*. Thus, for complete destruction of an ice cover, hole spacing should be about 15*t*. For weakening of an ice cover, spacing can be greater then 15*t*. Simultaneous detonation (or nearly so) provides the best results for breaking up large sections of a river. Work should proceed from the downstream edge of the ice cover, allowing the river flow to carry away ice broken by the blast. The majority of the ice is broken up into small pieces less than 10 centimeters (4 inches) across; however, it is not uncommon for pieces as large as 0.9 meters (3 feet) in diameter to be hurled 18 meters (60 feet) or more from the blast site (Moor and Watson 1971).

(*b*) These results are largely independent of explosive type "since the specific energy of typical explosive types varies within fairly narrow limits" (Mellor 1986). Furthermore, it appears that ice properties have little effect on the extent of damage as well. The various types of chemical explosives that have been used include ammonite, ammonium nitrate-fuel oil (ANFO), black powder, dynamite, C-4, C-3, TNT, thermite, and tetrytol (Bolsenga 1968). Of these ANFO and C-4 seem to be the most popular. The advantage of ANFO is that the components, by themselves, are not explosive, which simplifies storage and transportation of the materials.

(*c*) Charges can be placed by drilling holes in the ice, then dropping the charge through the ice and suspending it by a rope tied to a wooden crosspiece that bridges across the hole. The hole can also be made using shaped charges placed on the surface. For some types of explosives, weight may need to be added (e.g., bricks) to keep the charge under the ice cover. Proper safety procedures should be followed when handling explosives and carrying out the operation. These include obtaining proper permitting (including environmental), notification of the Federal Aviation Administration to assure aircraft are kept away from the blast area, and coordination with local law enforcement to ensure sightseers stay a safe distance away from the blast zone and overseeing evacuation of local residents if necessary (White and Kay 1997).

(2) *Compressed Gas.* Compressed gas cartridges (either carbon dioxide or air) are used by the mining industry as an alternative to chemical explosives. The carbon dioxide cartridges contain liquid carbon dioxide compressed to 13.8 MPa (2000 psi) in a shell that has a sealing disk that ruptures at pressures in the range of 70 to 130 MPa (10,150 to 18,850 psi). An electrically actuated chemical heater is submerged in the liquid CO_2. When the heater is fired, the pressure increases rapidly, the seal disk ruptures, and the CO_2 is released through the blast ports. The air cartridges contain a storage chamber filled with air compressed to 83 MPa (12,040 psi). On one end of the chamber is a pneumatically actuated valve which, when opened, allows rapid discharge of the compressed air.

(*a*) Tests using compressed gas to break ice were conducted by Mellor and Kovacs (1972) on lake ice. They found that the these systems (containing about 2 kilograms [4.4 pounds] of compressed gas released at 70 to 80 MPa [10,150 to 11,600 psi]) were equivalent to 0.5 kilogram (1 pound) of dynamite and were capable of breaking ice up to 0.5 meters (1.6 feet) thick, producing a crater diameter of 4 meters (13 feet) or more. Some advantages are noted by Mellor and Kovacs for use of this system over chemical explosives.

- The ice is largely broken in flexure, yielding larger ice fragments, and significantly reduced “flyrock.”

- Peak pressures even a few centimeters (inches) away from the shell are insufficient to damage hydraulic structures, ship hulls, etc.

(*b*) Nevertheless, similar safety precautions used for chemical explosives should be used for compressed gas blasting as well. Also, consideration for recovery of the reusable cartridges must be addressed.

(3) *Under-ice Combustion.* Ice can also be fractured in upward bending by the gas bubble created from combustion under ice. Mellor (1980) describes experiments using a combustion chamber filled with propane and air compressed to 410–650 kPa (60–95 psi) and ignited with a spark plug. This system was effective at breaking up to 30 centimeters (1 foot) of ice.

j. Other Icebreaking Methods.

(1) *Archimedean Screw Tractor.* Archimedean-screw tractors are amphibious tractors that use twin contrarotating Archimedean screws for propulsion. The screws are wound around large tanks that also serve as pontoons and provide the flotation for the tractor. Edworthy et al. (1982) describes using of an 11-tonne (2205-pound) Japanese built AST-002 tractor for ice management. Icebreaking was accomplished in two modes. Up to 45 centimeters (18 inches) of the ice was broken by the tractor climbing onto the edge of the ice, causing the ice to fail in flexure, and breaking off ice pieces 0.75 to 3 meters (2.5 to 10 feet) on a side. Ice up to 80 centimeters (32 inches) could be broken by “fatiguing” the ice, by repeatedly driving onto the edge and backing off or by rocking on the ice edge by quick forward and reverse motions. The AST-002 could break level ice up to 45 centimeters (18 inches) thick ice at a rate of 30,000 to 40,000 m^2/hr (323,000 to 430,600 ft^2/hr), while in ice 45 to 60 centimeters (18 to 24 inches) thick, the rate was

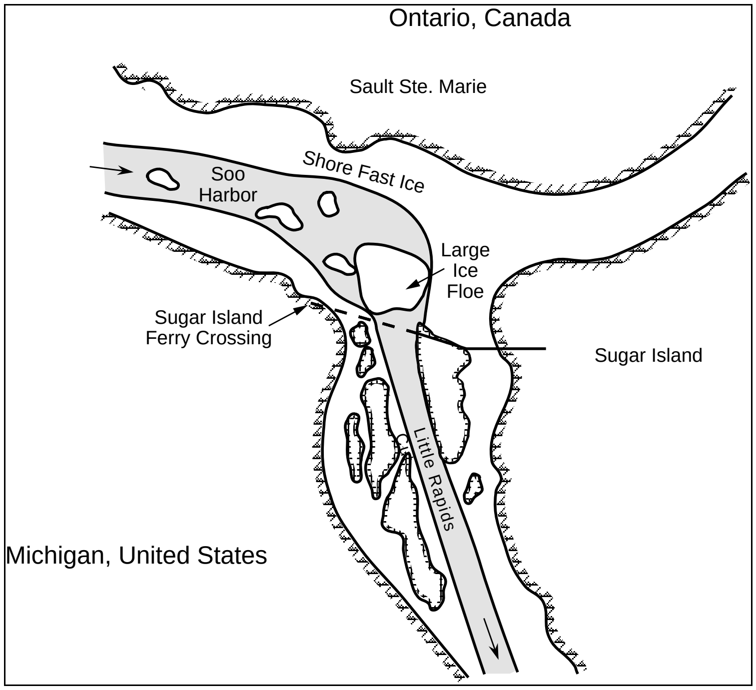
reduced to 6000 to 7500 m^2/hr (64,600 to 80,700 ft^2/hr). In brash ice (e.g., refrozen ship tracks), the AST-002 broke ice at a rate of about 42,000 m^2/hr (452,000 ft^2/hr).

(2) *Amphibious Excavators.* Amphibious excavators, such as the Finnish-built Watermaster or Canadian built Amphibex (Figure 3-11), can be used over large stretches of river for which there is poor access from the shore (provided there are not low bridges that limit travel by river). They offer an advantage over conventional icebreakers because they can operate in narrow, shallow rivers. These have been used extensively since 1989 to break ice in Canada (e.g., the Rideau and DuLoup rivers) and since 1995 in the northern United States. Using the backhoe to pull the 22-tonne (24 ton) excavator onto the unbroken ice cover breaks the ice. The ice fails in flexure under the weight of the excavator. It is small enough to be transported over road from site to site on a flatbed trailer. In ice that averaged 40 to 50 centimeters (16 to 20 inches), the Amphibex was able to break about 2000 m^2/hr (21,500 ft^2/hr) (Haehnel et al. 1995).

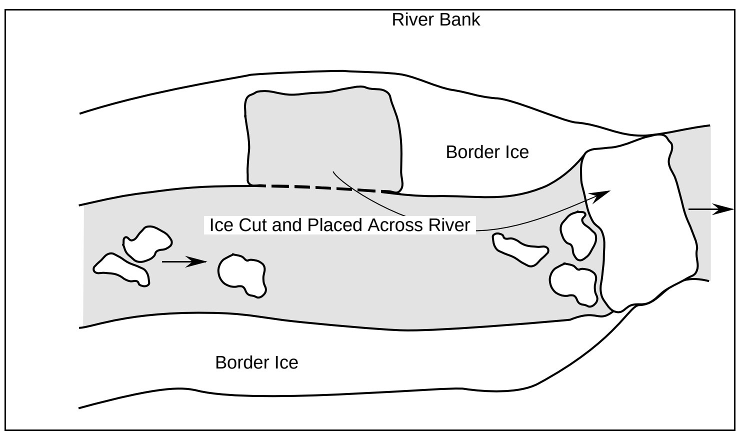
Figure 3-11. Breaking ice with an amphibious excavator on the Aroostook River, Ft. Fairfield, Maine.

k. Ice Bridging. The previously discussed mechanical methods have all focused on weakening or removing the ice cover. Ice bridging is a mechanical method that is used to change the way in which ice in a particular reach is formed or to control the flow of ice into a problem reach (Figure 3-12). An ice bridge is formed by cutting or breaking a large ice floe out of an intact ice cover (or border ice) and then placing it across the river to artificially create a blockage; hence, the ice bridge is used in much the same fashion as an ice boom.

(1) At the outlet to Soo Harbor an ice bridge is used to prevent ice from interfering with the Sugar Island ferry crossing on Little Rapids Cut (Figure 3-12a). Historically, the ice from the Soo Harbor would jam on the lower end of the Little Rapids Cut and cause ice to back up to the ferry crossing. By placing an ice floe at the entrance to the Little Rapids Cut, ice from the Soo Harbor does not enter the cut and ferry operation is unimpeded by ice.



a. Ice floe used to block ice from entering Little Rapids Cut.



b. Border ice cut from the shore and used to initiate an ice cover in a reach of rapids.

Figure 3-12. Examples of ice bridging.

(2) Figure 3-12b shows another use of an ice bridge: forming an ice cover over rapids. Quite often river rapids remain open all winter. Though an ice cover is not formed in this reach, the water is continuously exposed to subfreezing air temperatures that create tremendous amounts of frazil ice over the course of the winter. In slower downstream reaches, the frazil ice forms hanging dams and freezeup ice jams. To stop the production of frazil ice in these rapids,

border ice is broken or cut from the shore and then placed diagonally across the river. Drift ice and frazil from upstream is halted by this barrier and freezes into a solid ice cover.

(3) An interesting application of this method is used on the Lule River in northern Sweden (Billfalk 1984). Frazil ice generated on the section of rapids below the Vittarv Power Station created hanging dams and freezeup jams that caused flooding of residences and pump stations along the river. Additionally, the rise in the tailwater reduced the head for the Vittarv power station by as much as 2 meters (6.5 feet) (cutting the head by a third). An ice boom spanning the Lule River was installed downstream of the power station to form a stable ice cover over the rapids. Though the boom worked well for creating a cover above it, an extensive section of rapids below the boom remained open and generated enough frazil to still cause flooding. Consequently, the boom was redesigned with a removable section to allow passage of ice floes to the downstream rapids. The sheet ice at the downstream end of the rapids forms a natural ice bridge that stops the floes. Over time the floes form a fragmented ice cover over the entire rapids from the downstream cover to the boom. To speed up the formation of the cover through the rapids, ice was cut from the shore above the boom and floated into the rapids. Once the rapids were covered with ice, the boom was closed. This combination of ice bridging and use of an ice boom was successful in stopping the frazil ice production along this reach of the Lule. This is an excellent example of combined use of structural and nonstructural techniques to achieve the desired result.

3-3. Thermal Measures to Reduce the Risk of Ice Jam Formation. An ice cover deteriorates from weakening and melting caused by absorption of available thermal energy (Figure 3-13). Energy exchange at the ice–air surface is driven by air temperature, wind velocity, humidity, available short- and long-wave radiation, and albedo. At the ice and water surface, water temperature and velocity drive the energy exchange. Thermal weakening methods use available thermal energy to retard the growth or accelerate the deterioration of the ice cover by manipulating the absorption of thermal energy from one or more of these sources.

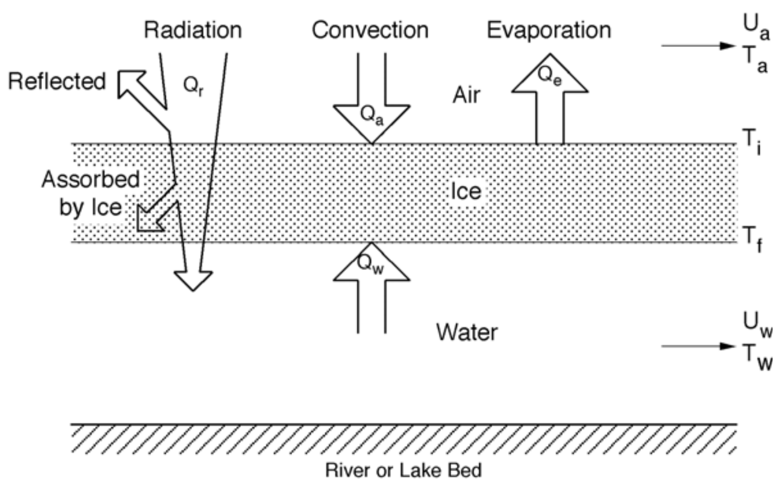


Figure 3-13. Various sources of thermal energy available for deteriorating and melting an ice cover. Q refers to the heat flux, U is velocity, and T is temperature.

a. Suppression of Ice Growth. One way to reduce the risk of ice jam formation is to reduce the volume of ice available to jam. This can be done by breaking the ice and removing it from the problem reach prior to the spring freshet, as was previously discussed under mechanical advance measures. Alternatively, measures can be taken to inhibit the growth of ice throughout the winter. Generally, the methods used to do this have focused on increasing the temperature of the river water by routing of available thermal sources. Two basic sources that have been used are thermal effluent and warm water from lake bottoms.

(1) The effect that suppressing ice growth has on wintertime operation can be seen at two U.S. Army Corps of Engineer projects, Lock and Dam (L&D) 14 on the Upper Mississippi River and Dresden Island L&D on the Illinois River. Both projects report considerably reduced ice problems because of power plants located upstream that discharge warm water into the river. To illustrate, on 5 December 1991 ice conditions on the Upper Mississippi stranded a tow pushing barges between L&Ds 15 and 16. That evening an ice jam formed on the pool of L&D 15 that brought river navigation to a standstill. It took 3 days for tows to break up the jam so that shipping could resume. Meanwhile, only 17 kilometers (10 miles) upstream, L&D 14 was experiencing no ice problems. The warm water discharge from a nuclear power plant about 40 kilometers (25 miles) upstream of L&D 14 significantly reduces the volume of ice produced above the project, resulting in open water or slight skim ice on the pool during much of the winter.

(2) Ice jam hazards can also be reduced by accelerating the decay and melt-out of the ice cover so that the ice present is either too weak or of insufficient volume to form a jam. According to Prowse et al. (1990a), the strength of the ice is inversely proportional to the ice temperature. During midwinter conditions, the top surface of a snow-free ice cover is at or near the ambient air temperature (–10 to –20°C [14 to –4°F]), while the bottom of the ice is at the freezing temperature. During the spring, the entire ice cover warms and becomes isothermal throughout its thickness at the freezing temperature. Though weakened from midwinter conditions, solid ice at its freezing temperature still retains 50% or more of its original strength, as determined from flexural strength measurements on columnar lake ice (Ashton 1986, Prowse et al. 1990a). Prowse et al. (1990a) show that further weakening of the ice cover is a result of the increase in ice cover porosity, which can reduce the ice strength to less then 10% of its original value. Once the ice becomes isothermal, as additional heat is added, melting of the ice takes place at the grain boundaries of the ice crystals, creating a porous ice cover with little loss of overall ice thickness. In addition to losing strength, the ice cover thins owing to warming air and water. If the spring freshet occurs after the ice has been allowed to rot naturally in place, there is little threat of jam formation. Often the spring freshet occurs before the ice has undergone much weakening or loss of volume, which can lead to ice jam formation and flooding. Ice deterioration has been accelerated principally by routing of warm water sources and increasing radiation absorption. Below are discussed some of the methods used to modify the thermal regime of the river to suppress ice growth or advance ice deterioration.

b. Routing of Warm Water.

(1) *Thermal Effluent.* Thermal effluent is available from a variety of sources, including power plant cooling water, sewage, and industrial discharge (Bolsenga 1968, Paily et al. 1974, Ashton 1979). Obvious benefits are realized from open circuit cooling of coal and nuclear fired

power plants, which take water from the river to cool the plant and then deposit the warm water back into river (e.g., reduced ice problems experienced at L&D 14 on the Upper Mississippi River discussed above).

(*a*) Cooling ponds for power plants are a ready source of thermal energy that can be used to retard ice growth or advance melting in the spring. For example, ice from the Kankakee River frequently jammed at the confluence with the Illinois and Des Plains River, flooding the City of Wilmington, Illinois. During the period from 1935 to 1986, ice jam floods occurred on the Kankakee in Wilmington, or outlying communities, 26 out of 52 years, and in 1982 alone damages totaled over $10 million. Furthermore, the ice released from the Kankakee River threatened the structural components of Dresden Island L&D; in 1982 two of the dam gates had to be replaced because of structural damage caused by ice released from the Kankakee. The Kankakee River ranges in width from 150–300 meters (500–1000 feet) and has a wintertime flow of 110–140 m^3/s (3885 to 4950 cfs). In 1987 a siphon system was installed in the cooling pond of the Dresden power station, which is adjacent to the Kankakee River, to route warm water from the pond to the river (Figure 3-14). The siphon was located about 7 kilometers (4 miles) upstream of the confluence with the Des Plains and Illinois Rivers. Three pipes, 0.75 meters (2.5 feet) in diameter, brought a total of 3.1 m^3/s (110 cfs) of 6°C (43°F) water from the cooling pond to the river. Two of the pipes discharged on either side of the river, and the third pipe discharged in the middle of the river. During operation in January of 1988, the siphon was able to open 4 kilometers (2.5 miles) of river after operating a week. Within 2 weeks of operation, the river was clear of ice from the siphon outlet to the confluence with the Illinois. The plot at the top of Figure 3-14 shows the water temperature in the river on 18 January 1988 shortly after the siphon started operating.

(*b*) Where possible ice problems can be reduced by location of thermal sources near problem reaches. However, usually ice problems on nearby rivers are not considered in design and location of power plants or other industrial plants that could be used as a thermal source. Thus, retrofitting of current plants may be required to take advantage of available thermal energy. Where direct discharge of thermal sources into rivers is not environmentally acceptable (e.g., industrial gray water), heat exchangers may be employed to transfer the heat from the thermal source to river water. Also, routing of thermal sources over land via long penstocks to a problem area could be used, though the transit distance would be limited by the cooling of the water in the penstock.

(2) *Natural Sources.* Low-grade thermal sources, such as lake bottoms, can also be used to melt ice or suppress ice growth. This warm water store is present because water reaches its maximum density at 4°C (39.2°F); thus, in a quiescent body of water, such as a lake, the water becomes stratified with the warm, dense water residing on the bottom, and the colder water (and ice) floating on top. Depending on the depth of the reservoir, the water can be as warm as 4°C (39.2°F) at the bottom (Ashton 1982). If this water is brought to the surface, it can be used to retard ice growth during the winter months, or advance ice melting in the spring. Desired results can be obtained with water temperatures as low as 0.2°C (32.4°F) (Ashton 1982). A possible way to accomplish this is to draw all of the outflow off the top of the reservoir during winter months. The less dense incoming cold water from the source river will remain on the top of the reservoir, and drawing the water off the top will result in discharge of only the cold water, pre-

serving the warm water until spring. During the spring, the outflow can then be drawn off the bottom and used to hasten melting of the ice in the outlet river (Ashton 1982).

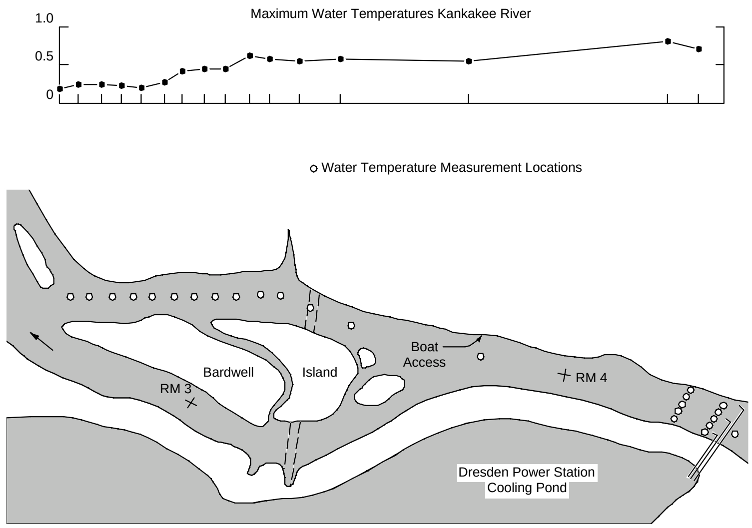


Figure 3-14. Siphons used to route warm water from the Dresden Power Station cooling pond for melting ice in the Kankakee River, Wilmington, Illinois. The plot shows the water temperature at various river sections downstream of the siphon outlets during operation on 18 January 1988.

(*a*) Warm water at lake and harbor bottoms has been routinely used to prevent ice damage to docks, marinas, and dam structures by being brought to the surface to melt the overlying ice. The warm water is principally transferred to the surface using bubblers and flow inducers (an electric motor with a propeller mounted in the front). With bubblers, the warm water is brought to the surface in a plume of rising air bubbles released from orifices located in the warm water reserve (Figure 3-15). Compressed air is delivered to an orifice (or manifold) on the lake bottom via an air line; the warm water becomes entrained in the rising air plume and is brought to the surface. This same effect can be obtained using submersible water pumps or flow inducers (both of which will be collectively be referred to as flow inducers). However, the flow characteristics of a (Ashton 1982)

> bubbler-driven plume is different than that of a submerged jet of water directed upward. In the former case the velocity of the plume is more or less constant with distance above the bubble source ... in the latter case the maximum velocity decays downstream of the pumping source .... Since the rate of melting is approximately proportional to the product of the water velocity against the ice undersurface and the temperature (above freezing) of the water, a pump located too far from the ice may produce little effect on the ice cover.

Thus, the outlet of the flow inducer must be very near the ice surface (Ashton 1982). Nevertheless, flow inducers can be effective at keeping large areas of water open. Michel (1971) reports that a 7.5-kilowatt unit was capable of creating an opening in the ice that was about 1.5 meters (5 feet) wide and 30 meters (100 feet) long in air temperatures as low as–29°C (–20°F), and a 550-watt flow inducer was able to open an area of about 12 × 10 meters (40 × 32 feet).

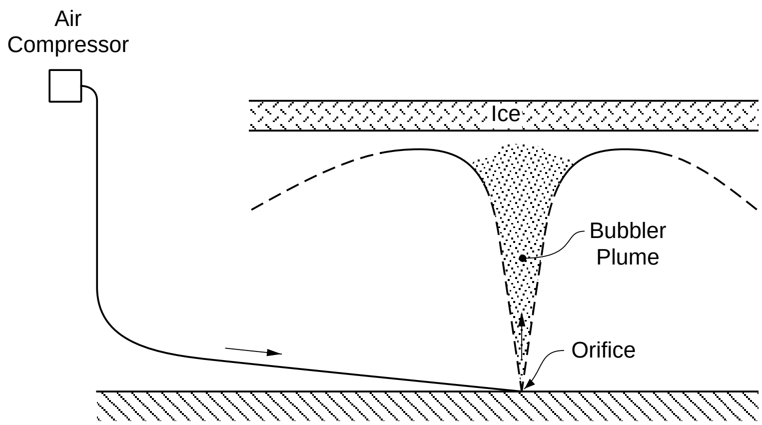


Figure 3-15. Schematic of a typical bubbler system.

(*b*) Though bubblers and flow inducers are effective at transferring warm water from the bottom of a lake or reservoir to suppress ice growth, they are of little use in rivers with velocities over 0.4–0.6 m/s (1.3 to 5.2 ft/s), as the water is quite often already fully mixed and the water temperature is typically less than 0.1°C (32.2°F). Furthermore, any available warm water is already warming ice through existing current flow, and bubblers or flow inducers cannot enhance this heat transfer. However, frequently, ice jams form at the confluence of a river with a lake or reservoir. In such areas bubblers and flow inducers could be effectively used to remove the ice cover in the receiving reach prior to the spring freshet.

(*c*) Another method under development that may prove effective at suppressing ice formation or advancing melt-out was tested in the spring of 1996 at Oshawa Harbor, Ontario, Canada. This 7.5-meter-long (25-foot-long) floating wave maker was effective at clearing a thin ice cover from a 15-meter-wide and 80-meter-long (50-foot-wide and 260-foot-long) section of the harbor. The wave maker is a corkscrew-shaped roller supported by pontoons. The roller, rotated by a 186-watt electric motor, creates a train of waves 15 centimeters (6 inches) high and about 1.2 meters (4 feet) long. The waves not only increased the surface velocity, but also advected warm water from as deep as half the wave length to the surface, thereby suppressing ice growth (Andersen and Allyn 1984, Hindley 1996). For this prototype, the mixing depth would only be about 0.6 meters (2 feet), so if this were to be used for suppressing ice growth or melting ice, a larger unit would need to be employed that extended the mixing depth. More field trials of this concept are planned.

c. Increasing Solar Absorption.

(1) *Surface Albedo Reduction.* Snow and white ice have surface albedos in the visible light spectrum ranging from 50–90% and 60–80%, respectively (Colbeck 1988, Prowse and Demuth 1992). In contrast, “black” or clear ice has an albedo of about 20% (Prowse and Demuth 1992). Thus, for all but bare black ice, much of the incident solar radiation is reflected off the snow or ice surface. Reducing the surface albedo of the ice or overlying snow increases the solar (short-wave) radiation absorbed and accelerates the rate of melting and deterioration of the ice cover. One way to accomplish this is by spreading a dark material on the surface (commonly referred to as dusting). Dusting has been used extensively in North America, Europe, and northern Asia to weaken ice prior to icebreaking operations, to advance the opening of harbors and waterways, and to prevent ice jams. Some materials that have been used for dusting include sand, fly ash (or bottom slag), coal dust, dyes and pigments, carbon black, petroleum fuels, and leaves (Arnold 1961, Williams and Gold 1963, Williams 1967, Cook and Wade 1968, Cavan 1969, Slaughter 1969, Moor and Watson 1971, Haehnel et al. 1996).

(*a*) The following properties are important to consider when selecting a material for dusting (Bonin and Teichmann 1949, Antrushin 1965).

- Absorptivity, *A*.
- Thermal conductivity.
- Density, ρ.
- State of aggregation (solid vs. liquid).
- Particle size (if solid).
- Viscosity (if liquid).
- Freezing point (if liquid).
- Toxicity and environmental compatibility.
- Solubility.

(*b*) The absorptivity is a measure of the amount of radiation absorbed by the material and is simply

$$A = 1 - \alpha \qquad (3\text{-}5)$$

where α is the albedo of the material. The absorptivity should be greater than that of the ice/snow surface. The average albedo (over the visible range of light) of some materials that have been used for dusting is shown in Table 3-1. The thermal conductivity relates to the ability of the material to transfer heat to the ice or snow. In general the thermal conductivity should be high. The density determines whether the material will float in the meltwater or remain on the ice surface; the material should have a specific gravity greater than one. The state of aggregation, particle size, viscosity, and freezing point all affect the type of equipment used to spread the material. Small particle sizes are preferable because they are readily handled in conventional crop dusting and spreading equipment. Low viscosity fluids can be readily applied with many available spray systems. Fluids that have a freezing temperature below the ambient air temperature can complicate application by freezing in the spray systems. As a minimum the freezing point of any liquid considered should be below that of water; otherwise, the material will be thickening the ice and possibly be acting as an insulator over the ice surface. The material should be nontoxic to simplify handling and to avoid detrimental effects to aquatic life, animals, and humans that use the waterway. Furthermore, the environmental impact of introducing of fine foreign matter into a river reach needs to be considered as well. For example, if a fine material is not indigenous to the river, it may interfere with the reproductive cycles of some aquatic life (Haehnel et al. 1996). Finally, the material should be insoluble in water to avoid the need for reapplication owing to dilution by melt-water. Other considerations include the availability and cost of the material, as well as the cost of application.

Table 3-1
Average Albedo Values of Various Surfaces and Dusting Materials

Surface or Material	Average albedo (%)	References
New snow	90	Colbeck 1988
Old snow	50	Colbeck 1988
White granular ice	60–80	Prowse and Demuth 1992
Black ice	20	Prowse and Demuth 1992
Water-covered ice	20–30	Williams 1967
Coal dust	2–5	Haehnel et al. 1996
Lamp black pigment	3	Bonin and Teichmann 1949
Cobalt blue pigment (Co_2O_3)	3	Bonin and Teichmann 1949
Sand	10–12	Haehnel et al. 1996
Dry dead leaves	20	Haehnel et al. 1996
Bark dust	20	Haehnel et al. 1996
Red pigment (Fe_2O_3)	26	Bonin and Teichmann 1949

(*c*) The albedo reduction of the snow or ice surface achieved by dusting is a function of the albedo of the dusting material and the amount applied. Williams and Gold (1963) found that the albedo of the ice surface decreased nearly linearly with increasing application density w (mass of material applied per unit area) up to some optimal w at which point the surface albedo remained constant. An empirically developed relationship to determine the optimum application density for a given dusting material is

$$w = 2/3\, C_m \rho d \qquad (3\text{-}6)$$

where C_m is a constant for a given dusting material, and d is the average particle diameter (Williams and Gold 1963). For Ottawa Valley crushed limestone, Williams and Gold (1963) found

C_m = 0.21 (Figure 3-16). Though, in principle, C_m should be determined for each type of dusting material, 0.20 can be used in general and can give satisfactory results. In any event, material should never be applied in a thick layer to the ice or snow surface, as this will result in insulating the surface and shielding it from solar radiation. Application densities of 200 to 700 g/m^2 (0.041 to 0.143 lb/ft^2) are generally used and lead to a reduction in surface albedo from 50–70% to about 10–20% (Williams 1967, Cavan 1969).

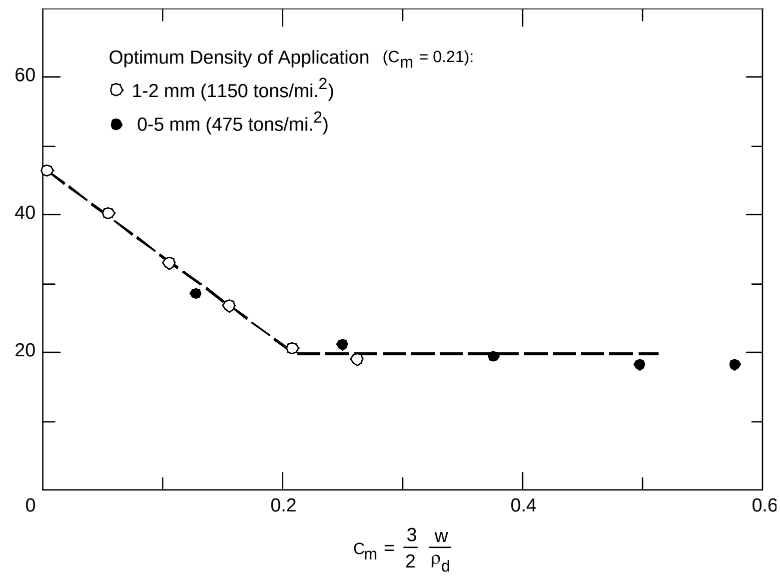


Figure 3-16. Albedo as a function of application density for Ottawa Valley crushed limestone applied to an ice surface (after Williams and Gold 1963).

(*d*) Equation 3-6 also points out the relationship between the application density and particle size. For a given dusting material, there is an inverse relationship between particle size and the resulting surface albedo, once the material is applied to the ice or snow surface. Thus, the smaller the particle size, the less material that is needed to reduce the surface albedo. Of course, the size of the particle must be balanced with other considerations as well; for example, particles must be of such a size and density that they will not be blown away by wind or washed off by meltwater. The effects of wind are particularly important if the material is to be applied by aerial crop dusting equipment. Experience has shown that particle size should range from 0.1 to 3 millimeters (0.004 to 0.12 inches) for best results (Arnold 1961, Williams and Gold 1963, Spetsov 1965, Cavan 1969).

(*e*) Reducing particle size appears to offer advantages in addition to reducing the amount of material that needs to be applied. According to Spetsov (1965), particles in the range of 0.25 to 0.5 millimeters (0.001 to 0.002 inches) penetrated more rapidly into the ice surface than did particles greater than 1–2 millimeters (0.04–0.08 inches) (in this work coal dust, phosphate flour, and black pigment were used as dusting materials). Given sufficient time and favorable weather, these small particles would penetrate through an entire ice cover that was as much as 1 meter (3.25 feet) thick, leaving behind ice that was severely weakened and honeycombed. Meanwhile, particles that were 0.5–1 millimeters (0.002–0.04 inches) in size did not penetrate farther than 25 to 30 centimeters (10 to 12 inches), and particles greater than 1–2 millimeters (0.04–0.08 inches) remained on the ice surface. Spetsov points out that it is an advantage to have a range of particle sizes in the mix, as the large particles that remain on the surface reduce the surface albedo and accelerate the melting of snow that has fallen on top of the cover after the surface has been dusted.

(*f*) In general dusting of a snow surface can increase the melt rate of snow by a factor of 10–15 (Bolsenga 1968). The dusted snowpack quickly becomes saturated with meltwater and consolidates because of the increase in solar energy absorbed. Cook and Wade (1968) point out that a cold snap will freeze this consolidated snow cover solid, and when this happens, the un-dusted snow will melt more rapidly upon return of warm weather.

(*g*) Dusting's greatest advantage appears to be its ability to weaken an ice cover (rather than reduce the thickness) and to accelerate removal of an overlying snow cover, thereby exposing the underlying ice cover to solar radiation sooner (Spetsov 1965, Bolsenga 1968). Nevertheless, reductions in ice thickness of 1 to 6 centimeters/day (0.4 to 2.4 inches/day) in dusted areas, vs. undusted areas, have been observed, which can lead to advancing the melt-out of ice by as much as 6–10 days (Arnold 1961, Bolsenga 1968, Slaughter 1969).

(*h*) In general, dusting operations should be carried out about 1 month before the historical ice-out date. Because an ice cover deteriorates little before the average air temperature reaches –2 to 0°C (28 to 32°F) (Bonin and Teichmann 1949, Williams 1967), there is no advantage to dusting much earlier than this. Thus, in regions where the river breakup is a result of a sudden thaw following a period of extreme cold, dusting will not be effective. Furthermore, as snow depths greater than 18 to 20 centimeters (7 to 8 inches) will block most of the radiation before it reaches the underlying dusting layer (Arnold 1961, Prowse et al. 1990b, Haehnel et al. 1996), timing of the dusting operation should be such that the bulk of the snowfall has ended for the season. Snowfall of more than 20 centimeters (8 inches) will necessitate that the dusting material be reapplied.

(*i*) The effect of sun angle (solar zenith angle) on the dusted surface should not be overlooked. The higher the sun is in the sky during the melt period, the more effective dusting will be. For example, when the sun angle is low, initial melting of the dust particles into the ice is quite rapid, yet once the particle has dropped into its melt hole, the sides of the hole shade the particle and the albedo of the surface quickly returns to its original value. However, when the sun is high in the sky the depth of the melt hole needs to be much greater to shade the dust particle and stop melting. More opaque ice amplifies this effect.

(*j*) The advantage goes to higher latitudes in this regard. For example, the solar zenith angle during the ice melt period is much higher in Canada and Alaska than in the Continental U.S., as ice-out at those latitudes typically occurs in late May and June. Two locations taken for comparison are North Dakota and Alaska. Table 3-2 gives the approximate latitudes, ice-out dates for each area, and the computed solar zenith angle. We see that the solar zenith angle is nearly twice as high in Alaska during the ice-out as it is in North Dakota.

Table 3-2
Computed Solar Zenith Angle for Alaska and North Dakota During the Ice-Out Period at each Locale

	Latitude (deg. North)	Typical ice-out date	Solar zenith angle (deg)
Alaska	63	June 1	41
North Dakota	45	April 1	22

(*k*) The most widely used method of applying dusting materials has been aerial crop dusting equipment (Antrushin 1965, Bolsenga 1968). Other methods include dusting by hand, pumping sand from the river bottom onto the ice (Moor and Watson 1971), and using a hydroseeder (Haehnel et al. 1996). Aerial dusting is relatively inexpensive and allows quick coverage of large areas (Figure 3-17a). To prevent clogging of the crop dusting equipment, the dusting material needs to be dried prior to loading. Spreading the material while it is still hot from the dryer has the advantage of causing the material to melt into the ice a small amount immediately after application, which makes the material less susceptible to being redistributed by winds. Typically, a swath of material about 9–15 meters (30–50 feet) wide is laid down by a single flyby.

a. Crop dusting aircraft.

b. Hydroseeder.

Figure 3-17. Equipment used for dusting.

(*l*) Pumping of river bottom sand and silt has the advantage of not introducing foreign materials to the river reach. Also, the wet slurry is not susceptible to redistribution by the wind. However, extracting the material from the river bottom disturbs the aquatic habitat and as such may not be environmentally acceptable.

(*m*) Use of the hydroseeder has proven to be a low-cost way to apply dusting in heavily populated areas or on narrow rivers that would be difficult to dust using aircraft. In this case, a slurry of the dusting material and water is stored onboard the hydroseeder truck. The easiest way to dust using this method is to spread the slurry with the cannon mounted on the deck of the truck (Figure 3-17b). However, this requires that there be easy access to the river (i.e., a parallel road running alongside the river). The range of application can be extended using the onboard 120-meter (400-foot) hose to reach less accessible areas (Haehnel et al. 1996). Though the hydroseeder has been tried using only leaf mulch, it is likely that other materials could easily be spread using this method as well.

(*n*) In a typical dusting operation, the objective is not to cover the entire ice surface, but rather to create lines of weakened ice for the ice cover to fail along, much in the same way ice cutting is used to weaken an ice cover. Typically, one or two lines of dusted material are laid down parallel to the river banks, preferably over the thalweg. Crossing patterns may be laid down over the longitudinal line as well. The resulting pattern leads to the breakup of the ice cover into small floes that are about half the river width.

(*o*) The success of dusting depends greatly on prevailing weather conditions, and the availability of sunlight. Heavy snows, snowdrifting, or persistent overcast conditions can render a dusting operation ineffective. For example, dusting operations had been carried out annually since 1968 on the Yukon River from Galena, Alaska, to Bishop Rock, a distance of 20–30 kilometers (12–19 miles). In this operation, only the snow-covered ice was dusted, leaving the bare ice undusted. Prior to dusting, the city of Galena had been flooded nearly annually. With dusting, the incidence of flooding was severely reduced, but there were still several floods during the 25 years of dusting. Nevertheless, experience on the Dvina and Onega Rivers in Europe (Bolsenga 1968) and the Yukon River in Alaska indicates that dusting greatly reduces the severity of ice jam flooding.

(2) *Ice Flooding.* Water on the top of an ice cover has an albedo of about 15% while white ice has albedo values of 60–80% (Prowse and Demuth 1992). Thus, flooding the ice cover with water can increase the absorption of solar radiation at the ice surface. However, Wake and Rumer (1979) point out that, as water temperature can be considerably higher than 0°C (32°F), evaporative cooling is increased, and longwave radiation input and heat transfer are reduced because of reductions in the temperature difference between the surface and air. Thus, the benefits of flooding an ice cover may not be as great as a consideration of albedo reduction may imply. Nevertheless, if there is an overlying snow cover on the ice, the water will serve to accelerate the melting of the snow, provided air temperatures are at or above freezing. Tests conducted by Moor and Watson (1971) support this conclusion. In these experiments, an ice surface was flooded by drilling 3.8-centimeter-diameter (1.5-inch-diameter) holes in the ice, and allowing water to flow onto it. Initially, the water gushed out of the holes, flooding the ice and snow cover. Within 24 hours, the snow around the holes had been depressed 5 centimeters (2 inches),

yet by this time the holes had refrozen. This approach may still have merit if larger diameter holes are used, which would prevent refreezing of the holes.

(3) *Snow Removal.* Ice decay can be accelerated by simply removing the snow layer that serves as an insulator as well as a reflector (Antrushin 1965, Williams 1967). In cases where the snow covers black ice, this alone will drop the albedo by 40% or more. The snow surface can be cleared using excavation equipment (e.g., bulldozers) or dusting.

(4) *Controlling the Type of Ice Formation.*

(*a*) Prowse and Demuth (1992) studied the decay in strength of river ice during spring thaw and found that an ice cover that is predominantly composed of columnar ice decays more rapidly than a "white" ice cover (small diameter grains composed of snow ice and frazil that is opaque in appearance). In this work, measurements of compressive ice strength using a borehole indentor were taken in adjacent areas of columnar and frazil ice covers over a 14-day period in April on the Liard River, Northwest Territories, Canada. During this period the compressive ice strength in the white ice stayed constant at about 17 MPa (2465 psi), while that of the columnar ice declined in strength from about 19 to 10 MPa (2755 to 1450 psi). There are several reasons for this. First, columnar ice is often very flat on the upper surface and is easily swept clean of snow by wind, which exposes it to direct solar radiation. White ice often has a rougher surface texture, which helps to trap snow, acts as an insulator to warm ambient air, and reflects solar radiation. Second, columnar ice is often translucent or transparent. When this is the case, it is called black ice, because it is dark in appearance and has a very low albedo in comparison to snow or white ice. Because of this low albedo, it readily absorbs large amounts of solar radiation, hastening its decay.

(*b*) If it were possible to manipulate the type of ice that formed in a given river reach, this might be another way to reduce ice jam threat by making the ice more susceptible to radiation decay, and thereby advancing melt-out. However, no attempts to manipulate the type of ice formed to reduce ice jam potential are known.

3-4. Chemical Measures to Reduce the Risk of Ice Jam Formation

a. The former U.S.S.R. has extensively used chemicals to remove an ice cover (Antrushin 1965, Bolsenga 1968, Michel 1971). The environmental impacts of putting large amounts of chemicals into a river or lake are typically unacceptable. Nevertheless, for completeness, a brief discussion of some of the chemical methods that have been used to reduce ice jam potential are summarized below.

b. In general the chemicals used are salts and thermochemicals. Salts depress the freezing point of water by dissolving into the water. The minimum temperature to which a saturated solution of the salt can depress the freezing point of water is the salt's eutectic temperature. At temperatures below the eutectic point, no melting occurs. Eutectic temperatures for some chemicals that have been used for melting ice are presented in Table 3-3. Also listed in Table 3-3 is the theoretical volume of ice that 1 gram (0.035 ounces) of salt can melt when the ice is at –5°C (23°F).

Table 3-3
Eutectic Temperatures and Volume of Ice Melted (per gram of salt with the ice at –5°C [23°F]) for Various Salts (after Michel 1971)

Anhydrous substance	Eutectic temperature (°C [°F])	Volume melted (cm^3[$in.^3$])
Calcium chloride ($CaCl_2$)	–5.0 [23.0]	10.1 [0.6]
Potassium chloride (KCl)	–10.7 [12.7]	10.3 [0.6]
Magnesium sulfate ($MgSO_4$)	–11.4 [11.5]	3.6 [0.2]
Ammonium nitrate (NH_4 NO_3)	–16.9 [1.6]	N/A
Sodium nitrate ($NaNO_3$)	–18.1 [–0.6]	7.5 [0.5]
Sodium chloride (NaCl)	–21.2 [–6.2]	12.2 [0.7]
Magnesium chloride ($MgCl_2$)	–33.6 [–28.5]	9.6 [0.6]

c. To give an idea of the amount of salt required to carry out such an operation, Antrushin (1965) reports an application density of 0.35 kg/m^2 (0.072 lb/ft^2) for sodium chloride is required to melt 10 centimeters (4 inches) of ice at a temperature of –10°C (14°F). Spetsov and Shatalina (1965) note that this is most effective when it is applied in narrow strips, much like in a dusting operation.

d. Thermochemicals produce heat when mixed together; thus, the melting is a result of the exothermal reaction. Some of the chemicals that have been used include (Antrushin 1965, Michel 1971) the following.

(1) Calcium chloride and unslaked lime.

(2) Powdered aluminum and copper vitrol.

(3) Powdered aluminum and sodium hydroxide.

e. Because the resulting chemical reaction can be quite violent, the chemicals are applied by separate passes of aircraft; the first aircraft carries one chemical and the second carries the other (Antrushin 1965). Michel (1971) reports that an application of powdered aluminum and sodium hydroxide melted over 1 meter (3.25 feet) of ice in 2 days.

f. Chemical weakening has also been achieved by modification of the growing ice. Michel (1971) describes application of a "saphonated substance derived from fatty acids" that produced a weak ice cover that was "mushy and sponge-like."

3-5. Breaking Ice Jams. Up to this point, the focus has been on ways to prevent ice jam formation by weakening or removing the antecedent ice cover before the spring freshet occurs. However, in many cases nonstructural methods are used to remove an ice jam that has formed. This Paragraph addresses some of the techniques that have been employed to breach a jam once it has formed. In many cases some of the same equipment and methods that are used to prevent a jam can also be used to break a jam, but breaching a jam is typically an emergency response that requires rapid mobilization of resources to minimize flood damage or navigation delays and avoid loss of life. Rapid response is best achieved when advance planning has been carried out to make sure the necessary equipment is available, personnel are trained and ready, and permits are in place.

a. Blasting. Blasting ice jams requires consideration of several factors that are not present when breaking level ice. First, in the few hours after a jam has gone into place, it is usually not stable enough to hold personnel or equipment. However, these first few hours, while the hydrograph is still on the rising limb, is the time that the blasting operation will have the greatest chance of success, as there is still sufficient flow to clear the jam. Thus, charges have been placed by helicopter or by throwing them from shore (Bolsenga 1968, White and Kay 1997). The blasting should proceed from the toe upstream into the jam. Second, for maximum effectiveness, the charges should be placed below the water, but this may not be possible if the personnel cannot be put on the jam. If the charges cannot be placed under the jam, they should be placed as deep into the jam as is practical by putting them in naturally occurring holes and crevasses. Once the charges are placed, the best results are obtained when they are detonated simultaneously. In general the charge size should be about the same as given in Equations 3-2 to 3-4, though the charge size might be slightly larger or spacing reduced to compensate for not being able to set the charge under the ice. Furthermore, the broken ice in the jam will also act to absorb much more energy than an unbroken cover, so spacing may need to be adjusted during the course of the operation to assure that the craters overlap.

(1) Often jams form when broken ice encounters a stable, unbroken sheet ice cover. In this case removal of the sheet ice is sometimes sufficient to release the jam (Michel 1971). Under these conditions personnel may be safely put on the stable ice cover and charges placed under the sheet ice according to the guidance provided in Equations 3-2 to 3-4.

(2) If charges are placed by being thrown from the shore, the charge size will need to be greatly reduced for them to be hurled any distance. Charges of 2 to 3 kilograms (5 or 6 pounds) thrown from the shore were used successfully to clear a channel 600 meters long × 150 meters wide (2000 feet long × 500 feet wide) in a jam on the Missouri River (Bolsenga 1968).

(3) In rare cases only a few charges placed at the toe of the jam may be sufficient to break the “key” that is holding the jam in place, and will cause the release of the entire jam. This was the case for a jam that formed on the Walhonding River at Warsaw, Ohio, in January 1997. Two charges (about 2 kilograms [4 pounds] each) placed at the toe of the jam were successful at releasing the entire 1-kilometer-long (0.6-mile-long) jam. More commonly though, extensive blasting is needed to break a jam. For example, a 3.3-kilometer-long (2-mile-long) jam that formed in February 1997 on the Platte River upstream of Ashland, Nebraska, required 1½ days and about 12,000 kilograms (26,500 pounds) of explosives to be broken (White and Kay 1997).

(4) In this latter case the blasting operation commenced within 2–3 hours of jam formation, which appeared to be a decisive factor in its success. Contrast this with a blasting operation that was carried out on a jam that formed on the Platte River in 1993, also near Ashland (White and Kay 1997). An initial jam had formed in early February, causing minor flooding. This jam remained after the flood waters receded and froze in place. This jam was then an obstruction for the spring ice breakup and caused a 6.4-kilometer-long (4-mile-long) jam on 8

March, resulting in numerous levee breaches and extensive flooding. Blasting on this jam did not begin until the 16 March. It took 2 days to blast a channel through the jam, which allowed the water levels to decrease, by which time extensive damages to farmland, residential property, highways, levees, and utilities had already been sustained. A more rapid response, either in February to clear the initial jam or at the formation of the jam on 8 March, might have helped to reduce damages significantly.

b. Towboats and Icebreakers. Towboats and icebreakers have been used extensively to break ice jams. Though icebreakers are better equipped to break jams, towboats are often "Johnny-on-the-spot" to handle ice problems that develop. Despite the type of vessel, the basic strategy for breaking the jam is the same. As with blasting, the operation should start at the toe of the jam and work upstream. At least two vessels work together to break away ice masses from the central part of the jam (Bolsenga 1968, Michel 1971). Additional vessels may be on hand to patrol the loose ice and prevent further jamming downstream. This may be carried out in conjunction with blasting operations as well, with the prop wash from the vessel helping to clear blasted ice (Bolsenga 1968).

(1) An example of icebreaking using towboats took place on the upper Mississippi River at L&D 15 during December 1991. As previously discussed, the 4-kilometer (2.5-mile) jam formed on 5 December, halting river traffic. Towboats that were on site were pressed into service and were used to break the jam. The jam had formed on the pool behind the dam at L&D 15. Two towboats worked in the shipping channel breaking away portions of the jam. Meanwhile, a third towboat was tied to the outer guide wall of the lock, and used its prop wash to flush the floating ice over the dam. Occasionally, the passage to the dam would become blocked, and towboats would be dispatched to reopen the channel. Working close to the dam to clear such a passage is dangerous because if the jam broke and started moving it could push the towboat up against the dam. To protect against this, two towboats were tied together, so, if the jam started to run, the combined power of the two boats would be sufficient to overcome the force of the driving ice and allow the towboats to move to a tether point while the ice passed. However, even this precaution is not guaranteed to work against a large jam. After 3 days, the jam finally broke loose and moved en masse over the dam.

(2) Another technique for clearing ice was employed at L&D 19 in Keokuk, Iowa. The ice was cleared and directed toward the dam by tying two towboats together in a T shape, with one boat pushing the other like a plow. The resulting passage was much wider and less likely to become blocked by floating ice.

c. Excavation. Construction equipment has been used to remove jams as well. The type of equipment that has been used includes excavators, bulldozers, and dragline and clamshell buckets. Amphibious excavators have also been used in Canada to break ice jams on deeper rivers where conventional excavators cannot be deployed. Working from the downstream end of the jam, the excavators break up and remove the ice from the channel. Ideally, the ice is piled on the shoreline. If this is not possible, the ice may need to be removed from the river altogether and trucked away from the site.

(1) A crane with an I-beam as a wrecking ball was used in the spring of 1992 to break up a jam on the Winooski River in Montpelier, Vermont. Working from the shore, the crane used the weight to break up a large floe at the toe of the jam, thereby releasing the jam.

(2) An ice jam on Saranac River, near Plattsburg, New York, was removed during the winter of 1996 using a combination of excavation and blasting (White and Kay 1997). Ice at the toe of the jam was loosened using a backhoe working in the stream channel. The ice was then pushed to the side of the river using bulldozers. Once the channel was cleared to within 60 meters (200 feet) of the upstream end of the jam, the excavation equipment was removed from the river and the remaining jam was removed using explosives. Working in the river channel raises concerns about safety, especially if the jam is unstable. Thus, this type of operation should only be carried out on a grounded jam that has little or no water behind it so there is no risk of it releasing while equipment or personnel are in the channel below the jam.

(3) Ice jams have occurred almost annually on the Lamoille River in Hardwick, Vermont. Excavation equipment working from shore and off bridges is used to loosen the ice jams as they form, and keep the ice flowing through town. In this case it is a combination of experience and the rapid response of the town highway crew that prevents extensive jam formation and flooding in the town. However, the town of Hardwick has not always been successful at removing the jam before it becomes grounded and causes damage. Figure 3-18 shows excavation equipment working at Hardwick to remove a 2- to 3-meter-thick (6.5- to 10-foot-thick) grounded jam.

Figure 3-18. Breaching an ice jam in Hardwick, Vermont, using excavation equipment working from the shore and a bridge (bridge is not shown, but is just beyond the left edge of the photograph).

3-6. Cost and Performance of Nonstructural Measures

a. Available cost and performance information, in terms of ice destruction capability, for the nonstructural methods discussed, is presented below. The fundamental differences in the nature of the methods presented make it difficult to directly compare the cost and performance among classes of methods. For example, when destroying ice via an icebreaker, reporting the cost of operation in terms of the area or volume of ice broken is reasonable. On the other hand, when weakening ice by cutting out large floes, it might be more reasonable to talk in terms of cost per lineal distance of trenches cut. Therefore, the cost and performance data have been compiled in terms of the basic nature of the operation.

b. A performance parameter that is commonly used is specific energy, E, which is the amount of energy required to remove/destroy a unit volume of material. Given p as the rated power, and $\dot{V}$ as the volumetric material removal rate then

$$E = p/\dot{V} \quad . \tag{3-7}$$

c. Other cost and performance data are similarly presented in terms of unit of ice destroyed (e.g., cost/area of ice destroyed per unit time, etc.).

d. For ice cutting operations, the cost and performance data are presented in terms of the volume of ice removed, which allows comparison independent of ice thickness and the kerf width of the tool. This information is presented in Table 3-4 in order of increasing specific energy. From Table 3-4 it is apparent that the mechanical cutters outperform the water and thermal cutters in terms of specific energy consumption and cost. Furthermore, the equipment that has been optimized for cutting ice, namely the channeling plow and the ICESAW, give the highest ice removal rates. Nevertheless, in terms of specific energy, the unmodified Case DH4 is about equal with the ICESAW; thus, there is readily available off-the-shelf equipment that can be used to cut ice efficiently. However, the ICESAW, Watermaster, and Amphibex being amphibious does offer an advantage when the ice thickness is marginal.

e. The cost and performance for breaking ice, expressed in terms of area of ice cover destroyed, are presented in Table 3-5. Again the methods are listed in order of increasing specific energy. In terms of specific energy, air cushion vehicles (ACVs) are clearly the most efficient for breaking ice. However, it is not clear that ACVs are the least expensive method. For example, for maintenance alone, Robertson (1975) reports that the *Voyageur* required about 11 hours of maintenance per hour of service; in contrast, the AST-002 required about 1 hour of maintenance per 20 of hours service (Edworthy et al. 1982). In terms of cost, icebreaking vessels are clearly the least expensive way to break ice, though their use is limited by river depth.

f. The cost per covered area of dusting is presented in Table 3-6, where the methods are listed in order of increasing cost. No performance data are given for dusting as it is difficult to quantify directly. Pumping appears to give the lowest cost (Moor and Watson 1971).

g. By far the most extensively used method is aerial dusting. From Table 3-5 it is apparent that the cost of aerial dusting can vary by a factor of 2–3. The low cost of dusting achieved at Galena is likely attributable to optimization resulting from 25 years of experience in dusting (Haehnel et al. 1996).

Table 3-4
Cost and Performance of Ice Cutting Equipment (adjusted to 1996 U.S. dollars)

Equipment	Specific energy (MJ/m^3)	Ice removal rate (m^3/min)	Maximum ice thickness (m)	Kerf width (cm)	Cost ($/m^3)	Mobilization/ demobilization ($)	References
a. SI Units							
Channeling plow	0.86	25	0.6	NA	—	—	Tsykin 1982
Case DH4	3.2–6.4	0.3–0.6	> 0.5	15	6.90*	2000	Labbé 1983
GPI-41	5.5	0.57	> 0.5	—	—	—	Tsykin 1982
Chainsaw for coal	5.9	0.49	1.8	8.2	—	—	Garfield et al. 1976
ICESAW	6.7	1.5	1.2	19	0.98†	—	Mykkanen 1997b
GPI trencher	8.6–17	0.3–0.6	1.5	15	—	—	Aleinikov et al. 1974
Chainsaw	14	0.098	1.8	1.4	—	—	Garfield et al. 1976
Homelite 550 chainsaw**	16–18	0.012–0.014	0.6	0.6	—	—	Coutermarsh 1989
Steam cutter	29–72	0.002–0.003	—	15–20	270.00††	5000††	Bojun and Si 1990
Ditchwitch 1620	35.7	0.020	1.2	12	33.00***	1200	Lever 1997†††
Watermaster	38.9	0.23	0.5	8	1.10	—	
Water jet	290–880	0.01–0.03	0.17	0.5–1.0	—	—	Calkins and Mellor 1976
Thermal	400–530	—	—	—	—	—	Mellor 1984
Laser	414	—	—	—	—	—	Mellor 1984
b. English Units	**(Btu/ft^3)**	**(ft^3/min)**	**(ft)**	**(in.)**	**($/ft^3)**	**($)**	
Channeling plow	3.1	882.9	2	NA	—	—	Tsykin 1982
Case DH4	85.9–171.8	10.6–21.2	> 1.6	38.1	0.20*	2000	Labbé 1983
GPI-41	147.6.5	20.1	> 1.6	—	—	—	Tsykin 1982
Chainsaw for coal	158.4	17.3	5.9	20.8	—	—	Garfield et al. 1976
ICESAW	179.8	53.0	3.9	48.3	0.03†	—	Mykkanen 1997b
GPI trencher	230.8–456.3	10.6–21.2	4.9	38.1	—	—	Aleinikov et al. 1974
Chainsaw	357.7	3.5	5.9	3.6	—	—	Garfield et al. 1976
Homelite 550 chainsaw**	430	042–0.50	2.0	15	—	—	Coutermarsh 1989
Steam cutter	778–1932	0.07–0.10	—	6–8	7.65††	5000††	Bojun and Si 1990
Ditchwitch 1620	958.2	0.7	3.9	30.5	0.93***	1200	Lever 1997†††
Watermaster	1044.0	8.1	1.6	20.3	0.03	—	
Water jet	7780–23620	0.35–1.06	0.6	1.25–2.54	—	—	Calkins and Mellor 1976
Thermal	10,735–14,225	—	—	—	—	—	Mellor 1984
Laser	11111.3	—	—	—	—	—	Mellor 1984

*Cost brought forward to 1996 US $ using Consumer Price Index.
†Using a currency exchange rate for 1996, 4.5 FIM = $1 US.
**Tested using a 0.6-meter (2 foot) cutting bar.
††Estimated using cost for conventional steam cleaning equipment as basis.
***Does not include cost of snow blower.
†††Personal Communication, J.H. Lever, CRREL, 1997.
NA— not applicable.

Table 3-5
Cost and Performance of Icebreaking Methods (all costs are adjusted to 1996 U.S. dollars)

Method/ Vessel	Specific energy (MJ/m^3)	Specific energy (btu/ft^3)	Cost ($/Ha)	Cost ($/ft^2)t	Ice thickness (m)	Ice thick-ness (ft)	Destruction rate (ha/hr)	Destruction rate (ft^2/hr)	References
Air cushion vehicle									
	0.007	0.2	—	—	—	—	—		Mellor 1980
Voyageur	0.004–0.006	0.11–0.16	—	—	0.3–0.75	1.0–2.5	10–260	1,076,000–28,000,00	U.S. Army 1982, Robertson 1975
ACT-100	—		—	—	0.3–0.7	1.0–2.4	—	323,000	U.S. Army 1982
Icebreaking vessels									
	0.1–1.7	2.68–45.6	—	—	—	—	—	—	Mellor 1980
	0.2	5.4	1003	0.01	0.3–0.4	1.0–1.3	3	323,000	Van der Kley 1965
"Project 16" Iicebreaker	—	—	455	0.0042	0.5	1.64	3–5	323,000–538,200	Tsykin 1970
Blasting (submerged)									
Chemical	0.12–0.38	3.2–10.2	—	—	—	—	—	—	Mellor 1986
Chemical	—	—	3,000*	0.03	0.5	1.64	—	—	Labbé 1983
Chemical	—	—	4,060†	0.04	—	—	—	—	Miner 1997
Chemical	—	—	5,000**	0.05	0.4	1.31	0.05††	5380	Van der Kley 1965
Compressed gas	0.23	6.2	—	—	0.3	0.98	—	—	Mellor 1980
Blasting (surface)									
Chemical	—	—	30,000**	0.28	0.4	1.31	0.1††	10,760	Van der Kley 1965
Other									
Amphibex™	0.94	25.2	1,770	$0.02	0.35–0.76	1.1–2.5	0.16	17,200	Haehnel et al. 1995
AST-002 (continuous breaking	—	—	—	—	0.45	1.48	3–4	323,000–430,600	Edworthy et al. 1982
AST-002	—	—	—	—	0.45–0.6	1.5–2.0	0.6–0.75	64,580–80,730	Edworthy et al. 1982

*Cost brought forward to 1996 US $ using Consumer Price Index.
†Using currency exchange rate for 1996, $ 1.37 CAN = $1 US.
**Using currency exchange rate for 1965, 3.6 guilders = $1 US.
††Estimated based on 4 men working to place and detonate charges.
Note: Using currency exchange rate for 1970, 1 rouble = $1.10.

Table 3-6
Cost of Dusting Operations in 1996 U.S. Dollars

Method	Cost ($/m²)	Cost ($/ft²)	Application rate (m²/hr)	Application rate (ft²/hr)	Location	Reference
Pumping	0.40*	0.04	2,400	25,833	Alaska	Moor and Watson 1971
Aerial Dusting	0.82	0.08	14,000	150,696	Galena, Alaska	Haehnel et al. 1996
Hydroseeder using cannon	0.88	0.08	8,000	86,112	Montpelier and White River, Vermont	Haehnel et al. 1996
Hydroseeder using extension hose	1.20	0.11	4,000	43,056	Montpelier, Vermont	Haehnel et al. 1996
Aerial Dusting	2.10†	0.20	8,000	86,112	Platte River, Nebraska	Haehnel et al. 1996, U.S. Army 1994

*Price brought forward from 1971 using the CPI.
†Price brought forward from 1993 using an inflation rate of 3% per year.

h. For comparison, the cost and performance data for these various methods shown in Tables 3-4 to 3-6 are also presented in Figure 3-19. The application rate given in Figure 3-19 is the rate at which the ice surface is treated with the specified method. In the case of icebreaking, this application rate is also the ice destruction rate. However, for dusting ice, destruction is a process that takes place over several weeks following the application and depends on the prevailing weather conditions for any given location and year. Thus, determination of a destruction rate for dusting is not trivial and cannot be done explicitly from the data presented in Table 3-6. For ice cutting, the application rate, and cost data presented in Figure 3-19 are based on cutting large sections* of an ice cover in the same fashion as pattern 1 shown in Figure 3-1b, with the herring-bone pattern repeated every 15 meters (50 feet). The ice was assumed to be 0.5 meters (1.6 feet) thick.

i. Methods on the left and top of Figure 3-19 are the least costly to apply, while those on the lower right are the most costly in terms of both time and money. Clearly, blasting is an expensive and slow method, while icebreakers are the quick and inexpensive. Many of the methods listed in Tables 3-4 to 3-6 did not have sufficient data to plot in Figure 3-19. One of the obvious omissions is air cushion vehicles, which perform far better on level ice than conventional ice-breakers, yet there are no cost data available.

* By assuming that large ice sections are being cut, the mobilization costs can be neglected since they are small in comparison to the overall cost of the operation.

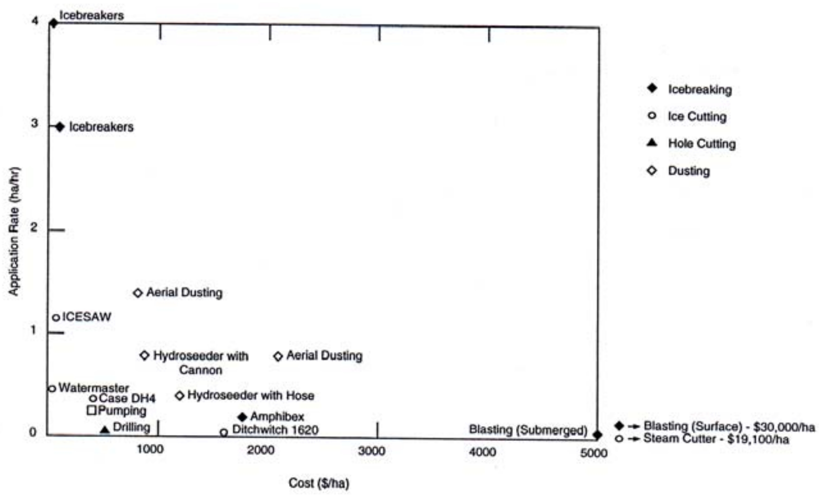


Figure 3-19. Cost and performance data for various methods of ice control. (1 ha= 10,000 m^2 = 107,640 ft^2)

3-7. Case Study

a. In addition to providing a cost comparison, the information in Tables 3-4 to 3-6 can be used for planning ice cutting operations. For example, a proposed operation may require weakening a 600-meter-long (2000-foot-long) stretch of river that is 36 meters (118 feet) wide with an average ice thickness of 0.5 meters (1.6 feet) (similar to the section of Beaurivage River weakened in 1982 and 1983). The time and cost required to accomplish this are estimated for three different methods: cutting, icebreaking, and dusting.

(1) *Ice Cutting*. For this operation, the pattern would be cut about every 15 meters (50 feet) apart, with the lines making an angle of about 45° with the bank (similar to pattern 1 in Figure 3-1b). This would require about 1700 meters (1 mile) of trenches to be cut. With a trencher equivalent to the Case DH4, the kerf width would be about 15 centimeters (6 inches) (Table 3-4), and the amount of ice removed would be 128 m^3 (4571 ft^3). With an average ice removal rate of 0.4 m^3/min (14.1 ft^3/min), it would take approximately 5 hours to accomplish this with a single trencher, and cost about $2900 (including mobilization costs).

(2) *Icebreaking*. If two-thirds of the channel width were to be opened, then the area of ice to break would be about 1.4 hectares (0.35 acres). The ice is proposed to be broken by blasting. From Table 3-5 the cost for blasting 1 hectare (0.25 acres) is about $4000 on average, so this operation would cost about $5600 and take about 3.5 working days (time estimate based on four people setting and detonating charges).

(3) *Dusting*. Again, the middle two-thirds of the channel will be weakened (about 1.4 hectares [6 acres]). On a river as narrow as 36 meters (118 feet), aerial dusting would be difficult to execute, so select the hydroseeder for this operation. If there is not good access from the shore, the plan would be to use the hose extension to spread the dusting material, which gives a rate of application of 0.4 hectares (0.1 acres) per hour. Thus, it would take about 3.5 hours to apply the

material and cost about $1700. The final cost may be slightly higher, depending on the dusting material used. The values given in Table 3-6 are for applying leaf mulch.

b. The ice cutting and dusting operations cost about the same, and in both cases the time is about 1 working day. In comparison, the blasting operation costs almost 2–3 times more and takes 6–8 times as long to accomplish. As previously mentioned, both blasting and cutting operations were carried out on 600 meters (2000 feet) of the Beaurivarge in 1982 and 1983; thus, estimated and actual values can be directly compared. The blasting operation carried out in 1982 cost about $6000 (in 1996 U.S. dollars). Similarly, the cost for cutting the same area was about $3000 and took about 8 hours. These figures agree well with the estimates of $5800 and $2900 for blasting and cutting, respectively.

c. In choosing any of the methods discussed in this case study, there are other factors that should be considered before final selection can be made, such as

(1) Effects of blasting on adjacent properties.

(2) Environmental impacts of dusting or blasting.

(3) Air temperature and available sunlight preceding breakup if dusting is to be used.

(4) Bearing capacity of the ice if equipment or personnel are going to be placed on the ice for any of these methods.

d. This Paragraph has provided a basic estimate of the cost of nonstructural operations, both in terms of time and money, yet there has been no mention of the relative effectiveness of these methods to reduce the frequency and severity of ice jams. The reason for this omission is that there is little available guidance that will allow prediction of ice jam potential based on ice strength, piece size, etc. Short of removing the ice cover from the entire river, there is no guarantee that any of these methods will prevent ice jam formation. To illustrate, during the 25 years of dusting the Yukon River at Galena, Alaska, there were several years that ice jams did form and cause flooding. However, the frequency and severity of the flooding was reduced in comparison to years before dusting was done.

e. There are some trends that can be gleaned from the collective experience in application of nonstructural ice control methods.

(1) Reduction in ice volume in the river reduces ice jam potential.

(2) Weakening the ice cover appears to reduce ice jam frequency and severity.

(3) Smaller ice pieces reduce the potential for ice jams to occur.

f. Using these as a general guide will aid in selection of nonstructural ice control methods.

3-8. Discussion

a. The foregoing presents a multitude of nonstructural measures that can be employed to reduce the risk of ice jam formation. Where possible, the effectiveness of these methods has been assessed. In terms of development, some of these are still in their infancy, while others are well advanced in terms of available guidance and field experience. Destruction of an ice cover by blasting falls into this latter category. This technique has been used successfully to both prevent ice jam formation and break existing jams. However, there is little guidance currently available to predict the reduction in ice jam potential from applying any of these measures. All that is clearly known is that the complete removal of ice from the river will eliminate the possibility of ice jam formation. Beyond this, theoretical or empirical relations that predict the marginal reduction of jam potential by weakening the ice (e.g., dusting) or reducing floe size (e.g., advance cutting of the cover) are not well developed. Further work in this area should focus on developing governing relationships that relate ice and river properties and meteorological conditions to ice jam potential and severity. Pertinent ice properties include ice cover thickness, spatial extent, strength, volume, and piece size. River characteristics of concern are channel morphology, water surface slope, water velocity, discharge, and typical breakup hydrographs.

b. Nonstructural methods may be used to extend the operating envelope of structural measures or to play a role in an ice control strategy that uses both structural and nonstructural components to provide the desired results. Future work will explore this possibility.

Section II
Structural Ice Control

3-9. Introduction

a. *General*. Structural solutions exist for a wide range of river ice problems. This Section reviews a variety of structural ice control methods in use today, focusing on recent performance. A main goal is to determine which areas of structural ice control are well developed and understood at present, and which ice problems do not lend themselves to a solution by current structural methods. The information assembled in this Section will provide guidance in selecting and adapting structural ice control methods for specific confluence ice problems. Ice control research and development during the last three decades has concentrated on sheet ice retention methods. Much of this work is described by Perham (1983) and Appendix B of this Manual. The difficult problem of breakup ice control has received less attention, particularly on larger rivers. This Section emphasizes recent developments in structural ice control as well as methods that could be applied to ice problems characteristic of river confluences. Few constraints have been placed on geographic location, scale, or structure type. Locations include sites in the northern United States, Canada, northern Europe, and Japan.

b. *Background*. The last three decades have seen much development in the field of structural ice control. The following is a brief summary of the general literature on structural ice control methods. Literature relating to single structures will be cited where appropriate later.

(1) Good background on river ice processes affecting the design of dams and booms to control frazil and breakup ice is given in *Winter Regime of Rivers and Lakes* by Michel (1971). During the sixties and seventies, the navigation and hydropower interests, along with various government agencies in the U.S. and Canada, fostered the successful development of sheet ice retention methods on the St. Lawrence River and the connecting channels of the Great Lakes. Perham (1983) and Appendix B provide descriptions of many of these structures, and Ashton (1986) contains a brief version of Perham's review. At the same time, structural ice control techniques were evolving in northern Europe, the main focus being on hydropower. Roen and Tesaker (1988) discussed a range of ice problems and structural solutions at hydroelectric plants in Norway, presenting five case studies. At a more general level, Carstens and Tesaker (1987) presented a general inventory of ice problems on rivers, listing possible structural solutions. Calkins (1984) presented six case studies of ice jam problems on rivers in the U.S. and Canada, in outline form, briefly describing existing and proposed structural solutions.

(2) A project by the consulting firm Cumming-Cockburn and Associates, Ltd. (1986a) produced a comprehensive overview of ice control methods on small rivers in Canada where dams, weirs, piers and booms were used successfully to mitigate both freezeup and breakup ice problems. Belore et al. (1990) also described a variety of structural methods, ranging from sheet ice control structures on the St. Lawrence River to weir-and-pier structures designed to control breakup ice on smaller Canadian rivers. Deck (1984) briefly presented a structural solution to the ice jam problems at Oil City in Pennsylvania. Deck and colleagues later drew on the Canadian experience with weir-and-pier structures to develop a design for a proposed ice control structure on Cazenovia Creek near Buffalo, New York (Gooch and Deck 1990).

(3) Jain et al. (1993) contains a summary of ice control methods, describing the point at which a nonstructural solution such as flow control may become more feasible than a structural one on the larger rivers in the U.S. The innovative methods of controlling pack ice off the northern coast of Japan described by Saeki (1992) are mentioned here because they could possibly be applied to ice problems at the confluences of large rivers in the U.S.

3-10. Sheet Ice Retention Structures. Sheet ice retention structures promote ice formation on water bodies with relatively low surface velocities (≤0.7 m/s [≤ 2.3 ft/s]), low energy slopes, and low Froude numbers (≤ 0.08) (Perham 1983). Hydraulic conditions must allow for arriving ice to accumulate against the structure (juxtapose), rather than be dragged beneath the surface during the formation period. The cover typically progresses from the structure in the upstream or windward direction, and arriving ice may be in the form of frazil, floes, or brash. The main goal of a sheet ice retention structure is to initiate ice cover formation. Once a solid cover has formed, the structure is usually not designed to add to the cover's overall stability. Although sheet ice retention structures are typically not designed to retain breakup ice, they may make breakup less severe by delaying the breakup of the upstream ice cover until the downstream ice has had a chance to clear out.

a. Purposes.

(1) Retention or stabilization of a sheet ice cover has a number of positive effects. Stabilizing the shore ice on a river or lake reduces the ice volume supplying potential ice jams at lo-

cations downstream. As an added benefit, a stable shore ice zone protects the shoreline and shoreline structures from the destructive effects of offshore ice movement. In cases of winter navigation, stabilization of the ice along the channel sides minimizes the ice volume in the navigation channel and increases the channel's ice-flushing capacity. At lake-to-river transition areas, special booms, some with navigation openings, have been developed to prevent lake ice from entering and clogging the narrower downstream channels.

(2) Formation booms may be placed on a river or canal to stop the downstream transport of frazil ice and promote the upstream progression of an ice cover. The hydropower industry in northern climates has used this type of boom extensively to promote the rapid formation of an ice cover upstream of their intakes early in the ice season, minimizing ice-related head losses and increasing winter power production. Though not specifically designed for the purpose, these booms, alone or in series, may help prevent ice floes from piling up and damaging hydropower intakes at breakup. In addition to increasing the reliability of winter hydropower production, formation booms have effectively reduced the ice jam threat to towns and properties along rivers by capturing frazil at favorable locations upstream of the historical ice jam sites.

b. Types. A wide variety of sheet ice retention structures exist, many of which are well described and illustrated by Perham (1983) and Appendix B. The list includes conventional floating booms, rigid booms, weirs, groins, and artificial ice islands. Many structures such as dams, bridge piers, and tower foundations, although not specifically designed to control ice, do serve that purpose. In addition, piers, piles, and pile clusters (dolphins) and, in some cases, sunken vessels have been used to stabilize a sheet ice cover.

c. Examples. Examples are presented according the general type of structure and the purpose of the ice control.

(1) *Ice Control at Lake-to-River Confluences and Channel Constrictions.* Lake-to-river confluences present a special ice control problem. Although there is a tendency for ice arches to form naturally at these locations, wind and wave effects, as well as vessel passages, can disrupt arch formation, causing lake ice to enter and sometimes jam in the narrower channel downstream.

(*a*) The Lake Erie ice boom, located near Buffalo, New York (Figure 3-20), prevents, to a large degree, lake ice from entering the Upper Niagara River. The 2682-meter-long (8800-foot-long) boom has 22 spans, each 122 meters (400 feet) long; each span has is made up of 11 steel pipe pontoons, each 0.76 meters (2.5 feet) in diameter, 9.14 meters (30 feet) long. Before the boom was rehabilitated in 1997 from timber to steel pontoons, during the early winter, wind-driven lake ice in the 10- to 20-centimeter (4- to 8-inch) thickness range would override the boom. These lake ice runs could result in massive jams in the Upper Niagara River, causing flooding and reductions in hydropower production at the plants at Niagara Falls (Abdelnour et al. 1994, Crissman 1994). Since 1997, performance has greatly improved with the exception of an incident in February of 2003, when a large field of pack ice remained frozen to the pontoons during an extreme wind event, causing portions of the boom to fail (Abdelnour et al. 2005).

Figure 3-20. Lake Erie ice boom.

(*b*) The Lake St. Francis ice boom, on the St. Lawrence River in Quebec, prevents wind-driven lake ice from entering the upstream end of the Beauharnois Canal during the late winter and early spring. The 24-kilometer-long by 1005-meter-wide (15-mile-long by 3300-foot-wide) canal diverts between 3962 and 7358 m^3/s(140,000 and 260,000 ft^3/s) from the St. Lawrence to the 1600-MW hydro station at Beauharnois (Figure 3-21). The 2377-meter-long (7800-foot-long) Lake St. Francis boom has a centrally located navigation opening, allowing for ship passage during the formation and breakup periods. (The St. Lawrence is closed to winter navigation above Montreal.) The opening also allows some frazil to pass downstream during freezeup, hastening the upstream progression of the ice cover within the canal. The boom units consist of rectangular steel pontoons. A review of the available literature and interviews with operators found no evidence of massive quantities of wind-driven lake ice overriding the Lake St. Francis boom, as is the case with the Lake Erie boom.

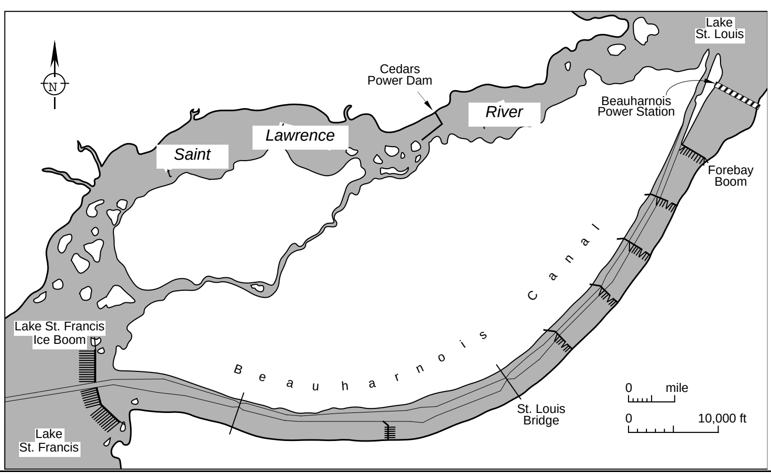


Figure 3-21. Locations of ice booms on the Beauharnois Canal.

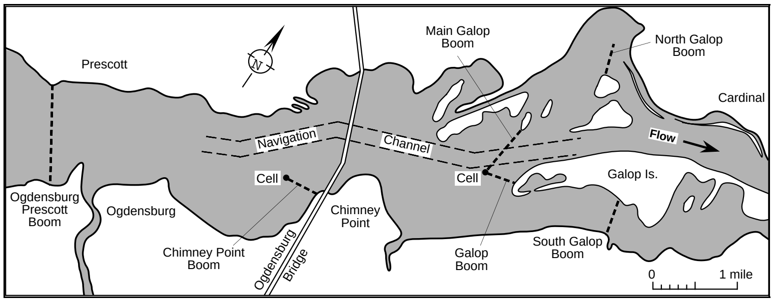
(2) *Ice Control for Hydropower.*

(*a*) Upstream of Montreal, the focus of the ice control efforts shifts from navigation and ice jam prevention to hydroelectric production. The Lake Erie and Lake St. Francis booms could be placed in this group, as they are both located upstream of hydrostations and their failure to perform results in production losses.

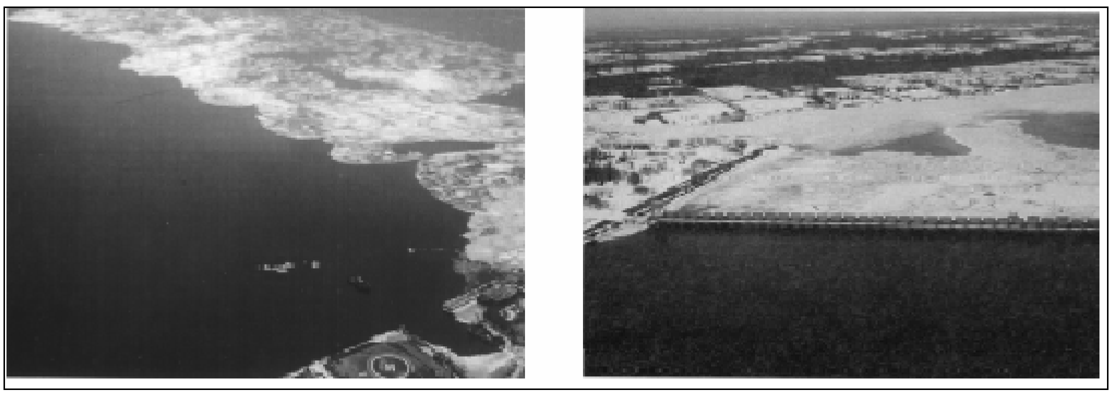
(*b*) Downstream of the Lake St. Francis boom, a series of six steel pontoon booms on the Beauharnois Canal promote the rapid formation of an ice cover, upstream of the power station (Figure 3-21). Rapid ice cover progression depends on flow reductions during the 7- to 14-day formation period. Because reducing flow reduces hydropower production, the operators closely monitor water temperatures and weather to decide when to form the cover. As with the Lake St. Francis boom, central gaps in the upstream booms allow some frazil and floes to move through to the downstream booms, speeding the upstream progression of the ice cover. The two booms nearest the forebay are constructed of double circular steel pontoons as shown in Figure 3-22. The four upstream booms within the canal, originally timbers, have been replaced in recent years by rectangular steel pontoons, reducing maintenance costs. Once the ice cover forms in the canal, flow increases smooth the cover's underside, decreasing hydropower head losses. Flow is again decreased for a short period at breakup to reduce the ice forces on the booms. Strain links on three of the anchor lines of the forebay boom provide valuable force data, which guide operators on when to reduce or increase the flow. Ice management at Beauharnois is estimated to increase winter production by an average of 200 MW (Perham and Raciot 1975, Perham 1975).

Figure 3-22. Boom on Beauharnois Canal, constructed of double steel pontoons.

(*c*) Ice control is equally important to hydropower production in the International Section of the St. Lawrence. The New York Power Authority and Ontario Hydro annually install six timber booms with a total length of roughly 4600 meters (15,000 feet) in the 13-kilometer-long (8-mile-long) reach from Galop Island to Ogdensburg (Figures 3-23a and b). The booms are part of an extensive ice management program, designed to maximize winter power production at the Moses Saunders Dam at Massena, New York, 65 kilimeters (40 miles) downstream. The booms form an ice cover upstream of Lake St. Lawrence, the dam's pool, reducing the production of frazil. Before the booms were installed in the fall of 1959, severe hanging dams formed at the up-stream edge of Lake St. Lawrence, resulting in significant production losses at the hydro stations at Massena. The booms have performed well, with only minor modifications, since their first deployment 34 years ago. Careful flow manipulation at the dam at Massena and the Iroquois control structure (Figure 3-23c), airborne surveillance, and field measurement of ice thickness and water temperature are all critical components of the overall ice management scheme on the International Section of the St. Lawrence (Perham 1974, Power Authority of the State of New York 1970).



a. Locations of booms.



b. Ice boom at Prescott, Ontario. **c. Iroquois control structure.**

Figure 3-23. Ice booms on the International Section of the St. Lawrence River.

(*d*) More recently, ice booms have been used successfully in northern Quebec during construction phases of the 10,300-MW James Bay Project on the La Grande River. Currently, there are no ice booms in use, however. On the 5300-MW Churchill Falls Project in Newfoundland, a boom promotes ice cover formation in Jacopie Lake, above the forebay. The boom also helps prevent jams in a channel constriction downstream at breakup (Atkinson and Waters 1978). Ice booms have been used upstream of hydropower dams in northern Europe, particularly in Norway and Sweden. In the late sixties, a boom made of double rows of 0.61-meter-diameter (2-foot-diameter) plastic pipe was installed on the Pasvik River, in the forebay area of the Hestefoss power plant on the Russian border with Norway. The plastic booms formed part of an elaborate ice control system involving stone groins and timber booms. The system was designed by Norwegian engineers to promote an ice cover during the plant’s construction (Kanavin 1970). The plant is now operated by the Russians and little is known about the recent performance of the booms (Roen and Tesaker 1988).

(*e*) Ice management on the Lule River in northern Sweden has similarities to methods used on the upper St. Lawrence. Upstream of the Vittarv power station, a 610-meter-long (2000-foot-long) boom spans the Lule River. Similar to the Beauharnois booms, a 100-meter-wide (330-foot-wide) central section allows floes to pass and contribute to the ice cover progression in a narrow reach downstream. The gap is closed once a cover has formed in the narrow reach. If the concentration of frazil floes is low during the formation period, large sheets of shore ice are broken or sawed free from locations below the boom and allowed to drift downstream to bridge in the channel, promoting arch formation. Like the International Section of the St. Lawrence, booms were installed only after major channel dredging projects failed to promote ice cover growth at all critical locations. Also like the upper St. Lawrence, the ice formation period is carefully coordinated with flow control at hydro stations up and down the river, and a special ice management group oversees the entire operation (Billfalk 1984).

(*f*) A physical model study by Decsi and Szepessy (1988) aided in the design of an ice boom on the Danube River, upstream of the dam on the Dunakiliti-Hrusov Reservoir, on the Hungarian–Czechoslovakia border. The 915-meter-long (3000-foot-long) boom stabilizes shore ice and prevents it from entering the forebay area. In conjunction with the effort to stabilize the shore ice, an ice-free main channel is maintained, allowing for conveyance of floes from upstream through the gates on the dam.

(*g*) Two ice booms were installed on the lower Vistula River in Poland during the winter of 1986 to hasten the formation of a stable ice cover and help prevent hanging dam formation on the upper part of the Wloclawek Reservoir (Grzes 1989). The first boom was located on the reservoir itself, and the second on the free-flowing river upstream of the reservoir. Similar to ice control on the International Section of the St. Lawrence, boom placement was done in conjunction with dredging to reduce the surface water current velocity.

(3) *Formation Booms to Prevent Ice Jam Flooding Along Rivers.* Formation booms have helped solve ice jam problems on pool-riffle rivers. Freezeup jams occur naturally at slope reduction points, progressing upstream, sometimes flooding towns and property. Thick frazil deposits may also increase the ice volume supplying potential breakup jams, or if the deposits remain in place at breakup, the frazil may stop ice floes from upstream, resulting in a breakup jam. A formation boom may be installed to create an ice cover upstream of the traditional problem area. The ice cover behind the boom reduces local frazil production and captures much of the frazil arriving from upstream.

(*a*) This was the design intent of the timber boom installed in 1989 on the Salmon River upstream of Salmon, Idaho, a town that had historically experienced a freezeup ice jam flood 1 out of every 3 years. During the Salmon boom's second year of use, in 1990–91, the right bank anchor was relocated 73 meters (240 feet) upstream as shown in Figure 3-24. The new configuration diverted surface flow and ice away from the zone of highest surface velocity, greatly improving the frazil capture efficiency. Although difficult to quantify because of the short period of record, the Salmon boom appeared to have a positive effect in terms of limiting the progression of potential freezeup ice jams below the town of Salmon during the winters of 1989–1992 (Axelson et al. 1990, White 1992). Owing perhaps to a trend of milder winters, the boom has not been installed since 1992.

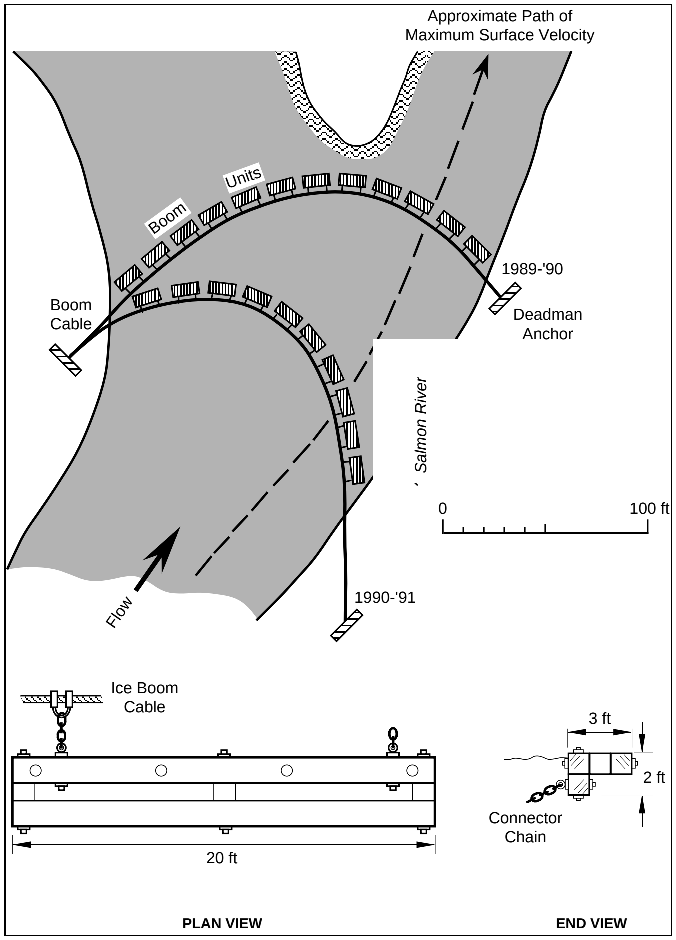


Figure 3-24. Two boom configurations tested at Salmon, Idaho.

(*b*) A well-sited formation boom on the Allegheny River (Figure 3-25) significantly reduced the volume of frazil depositing every winter at the mouth of Oil Creek near Oil City, Pennsylvania. The Allegheny boom, an innovative upstream vee [V] design, pushes flow and ice towards the shores, to capture frazil and form a cover at a location where a traditional single-sag boom had failed. The tip of the vee was connected by cables to anchors on each bank, eliminating the need for a mid-channel anchor. Because the hydraulic conditions at the site are marginal, successful ice cover growth behind the boom depends on flow reduction at an upstream dam during the formation period. This boom, in conjunction with a weir structure to trap frazil on Oil Creek, has significantly reduced the occurrence of breakup ice jam flooding in Oil City since its first installation in 1982 (Perham 1983, Deck and Gooch 1984).

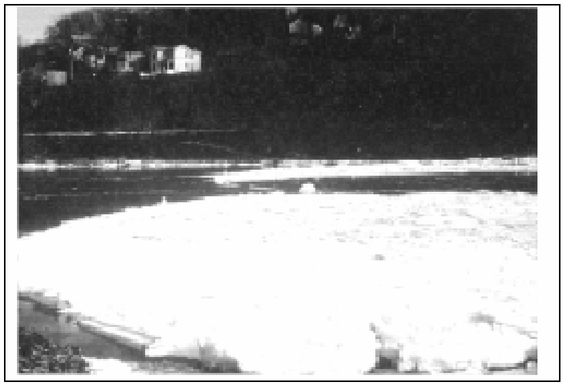


Figure 3-25. Allegheny River ice boom.

(*c*) A pair of 61-meter-wide (200-foot-wide) ice booms were installed in 1968 on the North Platte River, seven miles upstream of Casper, Wyoming, to protect a residential development from freezeup ice jam flooding. A physical model study by Burgi (1971), of the Bureau of Reclamation, found an upstream vee design optimal, similar to the configuration used over a decade later on the Allegheny River boom at Oil City. However, on the North Platte a single-sag design, rather than the upstream vee, was used, perhaps owing to the added complication of placing mid-channel anchors in a moveable-bed river. The design was also unique in that the 36-centimeter × 51-centimeter × 3.6-meter (14-inch × 20-inch × 12-foot) timbers had steel spikes protruding 15 centimeters (6 inches) above and below, in an attempt to increase frazil capture efficiency.

(4) *Groins.* With the exception of artificial islands, the Montreal Harbor ICS, and the Japanese sink-and-float booms, all structures described up to this point have been floating, flexible, seasonally deployed, and relatively inexpensive. None of the structures described so far cause a significant water level change in the absence of ice or act as a barrier to migrating fish. Aside from mid-channel anchors for multiple-span booms, ice booms have little negative effect on the riverbed. Much of this is in contrast to the next group of fixed-sheet ice retention structures, which includes groins, weirs, and dams.

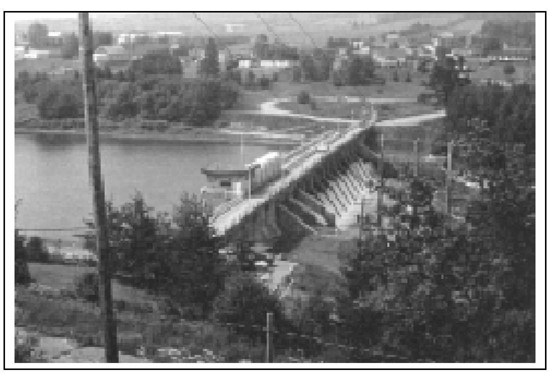
(*a*) As mentioned earlier, the majority of sheet ice retention methods are successful only under the hydraulic conditions of relatively low energy slope, low water surface velocity, and low Froude number. By raising the upstream water level, groins, weirs, and dams may create conditions favorable for the formation of a sheet ice cover. In addition, structurally raising the water level and reducing the surface water velocity may make the capture of ice behind a boom possible where it was not before.

(*b*) Stone groins, or jetties, extending perpendicularly into the channel from the shoreline, stabilize the shore ice and may, under the appropriate hydraulic conditions, encourage bridging and ice cover formation across the channel. The tops of these structures are typically above the water level during the freezeup period. As an added benefit, the groins raise the upstream water level, creating hydraulic conditions more favorable for ice cover formation, with or without the use of ice booms. Groins, because they do not cross the entire channel width, have an environmental advantage over weirs and dams as they do not totally obstruct navigation or migrating fish.

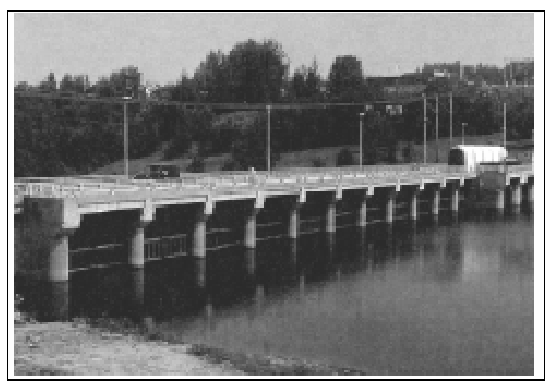
(*c*) A system of groins, used in conjunction with booms, promotes ice cover formation upstream of the hydrostation at Hestefoss in northern Norway (Kanavin 1970, Perham 1983). On the Burntwood River of the Churchill River Diversion Project, Manitoba Hydro uses two opposing groins, or wing dikes, to raise the upstream water level and promote ice cover formation (Perham 1983). Updated information on the performance of these structures is not available. Burgi modeled opposing groins as a means of enhancing boom performance on the North Platte, upstream of Casper, Wyoming (Burgi 1971). The groins were not built, however.

(5) *Dams and Fixed Weirs.* Although seldom constructed solely for ice control, the most effective ice control structure is a dam or weir. By raising the water level and reducing the water current velocity, these structures may allow the thermal growth of an ice sheet or serve as a barrier for the juxtaposition of frazil or frazil pans. The pool behind a dam or weir stores frazil transported from open reaches above, preventing its transport to a potential freezeup jam site below. A later part of this Section describes how weirs with piers reduce the severity of breakup ice jams by retaining a stable ice accumulation, thus limiting the ice supply to potential downstream jams.

(*a*) Sartigan Dam, upstream of St. Georges, Quebec, with a drop of 12 meters (40 feet), creates a 4-kilometer-long (2.5-mile-long) pool on the Chaudiere River (Figure 3-26). The dam was designed and built in 1967 for the sole purpose of ice control (Michel 1971). Much of the frazil that once contributed to the severe jams at St. Georges is now stored beneath the pool's ice cover. Small stone weirs, some experimental, have been used to form pools and trap frazil on other rivers in Quebec, Ontario, and northern New England (Perham 1983, Cumming-Cockburn and Associates Ltd. 1986a).



a. Downstream side.



b. Upstream side, showing the ice retention grates.

Figure 3-26. Ice control dam on the Chaudiere River at St. Georges, Quebec.

(*b*) A 1.8-meter-high (6-foot-high), concrete-capped, rock-filled gabion weir with sluiceway slots on the Israel River has provided the town of Lancaster, New Hampshire, some ice jam relief by reducing the frazil quantities historically deposited downstream of town. Although designed to retain frazil, the weir to some degree acts as a barrier to breakup ice, as shown in Figure 3-27 (Perham 1983, Axelson 1991). The weir is now in disrepair, with its fish passage sluices and its impoundment partially filled with gravel. Charged with its maintenance, the town is discussing options with the state for removal of the weir, in spite of no ice jam floods occurring in Lancaster since the weir's installation in 1981.

Figure 3-27. Ice control weir on the Israel River, Lancaster, New Hampshire, July 1994.

(*c*) The 93-meter-wide (306-foot-wide) gated concrete weir, shown in Figure 3-28, creates a 1.5-meter-deep (5-foot-deep) pool to trap frazil on Oil Creek in Pennsylvania. The weir is part of the solution to Oil Creek's historically severe ice jam problem. Initially, a boom was seasonally installed upstream of the weir until it was found that an ice cover formed behind the weir without the boom in place. Although not the original design intent, the Oil City weir affords some degree of breakup protection by delaying movement of the upstream ice until the downstream ice has had a chance to clear out.

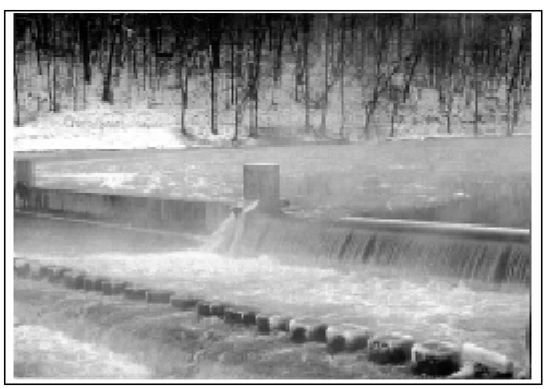
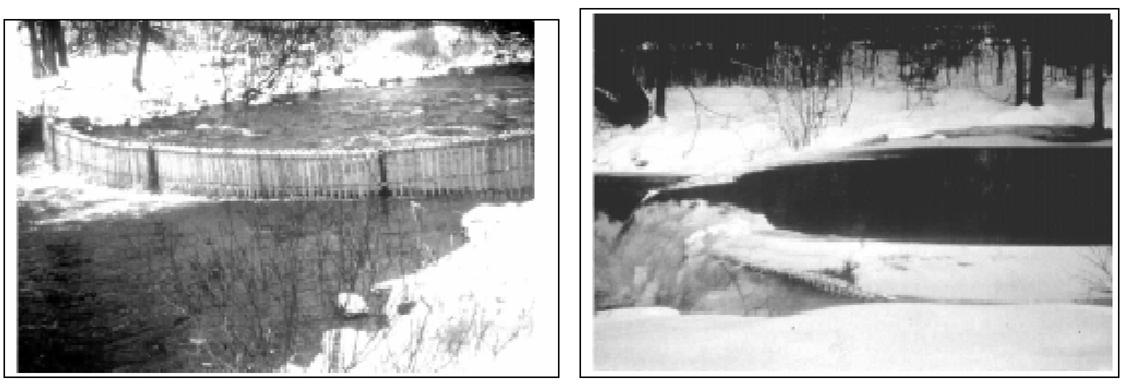


Figure 3-28. Ice control weir on Oil Creek, upstream of Oil City, Pennsylvania.

(*d*) As an example of the effectiveness of a system of dams in ice control, the upper Mississippi above St. Louis contributes little or no ice to the severe ice jam problems in the undammed middle Mississippi, between St. Louis and Cairo, Illinois. Most of the problem ice originates in the Missouri River, undammed for 1287 kilometers (800 miles) above its confluence with the Mississippi, or from ice generated in middle Mississippi itself. In addition, many of the ice control measures, existing or proposed, are in response to the removal or decay of existing dams across the northern United States and southern Canada. There has been a marked increase in ice jam flood frequency on smaller rivers as small mill dams fall into disrepair and are removed.

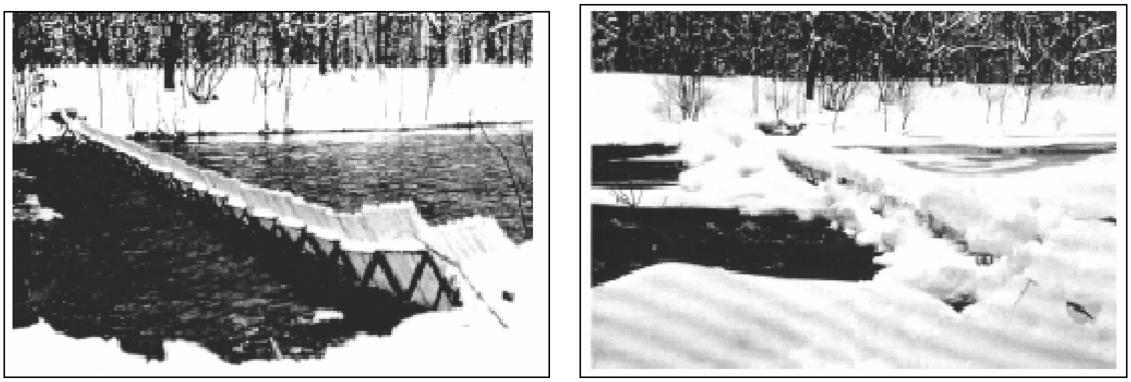
(6) *Removable Weirs.* Experimental tension weirs placed in small rivers have successfully created pools and ice covers for the purpose of limiting frazil production. Researchers at CRREL initially used a structure consisting of vertical wood 2×4s attached to top and bottom cables, referred to as a fence boom (Figure 3-29) (Perham 1986). The intent was for frazil to accumulate in the gaps, creating an ice dam and an impoundment. Field tests were relatively successful but scour was a problem in unarmored riverbeds. Other materials such as chain link fence were tried with relative success (Foltyn 1990).



a. Installed condition. **b. After ice cover formation.**

Figure 3-29. Fence boom installed on the Mascoma River, Lebanon, New Hampshire.

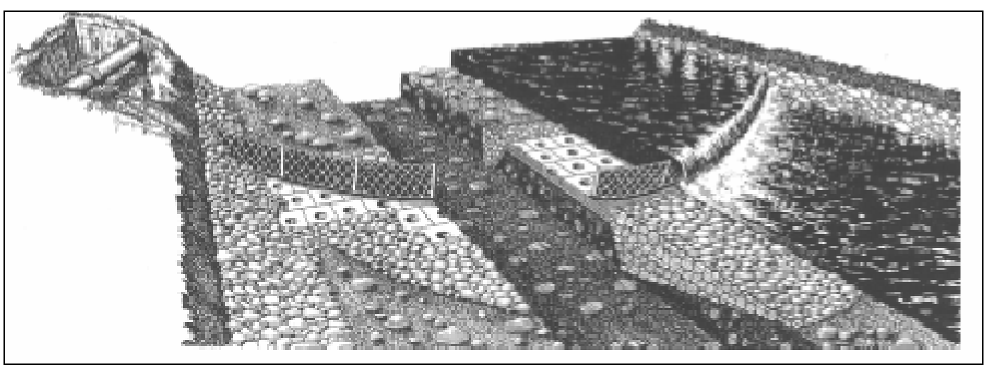
(*a*) Mineta et al. (1994) reported the successful deployment of a freestanding fence boom or "ice fence" on the Penkeniuppi River on the Japanese island of Hokkaido. Inspired by Perham's fence boom, this structure is made up of 0.91-meter-wide (3-foot-wide) individual steel frames supporting 1-meter-long (3.3-foot-long), 2×2 wood pieces, inclined away from the flow at 60 degrees. The gap width is 7.1 centimeters (2.8 inches) and the frames are connected by steel pipe. Figure 3-30 shows the units spanning a 27.4-meter-wide (90-foot-wide) riffle section of river, 305 meters (1000 feet) upstream of a small power dam. Since installed in 1991, the ice fence has eliminated the previously frequent interruptions to power production resulting from frazil accumulations at the intakes. The frazil accumulation that forms behind the structure at the channel center diverts water flow towards the banks, where velocities reach 1.1 m/s (3.5 ft/s), resulting in some bed scour. To reduce the scour, the banks are armored with stone-filled gabions. The structure was developed through a cooperative effort between engineers at Iwate University and the Hokkaido Electric Power Co.



a. 24 December 1991. **b. 23 January 1992.**

Figure 3-30. Ice fence on the Penkeniuppi River in northern Japan. (Photos courtesy of Kenichi Hirayama and the Hokkaido Electric Co.)

(*b*) The winters of 1993 and 1994 saw successful field demonstrations of an impermeable tension weir at a site on the Ompompanoosuc River in Union Village, Vermont. The 18.3-meter-wide (60-foot-wide) structure, consisting of vertical steel posts, a wire rope mesh, and a rubber-like fabric, created a 0.91-meter-deep (3-foot-deep) pool, initiating the formation of a smooth sheet ice cover (Figure 3-31). Concrete and riprap bed protection prevented all but minor scour. The Union Village structure fulfilled its design objectives of low cost, easy installation, and applicability to small, unnavigable rivers. The issue of scaling removable weir technology up to larger rivers is worth examining, as these structures do not interfere with open water season uses of the river such as navigation and recreation.



a. Schematic showing the weir, anchors, and bed protectors.

Figure 3-31. Tension weir on the Ompompanoosuc River at Union Village, Vermont.

b. Ice cover formed behind the weir.

Figure 3-31 (cont'd). Tension weir on the Ompompanoosuc River at Union Village, Vermont.

(7) *Inflatable Dams*. Inflatable dams are increasingly common on northern rivers, their main use being crest control on existing concrete weirs. The structures perform well in ice and do not experience the seal leakage and icing problems common to conventional steel gates. They also survive the breakup ice run, which is often not the case with conventional wooden flash-boards. Inflatable dams cost less and are more environmentally acceptable that fixed control weirs because, when they are deflated and lying flat in their sill, they do not impede fish passage or collect sediment. A 4.5-meter (15-foot) inflatable dam installed in 1992 on the Mississquoi River in Highgate Falls, Vermont, allowed Swanton Electric to raise the pool, eliminating previous problems with frazil blackage of their hydro intakes. The structure also has beneficial effects during breakup (see Paragraph 3-11*e*).

(8) *Frazil Collector Lines and Ice Nets.* Tests of ice cover formation using arrays of ropes, or frazil collector lines, by Perham (1981, 1983) were relatively successful (Figure 3-32). Tangling of the lines in turbulent water was a problem, however. In addition, should the lines be carried away at breakup, they might present a nuisance or hazard at downstream locations. Sahlberg (1990) described a similar method, “ice nets,” to capture frazil and cause an ice cover to form. Ice nets were successfully deployed in the winter of 1989–90 in front of the intakes at the Stornorrfors hydrostation on the Ume River in Sweden. In their few applications to date, frazil nets and lines have promoted ice cover growth in channels with surface velocities as great as 0.91 m/s (3 ft/s), compared to 0.76 m/s (2.5 ft/s), the upper velocity limit for other sheet ice retention structures.

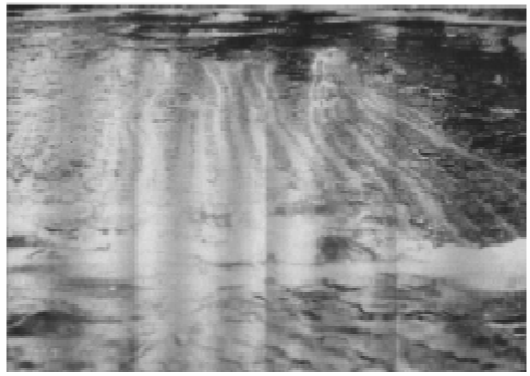


Figure 3-32. Frazil collector lines being tested on the Mascoma River, 1981. The view is looking upstream. Frazil accumulates on the individual lines, which are floating near the surface.

3-11. Breakup Ice Control Structures. Many of the previous examples illustrate the difficulty in categorizing sheet ice retention structures separately from structures to control breakup ice, as many perform both roles. This Paragraph will describe structures whose main function is breakup ice control. Section III will describe important aspects in breakup ICS design. The technology for breakup ice control is less developed and less well documented than sheet ice retention technology. In many ways, the problem is more complex. A breakup ice control structure may be designed to cause an ice jam at a desired location. Forces on a breakup ice control structure are typically much greater than on a sheet ice retention structure. On steep rivers with dynamic breakups, forces on the ice accumulation may be sufficient to cause internal failure and thickening of the accumulation by shoving, rather than by juxtaposition, as with sheet ice retention. Forces resulting from momentum transfer, both from within the ice accumulation and from direct impact of ice pieces on the structure, are much greater than in the sheet ice retention case. A breakup ice control structure may cause the ice to thicken to the point where flow is impinged along the bed or banks, resulting in scour. For this reason, a significant part of the cost of the structure may lie in bed and bank protection. Discharges associated with breakup often reach flood levels, in contrast with the base flow levels commonly associated with the freezeup period. The design of a breakup structure must address the issues of ice supply, ice storage, flow relief, and ice accumulation stability. If the breakup and annual peak flows coincide, as is often the case, the breakup structure must be designed to retain the upstream ice while passing the flood flow. This may be achieved either by storing ice behind a grounded jam in the main channel while bypassing the flow in the overbank, or by storing the bulk of the ice in the floodplain areas while routing the flow under a stable, floating ice accumulation in the main channel. For the grounded jam with bypass flow in the floodplain, erosion protection must be provided, particularly where the flow exits from and returns to the main channel. A weir is usually needed if relief flow is to pass under a stable floating ice accumulation in the main channel, because design velocities must be low enough, and the depth of flow great enough, to avoid excessive thickening.

a. Purpose. The purpose of a breakup ice control structure may be simply to retain the breakup ice run at an undeveloped location upstream of the historical ice jam problem site, reducing the flood threat to settled areas. River towns at transition points from steep to mild slope pose a particularly severe ice jam problem, as their location not only favors the deposition of frazil but provides a likely stopping place for the breakup ice run. These changes in slope often coincide with river confluences. As mentioned previously, many breakup structures such as weirs have the dual purposes of creating an impoundment to capture and store frazil during the course of the winter, as well as retaining the breakup ice run.

b. Types. Wire rope breakup structures have been used on small rivers in New England with limited success. If the intent is to create a grounded jam, a breakup ice control structure may be as simple as a line of boulders or piers, spaced at intervals across a river channel. Weir structures and weirs with piers have successfully retained floating ice accumulations, reducing ice jam severity at downstream locations. In addition to their value in trapping and storing frazil, large dams are extremely effective barriers for breaking up ice runs. Inflatable dams are a new, low-cost alternative for controlling breakup ice jams. Some unique structures prevent breakup ice from passing dam spillways. Finally, structures designed to withstand the forces generated by pack ice off the northern coast of Japan might be applied to breakup ice problems on major U.S. rivers.

c. Examples.

(1) *Wire Rope Structures.* Two wire rope ice retention structures, used on northern New England rivers in the 1970s, had only limited success. The first was a war surplus submarine net tested on the Israel River at Lancaster, New Hampshire, and the second was a boom made of used ski lift cables and truck tires, used on the Lamoille River at Hardwick, Vermont. Recent physical model tests by Morse et al. (in review) show innovative pier-net and boom-net ICS as a potentially viable breakup ice control method. Though floating booms are traditionally considered ice formation structures, Fleet Technology Ltd. of Canada has installed a series of three steel pipe booms on Riviere des Prairies, Quebec, that retains the breakup ice run at water velocities as high as 3.9 ft/s (1.2 m/s).*

(*a*) Perham (1983) reported the use of an experimental breakup boom on the Chaudiere River in Quebec in the sixties. Available descriptions are sketchy. Apparently the boom resembled a horizontal rope ladder constructed of two 2.54-centimeter (1-inch) cables and structural steel rungs. The spaces between the rungs were filled with wooden blocks. Attached to heavy concrete shore anchors, the boom was expected to retain breakup up to a discharge of 7200 cfs (204 m^3/s) (the four-year flood). The boom was used in conjunction with a stone weir, which was located a short distance downstream.

(*b*) At Hardwick, Vermont, two booms constructed of used ski lift cables and truck tires are installed on the Lamoille River each winter. In order for the tires to stand vertically, the cables are relatively taut, even in the no-load condition. Because of this no-sag design, cable forces during the ice run are high enough to cause failure. Nevertheless, by temporarily retaining up-

*Boom proposal to Alcoa by Fleet Technology, Inc.

stream ice, the tire booms appear to stagger the arrival of ice and water surges in the thickly settled reach downstream, reducing the chance of a serious ice jam.

(2) *Piers and Boulders.* A pier structure on the Credit River has protected property downstream in Mississauga, Ontario, since its construction in 1988 (Figure 3-33). The ice control structure consists of 14 concrete piers on 2-meter (6.6-foot) centers. The tops of the piers are roughly 0.5 meters (1.5 feet) above the 1.5-year open water flood level. A grounded jam forms behind the piers, with the top of the ice rubble 0.91 meters (3 feet) above the top of the pier height. The resulting impoundment is designed to store 95,000 cubic yards (72,600 cubic meters) of ice, two thirds on the right floodplain and the remaining third in the channel. Relief flow passes around the structure on the right floodplain, which is spanned by two rows of armor stone, also with 2-meter (6.6-foot) gaps. To encourage relief flow to enter the floodplain, the tops of the armor stone are 0.5 meters (1.5 feet) lower than the tops of the piers in the main structure. Aside from some scour, occurring where relief flow from the floodplain reenters the main channel, and ongoing debris removal, the structure has performed well to date (Cumming-Cockburn and Associates Ltd. 1986b).

(*a*) A granite-block breakup ice control structure, shown in Figure 3-34, was constructed in the Lamoille River, upstream of Hardwick, Vermont, in September 1994. The four blocks are located at the downstream end of a natural pool, with a gap width of 4.3 meters (14 feet). Two smaller blocks bolted to the sides of each of the main blocks increase stability, bringing the total weight to 40 tons (36,280 kg). The upstream faces of the blocks are sloped at 45 degrees. The block tops are roughly 1 foot above the elevation of the right floodplain, which passes the relief flow but is not intended as an ice storage area. A major portion of the structure’s cost lies in riprap for bed and bank protection in the vicinity of the blocks, and also along the banks where the relief flow leaves and re-enters the main channel. The design process included a physical model study in the refrigerated research area in the Ice Engineering Facility at CRREL (Lever 1997). Lever and Gooch (2005) report 16 breakup ice events in the 11 years since construction with no ice jam flooding in the village of Hardwick. This compares 9 ice jam flood events from 1964 to 1993, three of which were severe. The analysis found the ICS to reliably retain ice when floe thickness was 1 ft or greater. In the event of thinner floes, the ice either held at the structure for several hours or passed between the granite blocks, but in no cases did significant breakup ice jams form downstream in Hardwick Village.

(*b*) Three poured concrete “icebreaker” blocks were installed in the Mohawk River, 1.6 kilometers (1 mile) above the village of Colebrook, New Hampshire, some 50 years ago. The bed slope at the blocks’ location is relatively steep, and the blocks do not stop the breakup ice run. After consulting with researchers from CRREL, the New England Division of the Corps of Engineers in the early sixties planned to create an ice storage reservoir to alleviate the ice jam flooding at Colebrook. The proposed timber crib structure, with a centrally located concrete spillway, was never built, however.

Figure 3-33. Credit River ice control structure following breakup, March 1994. Note the ice stored on the right flood plain. (Photos courtesy of Harold Belore.)

Figure 3-34. Cut granite block ice control structure in Hardwick, Vermont, following breakup, March 1995.

(*c*) Two pier structures in Hungary protect the villages of Jaklovce and Zilnia from ice jam flooding (Brachtl 1974). Both structures consist of 20-centimeter-diameter (8-inch-diameter) concrete-filled steel piles, on 2-meter (6.6-foot) centers, inclined in the downstream direction. The tops of the piles are roughly level with the floodplain elevation. The structures are designed to convey a flood discharge with the entire structure clogged with ice or debris. Installed around 1970 to solve ice jam flood problems created by reservoir construction, little is known about their performance since 1974. The Hungarian structures are similar to the structure on the Credit River. Both use piers, spaced at 2 meters (6.6 feet), to create grounded jams, forcing relief flow and ice onto the floodplain.

(*d*) A low-cost concrete pier structure was developed through a physical model study done at CRREL (Lever et al. 2000). Similar in concept to the Hardwick structure, it has nine 1.5-meter (5-foot) diameter, 3-meter (10-foot) high cylindrical piers with 3.7-meter (12-foot) gaps between. Built in 2005, the ICS is designed to retain breakup ice runs on Cazenovia Creek near Buffalo, New York, reducing ice jam flood damage. A grounded jam forms in the main channel behind the piers, while relief flow bypasses the jam in an adjacent floodplain (Figure 3-35).

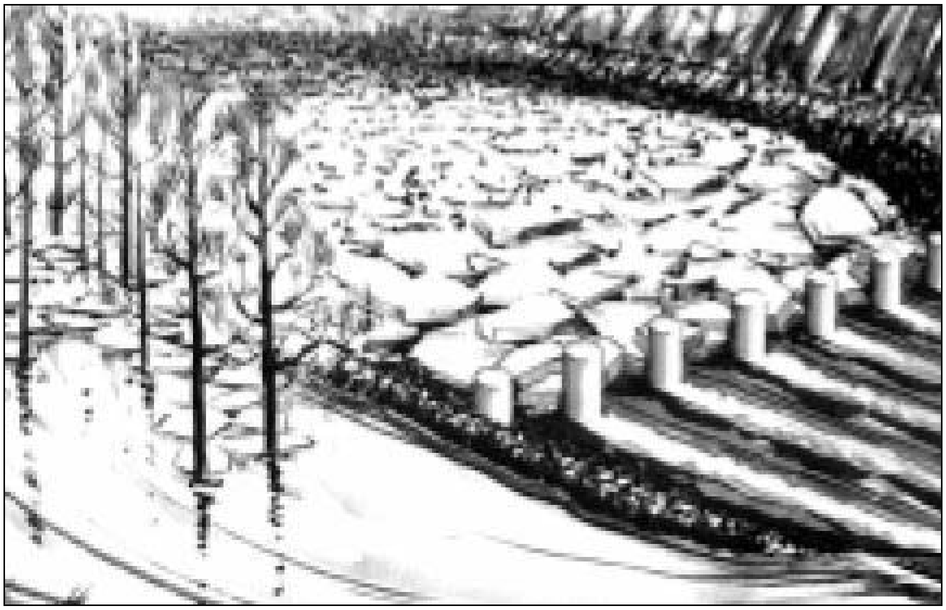


Figure 3-35. Conceptual drawing of Cazenovia Creek ICS.

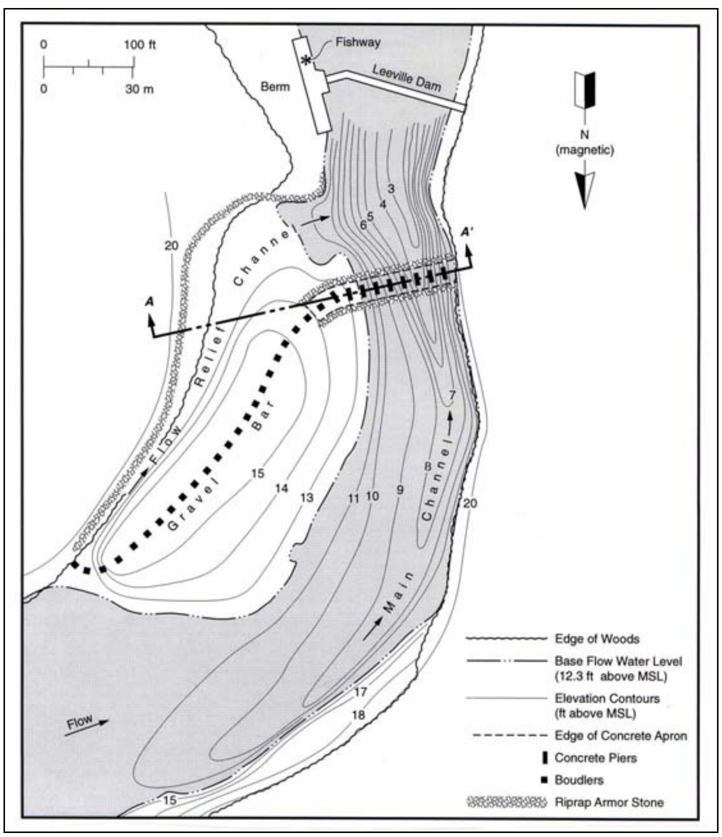


Figure 3-36. Plan view of the Salmon River ICS.

(*e*) A second pier structure is now under construction on the Salmon River, which flows into the Connecticut River below East Haddam Connecticut. CRREL and the New England District of the Corps developed a design that uses nine rectangular concrete piers, spaced 12 feet apart, to retain ice in the main channel upstream of the dam, and a row of boulders to keep ice off an adjacent gravel bar intended to convey relief flow (Figure 3-36) (Tuthill et al. 1995, Tuthill and White 1997). The design will include a dredged basin upstream of the piers to trap silt and sand. The ICS will mitigate a breakup ice jam flood problem that resulted from the lowering of a small dam in 1979 for reasons of safety and fish passage.

(3) *Weirs with Piers.* A 4.6-meter-high by 79.3-meter-wide (15-foot-high by 260-foot-wide) concrete weir topped with 1.8-meter-high (6-foot-high) piers on the Ste. Anne River protects the town of St. Raymond, Quebec, from breakup ice jam flooding (Figure 3-37) (Deck 1984). The piers are spaced roughly 6.1 meters (20 feet) apart. An earth berm connects the structure's left end to the higher ground to the left of a 152-meter-wide (500-foot-wide) floodplain. The structure creates an ice storage reservoir 213-meters-wide (700-feet-wide) by 900 to 1200 meters (3000 to 4000 feet) long, passing the relief flow beneath the ice accumulation in the main channel and directly over the weir. The design intent was to reduce the approach velocity and water surface slope so that ice floes arch between the piers and excessive ice accumulation thickening and grounding do not occur. In addition to retaining the breakup ice run, the pool behind the weir intercepts frazil ice, preventing its deposition in the flat-lying section downstream in the village of St. Raymond. Recent reports by Morse et al. (in review) indicate that the structure does not always retain ice, however, and ice jams still flood the village to some extent.

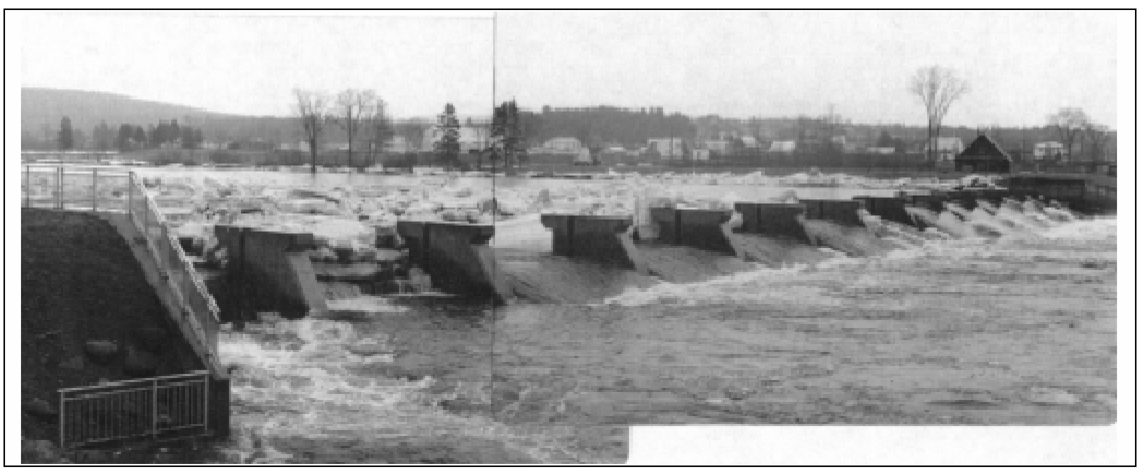


Figure 3-37. Weir with piers ice control structure on the Ste. Anne River, St. Raymond, Quebec. (Photo courtesy of Marc Delagrave, Roch Itée Groupe-conseil, Sainte-Foy, Quebec.)

(*a*) Information on the design approach and performance of the St. Raymond structure was difficult to find. The design process was somewhat empirical, relying on the successful experience with the ice control dam at St. Georges. During breakup, a floating accumulation of broken ice pieces, and not sheet ice, arches between the piers. A similar breakup structure was planned but never built on the Becancour River, near Trois Rivieres, Quebec. The design included a weir to create upstream hydraulic conditions for a stable floating equilibrium ice accumulation, for the expected range of breakup discharges. The plans for the Becancour structure included a 43-meter-wide (140-foot-wide) weir with piers spaced at 6.1 meters (20 feet) and a gated bottom outlet.

(*b*) The St. Raymond structure influenced the design of a similar breakup ice control structure for Cazenovia Creek near Buffalo, N.Y. (Gooch and Deck 1990). Although a promising design was developed through a physical model study at CRREL, lack of funding prevented construction of the prototype. Instead, a design was developed at CRREL for a low-cost pier structure that was built in 2005 [See subparagraph 3-11(2)(*d*)].

(4) *Breakup Ice Retention at Dam Spillways.* The Sartigan Dam at St. Georges, Quebec (Figure 3-26), is mentioned again in this Paragraph owing to its role as a breakup ice control structure (Michel 1971, Perham 1983). The dam is a larger version of the Ste. Anne River weir-with-piers structure at St. Raymond, with eleven 6.1-meter-wide (20-foot-wide) overflow gates, separated by concrete piers. The gates are equipped with steel grates with 0.61-meter-wide by 1.1-meter-high (2.0-foot-wide by 3.5-foot-high) openings to retain breakup ice. Morse et al. (in review) reports that the grates are probably not necessary, as the ice run typically stops at the head of the impoundment and does not reach the dam gates. Residents of St. Georges interviewed in 1994 believed that the dam has solved the town's historical ice jam flood problem.

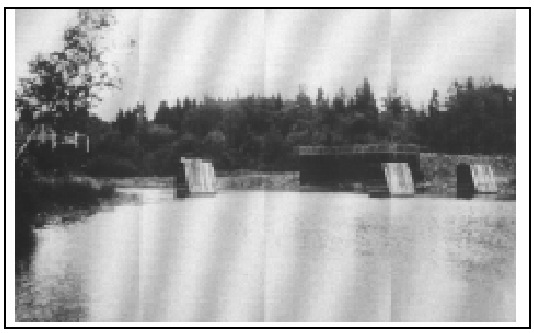


Figure 3-38. Rock-filled timber cribs upstream of the dam at Cherryfield, Maine.

(*a*) A 2.1-meter-high (7-foot-high) timber crib dam, designed by the Corps of Engineers, was constructed on the Narragaugus River in 1961 to protect the town of Cherryfield, Maine (roughly 1.6 kilometers [1 mile] downstream), from breakup ice jams (Figure 3-38) (Perham 1983). Upstream of the dam are three rock-filled timber cribs on 15.2-meter (50-foot) centers, designed to prevent large pieces of sheet ice from passing the dam's 43-meter-wide (140-foot-wide) central spillway. The dam creates an ice storage reservoir and is similar to the proposed ice control project for the Mohawk River at Colebrook, New Hampshire. During an intense rainfall event in February 1968, the sheet ice behind the dam remained intact. There was sufficient ice downstream of the dam to supply a jam in Cherryfield, however. This experience and others show that an effective breakup ice control structure needs to be quite close to the site being protected. Although there have been frequent small jams in Cherryfield since 1968, there have been no incidents of ice jam flooding, suggesting that the dam continues to have a positive effect. The ICS was observed to perform as designed during a breakup in March 2005.

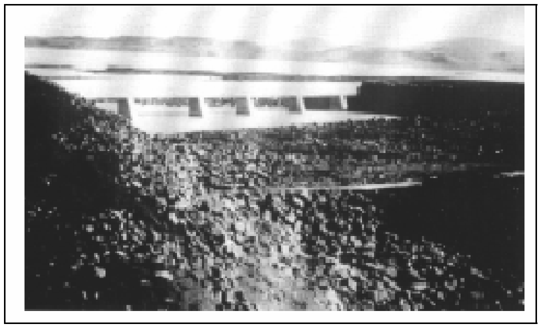


Figure 3-39. Spillway barrier at the outlet of the Sigalda Reservoir in Iceland.

(*b*) A fixed concrete spillway barrier at the outlet of the Sigalda Reservoir in Iceland was designed to prevent ice floes from entering the Tungnaa River and damaging the hydroelectric installations downstream during low-frequency, high-discharge events (Figure 3-39) (Perham 1983). No extreme runoff events have occurred to test the structure's effectiveness since its construction in 1977.

(*c*) A timber boom in conjunction with a warm-water pumping system prevents large ice floes from passing the spillway at Dickenson Dam on the Heart River in North Dakota. The boom was installed in 1984 after a large floe damaged the crest gate during breakup. The boom has performed well, requiring only minor maintenance. The design is unique in that the main cable is guyed out at two points to counterweights, to conform to the spillway layout (Burgi and Krogstad 1986).

d. Pack Ice Barriers. Yamaguchi et al. (1981) developed a removable pack ice barrier, constructed of ballasted 55-centimeter-diameter (22-inch-diameter) steel pipe. The structures, shown in Figure 3-40, are 5.8 meters (19 feet) high and 10 meters (33 feet) long. Placed in rows, the barriers have protected shorelines and shoreline structures from damage by 0.4- to 0.5-meter-thick (1.3- to 1.6-foot-thick) wind- and wave-driven pack ice in the Sea of Okhotsk. In rock bed situations, no foundations are needed. Water can flow freely through the structures' legs, so the effect on marine life is minimal. Saeki (1992) reported the successful performance of the pack ice barrier and described similar structures. Although this is a marine application, structures of this type could be adapted to retain breakup ice on major U.S. rivers. Problems of water level fluctuation and foundations in soft sediment or movable-bed rivers would have to be overcome, however.

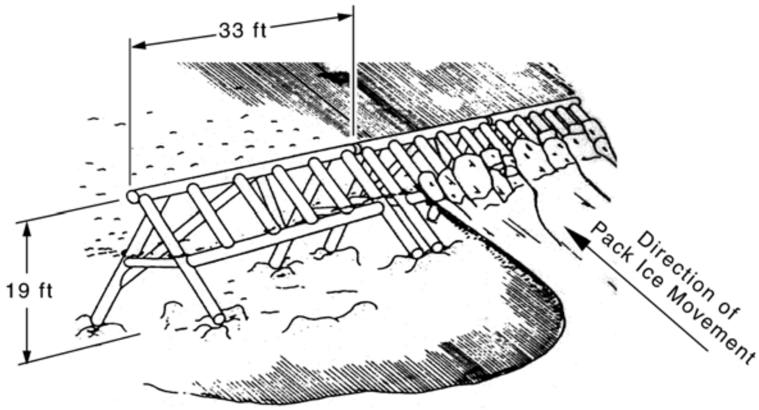


Figure 3-40. Pack ice barrier, Saroma Lagoon, Sea of Okhotsk. The direction of ice movement is from lower right to upper left. (After Yamaguchi et al. 1988.)

e. If an inflatable dam has sufficient height, a constant pool elevation can be maintained during the passage of the breakup hydrograph, preventing or delaying breakup of the pool upstream of the dam. This is the case with the inflatable dam on the Mississquoi River at Highgate, Vermont. As the discharge increases, the dam deflates, maintaining a constant stage and preserving the ice cover on the pool. This intact ice stops the upstream ice run and also provides time for the ice cover downstream of the dam to break up and clear out. Since the inflatable dam was installed in 1992, there has been no ice jam flooding downstream of it.

3-12. Design of Breakup Ice Control Structures. This Paragraph provides engineering design guidance for breakup ice control structures (ICSs). Basic ICS types, their purposes, advantages, and disadvantages are briefly described. The basic approach, theory, and numerical and physical models used in breakup ICS design are presented and illustrated through case studies, such as the Cazenovia Creek ICS, which is described in detail by Lever et al. (2000). The purpose of a breakup ICS is to retain the breakup ice run upstream of a traditional ice jam problem area. For example, the ICS might be sited to retain the ice run in an uninhabited section of river, preventing ice jamming and flooding in a thickly settled area downstream. More recently, breakup ICSs are being considered as a means of preventing ice-related scour associated with dam removals or contaminated sediment remediation projects. In the case of dam removal, an ICS would retain ice that once stopped behind the dam, preventing its transport downstream to jam and flood a populated area. For contaminated sediment remediation, an ICS might be located upstream of a capping project to prevent ice jams in the project area and under-ice scour of the cap and underlying bed material (Alcoa 2004). Breakup ice control structures are defined as river projects with the primary purpose of retaining the breakup ice run. The full range of breakup ICS types are described in Paragraph 3-11 and details on selected structures can be found in Tuthill (2005). This Paragraph on breakup ICS design also provides background grouping structures in the categories of i) dams and weirs, ii) weirs with piers, and iii) simple piers and boulders.

a. Dams and Weirs as Ice Control Structures. Although not their primary purpose, larger gated dams provide extremely reliable ice control as they typically retain the breakup ice run for all but the highest flows. Depending on the pool configuration and ice and flow conditions, overflow weirs may also retain or delay the breakup ice run, particularly where the pools contain significant frazil ice deposits that tend to lock the ice cover in place. Drawbacks of dams and weirs are capital expense and environmental disruption, as they trap sediment, impede fish passage, and in some cases, interfere with recreational uses of the river.

b. Weir with Piers ICS. Weirs with piers spaced along the top are designed to retain the breakup ice and allow water flow to pass beneath the ice accumulation and over the weir crest. To be successful, pool depth must be sufficient to create a mild upstream water surface slope and relatively low water velocity within the breakup discharge range. Under these conditions, downstream forces on the ice attributable to water drag and gravity will be low enough that the ice accumulation arches between the piers without thickening excessively. A number of these structures have seen moderate success in southern Canada, the Riviere Ste. Anne ICS in St. Raymond, Quebec, being an example (Tuthill 1995, 2005). Drawbacks are cost, eventual sedimentation of the pool, and the barrier posed by the structure to fish migration and recreational uses of the river. Also, depending on pier spacing, discharge and ice conditions, this type of structure may fail to retain the breakup ice run (Morse et al, in review).

(1) *Pier ICS with Floodplain Relief Flow*. This Paragraph focuses on simple bottom-founded pier structures that are generally favored over the above-described structures owing to their lower cost and lower environmental impact. The Hardwick Vermont, ICS shown Figure 3-41 is an example. As the name implies, these structures consist of concrete piers or boulders spaced across the main river channel that retain ice arriving from upstream. Most of the water flow passes beneath the ice accumulation or bypasses the structure via an adjacent floodplain or engineered flow relief channel, while a small portion of the total water discharge passes through the ice accumulation as porous flow. Pier spacing is designed such that the ice pieces bridge between the piers or ground immediately upstream. Once flow depth exceeds the bank height, water escapes onto the floodplain to bypass the jam in the main channel. A good design will provide sufficient floodplain or relief channel capacity to limit stage rise much beyond bankfull and avoid jam failure. In the absence of trees lining the bank edge, additional piers or boulders may be required to prevent ice from leaving the main channel and clogging the flow relief channel. Some designs include a rock berm along the floodplain margin to prevent flow from re-entering the main channel in the vicinity of the piers and eroding the jam. Jam failure modes include under-ice erosion and ice blowout between two or more of the piers, or in the case of very high water discharge, ice floes may be carried over the top of the piers. The ice retained at the structure will occupy a large portion of the flow area and, in many cases, cause high velocity flow near the channel bed and sides. Owing to the high water velocities in and around the structure, scour protection is an important for ICS design, often representing a major portion of the project cost.

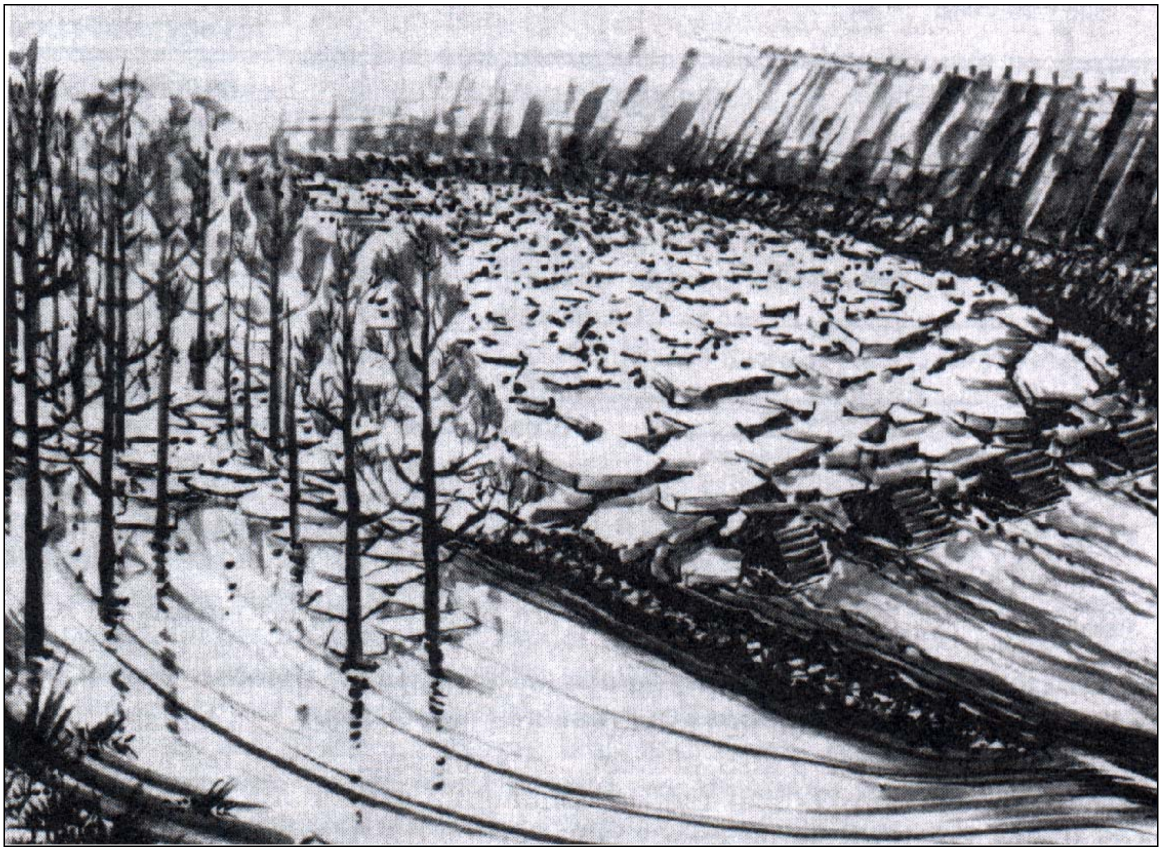


Figure 3-41. Concept drawing of the Hardwick, Vermont, ICS, which retains the breakup ice run behind boulders in the main channel while relief flow bypasses the structure via the floodplain.

(2) *Pier ICS without Floodplain Relief Flow*. A limitation of pier ICS designs with over-bank flow relief is that many sections of river lack adjacent floodplains for bypassing flow around the jam at the piers. If the cross-sectional flow area is large enough, and the breakup discharge sufficiently moderate, it may be possible to pass the water flow beneath a stable ice accumulation retained within the banks of the main channel. Physical model tests at CRREL and Laval University (Morse et al., in review) indicate that, for sections of river with high banks and no floodplains, the discharge at which ice blowout and jam failure occurs is about half that of a reach with an adjacent floodplain to bypass water flow.

(3) *Pier ICS with In-Channel Relief Flow.* A new concept termed "in-channel relief flow" uses a longitudinal row of piers aligned parallel to one bank. These longitudinal piers provide and open water flow path around the jam that forms behind the piers across the main channel. Recent numerical simulations predict that in-channel relief flow will sufficiently reduce under-ice water velocities to prevent ice jam blowout between the piers of an ICS (Tuthill et al. 2005a). Although untested in prototype, the concept is mentioned in this manual since it may provide a viable means of retaining ice at sites without adjacent floodplains for bypass flow. Figure 3-42. shows a schematic plan of a pier ICS with in-channel relief flow.

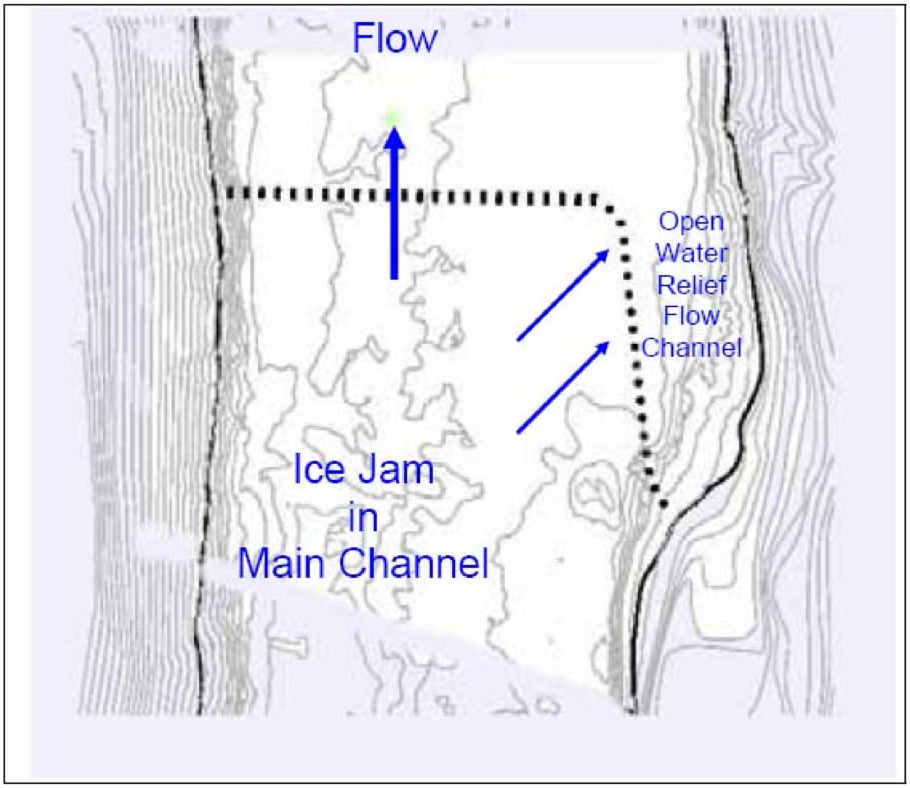


Figure 3-42. Example of pier ICS with in-channel relief flow.

c. Ice Booms for Breakup Ice Retention. Another new concept developed by Fleet Technology* uses floating booms to delay release of ice cover breakup and retain the breakup ice run. Although floating booms have been used for decades to capture frazil and brash ice under quiescent hydraulic conditions typical of the ice formation period (water velocity ≤ about 2.3 ft/s [0.7 m/s], Froude Number ≤ ~0.1), until recently booms were not considered for breakup ice control. Fleet Technology has demonstrated the feasibility of steel pipe booms placed in series to retain breakup ice at water velocities above 3 ft/s (0.9 m/s) on Riviere des Prairies in Quebec (Abdelnour 2003). Advantages of booms over bottom founded piers are the lower capital cost and minimal environmental disruption. Disadvantages are the annual time and cost of installing and removing the boom, and the lower level of confidence in booms for breakup ice retention compared to pier structures.

d. Upstream Water Level Rise Resulting from ICS. Regardless of structure type, upstream water level rise is a critical ICS design issue. Because an ICS will cause a jam where none may have occurred before, upstream land may experience higher water levels with greater frequency. A careful analysis of upstream effects is therefore an important part of breakup ICS design, as it affects the process of land acquisition and obtaining flood easements. Depending on the site, land issues may have a large impact on project cost, and the public acceptance of the project.

* Fleet Technolgy LLC http://www.fleetech.com/CRTC/Booms/crtc_icebooms.htm

e. ICS Reliability and Potential Failure Modes. Reliability is a major consideration in ICS design. A common scenario for both the natural and ICS cases is for ice breakup and jams to occur on the rising limb of the hydrograph. Following jam formation, as discharge continues to increase, so will the downstream forces and hydrostatic head acting on the ice accumulation behind the piers. Possible outcomes range from gradual melting in place or metered release through one or two of the pier gaps, to a massive release between multiple piers. Great care must be taken to avoid this third type of scenario, as the ICS may pose a greater public hazard than the one it is trying to prevent. In light of this, a careful and conservative design approach is advisable.

f. Examples of Existing Breakup Ice Control Structures. Examples of successful existing breakup ice retention structures including dams, weirs, weirs-with-piers and pier structures are described in Tuthill (2005).

g. Design Considerations.

(1) *Characterization of Existing Ice Regime.* An initial step in breakup ICS design is to characterize the existing ice regime and the ice jam problem. The ice regime is defined here as the overall process of ice cover formation, maximum ice extent and thickness, the nature of the ice breakup, and the degree of variability from year to year. An understanding of the frequency and severity of past ice jam events is also critical in ICS design. Based on knowledge of the ice regime and the history of past ice events, an estimated "worst-case" ice event can then be developed for use in ICS design. Tuthill et al. (2005a) describes methods for calculating probabilities of occurrence of historical ice events.

(*a*) *Historical Research.* Background ice jam research typically begins with a review of historical ice events. A good source is the CRREL ice jam database[*] (IJDB), which now contains information on over 14,200 ice events. Historical ice jam information sources also include local newspapers, libraries, town records, and discussions with locals familiar with the river. Concurrent review of hydro-meteorological records can focus the historical research by identifying periods needing more detailed review.

(*b*) *Important Data on Ice Events.* Important data include event dates, peak ice jam stages, damages, and the discharge hydrographs surrounding the ice events. Air temperature data allow estimates of pre breakup ice thickness. Knowing whether the melting period leading up to ice release was gradual or rapid is important, as a quick thaw and breakup typically produce thicker, stronger ice pieces that are more likely to form severe jams. Precipitation data are also important as rainfall is often a key ingredient in dynamic breakups that result in severe ice jams. Data on the snow pack and degree of frost in the ground are important, as they affect the runoff response and the form of the breakup hydrograph. For un-gaged basins, hydrograph comparison techniques of hydrologic models that incorporate snowmelt are be useful in reconstructing hydrographs surrounding historical breakup ice jam events.

(*c*) *River Inspection.* A river inspection may help validate the findings of the historical ice jam research. Often riverbanks will show evidence of past ice events in the form of ice scarred

[*] http://www.crrel.usace.army.mil/ierd/ijdb/

trees. The spatial extent, height, and density of the tree scars indicate where ice jams have occurred, the maximum ice-affected water levels, and, to some extent, the ice jam frequency. By sawing a tree with multiple scarring and healing cycles and counting annual growth rings, one can actually date historical ice events. Tuthill et al. (2005b) provides a more detailed analysis of ice jam tree scars as an indicator of past ice jam frequency and severity.

(*d*) *Ice-Affected Rating Curve.* Based on historical event and hydro-meteorological data, an ice-affected rating curve can be constructed for the study reach. This stage–discharge relationship is useful in ICS design as it provides an estimate of the water level rise necessary to break up and transport the ice cover, the discharge range within which ice jams typically exist, and the approximate discharge at which an ice jam will release. Lacking a nearby stream gage, a simple hydraulic model such HEC-RAS with the ice option can be used to construct the ice affected rating curve. Figure 3-43 shows ice-affected rating curve for an upstream location, constructed using the HEC-RAS model and Figure 3-44 shows the stage and discharge hydrographs for the Winooski River at the Montpelier, Vermont, gage for an extreme ice jam that occurred in 1992.

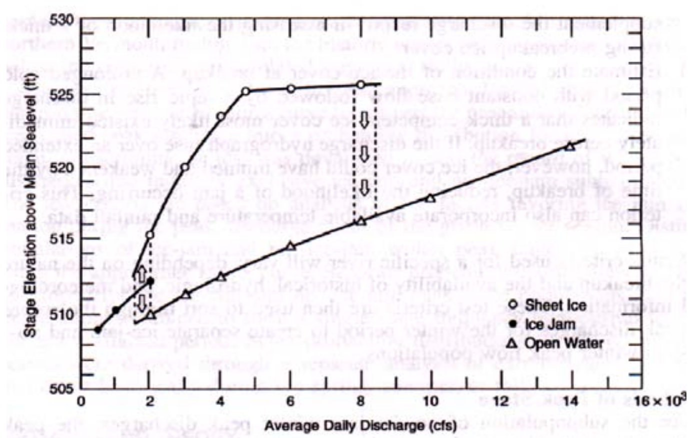


Figure 3-43. Ice-affected rating curve for the 1992 Montpelier ice jam.

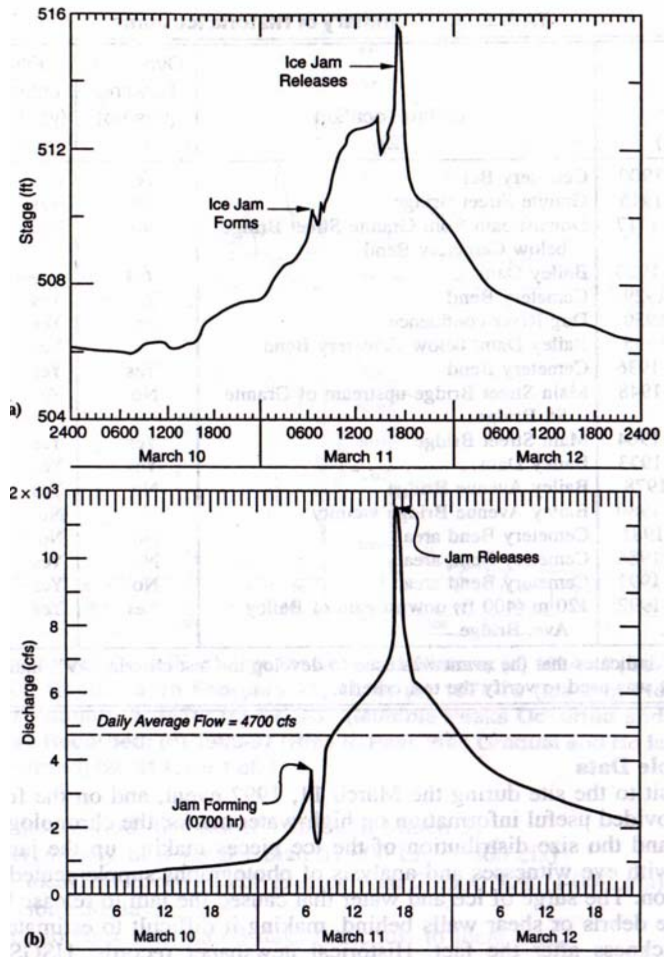


Figure 3-44. Stage and discharge hydrographs for the Winooski River showing the formation and release of the 1992 ice jam at Montpelier, Vermont.

(*e*) *Ice Jam Volume, Ice Sources, Nature and Sequence of Breakup.*

- Other important design considerations relate to pre- and post-breakup ice volumes, and the nature of the ice breakup. This requires a good estimate of the maximum probable ice supply and knowledge of where the upstream ice originates, as well as the nature and sequence of breakup. For example, on some rivers, breakup may progress very rapidly down a long reach of river to form a single large jam at the downstream end. In this case, the portion of the total ice supply that melts or deposits along the banks may be relatively small. At the other extreme, breakup may occur as a downstream progressing series of jams and releases with significant en-route ice losses from melting and ice deposition along the floodplains. En-route ice losses from melting and deposition vary greatly from nearly 0 to as high as 90 percent, and the loss fraction generally increases with channel distance and ice travel time. On many rivers, features such as dams, pools, bridges, tight bends, islands or constrictions may cause upstream ice jams that limit the ice volume that reaches a downstream jam site or ICS. When relating ice jam volume and the pre-breakup ice supply, it is important to consider ice jam porosity, which is on the order or 40–50 percent. Additional information and methods for calculating on en-route ice losses can be found in White (1999) and Lever et al. (2000).

- With an estimate of the probable maximum pre-breakup ice thickness, one can construct a cumulative ice volume curve vs. channel distance for the river as shown in Figure 3-45. HEC-RAS has a cumulative ice volume output option, which greatly simplifies this task, but, lacking surveyed channel geometry, one can construct the ice volume curve based on river widths and reach lengths scaled from USGS mapping. Combined with a knowledge of the probable source reaches and the en-route ice losses, this ice volume curve is useful in subsequent simulations of ICS site alternatives, because one can estimate the portion of the ice volume intercepted by the ICS and the reduced ice volume that reaches the traditional jam location downstream.

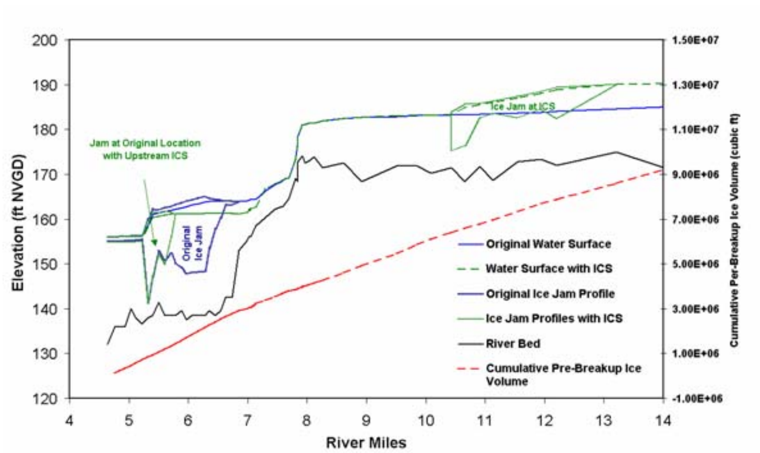


Figure 3-45. HEC-RAS simulations of existing-conditions ice jam compared to ice jam profiles resulting from upstream ice retention. The cumulative pre-breakup ice volume is also shown.

(2) *ICS Site Considerations*. Important factors in ICS site selection include hydraulic conditions, channel morphology, the existing ice regime, and the potential effects on upstream lands. As mentioned in the above discussion of ice volume, the ICS must be located close enough to the problem area that it retains sufficient ice to prevent downstream ice jam flooding or under ice scour, depending on the purpose of the structure. Again, this requires a good estimate of the maximum probable ice supply and knowledge of where the upstream ice originates, as well as the nature and sequence of breakup.

(*a*) For the expected breakup discharge range, hydraulic conditions near an ICS must be sufficiently mild that a stable ice accumulation can exist upstream of the piers. Also, the under-ice water velocity must be low enough to avoid ice erosion and piping beneath the jam, which can lead to blowout between the piers and jam failure. As mentioned above, a number of successful breakup ICS designs take advantage of an adjacent floodplain area to bypass water flow around the jam that forms in the main channel. This relief valve mechanism limits upstream stage rise and prevents excessive water velocity in the ice jam toe region.

(*b*) Finally it is important to consider the ice conditions directly upstream of the structure at the time of breakup. Ideally, the ICS reach will be sufficiently flat that the breakup ice run from upstream will impact a semi-intact sheet ice upstream of the piers rather than the piers themselves. This will ensure that large rather than small ice floes pile against the piers, reducing the tendency for jam failure and ice blowout between the piers.

(3) *Modeling Existing Conditions and Candidate ICS Sites.* Modeling approaches range from simple 1-D flow equations with an ice cover of equilibrium thickness to sophisticated numerical and physical ice–hydraulic models. Depending on the specific ICS application and needs, these calculations and models provide estimates of ice accumulation stability, ice jam volume, and upstream effects, both at the candidate ICS site and in the original ice jam location. Numerical ice–hydraulic models useful in ICS design range from the widely used, steady-state, one-dimensional HEC-RAS model (U.S. Army 2000) to more sophisticated models such as DynaRICE (Shen et al. 2000) and the CRREL DEM (Daly and Hopkins 2001). The latter two multi-dimensional numerical models with unsteady hydraulics and ice dynamics are excellent ICS design tools, but require considerable experience to use. Physical ice–hydraulic models provide the greatest design confidence, especially where three-dimensional ice–structure interaction and ice erosion processes are involved; however, the physical model studies are usually more costly and require more time to accomplish. Choice of modeling approach will depend on the scale of the project and the reliability required, as well as the project schedule and funding. For example, it may not make sense to spend a significant portion of the total available funds on a physical model study of a conventional ISC design at a site where hydraulic conditions are known to be relatively mild. On the other hand, if the consequences of ice jam failure at the structure are high, or the design is unconventional in nature, then the cost of more sophisticated numerical modeling or a physical model study are probably good investments.

(*a*) *Model Calibration to Existing-Conditions Ice Event.* A first task is to simulate the existing-conditions historical ice jam event based on the information collected in earlier. Important calibration parameters include ice jam location and extent, maximum ice jam water levels, and, if available, ice jam thickness. Ice jam extent is usually known, particularly the location of the downstream end of the jam, or ice jam toe. Ice jam stage can be estimated from maximum observed flood levels, or reconstructed after the fact from photos or anecdotal evidence. Ice jam thickness is more difficult to determine but can sometimes be estimated by the height of ice rubble in shear walls left behind after the jam releases.

- Numerical or physical modeling of existing-conditions ice jam can then be compared to simulated ICS site alternatives as shown in Figure 3-45. In many cases HEC-RAS, with a few assumptions, is adequate for ice jam simulation related to ICS design. Advantages of HEC-RAS are its simplicity and that many hydraulic engineers are familiar with its use. For these reasons. ice jam modeling using HEC-RAS is discussed in the following.

- The HEC-RAS ice jam routine treats the ice accumulation as a granular material using Mohr-Coulomb theory to calculate internal stresses. Downstream-acting forces on the floating ice accumulation of water drag and gravity are transferred laterally through the granular ice material to be resisted by bank friction. In the simplest sense, the ice accumulation reacts to increased downstream forces by thickening. The model does not account for unsteady effects such water or ice acceleration, nor can it simulate ice jam grounding or porous flow through the ice jam. In addition, the HEC-RAS user must specify the locations of the downstream and upstream ends of the jam. Still it is possible to simulate certain ice jam conditions with fair accuracy, particularly in the jam mid-section where ice thickness and the downstream-acting forces are fairly uniform.

- Although ice jams commonly form under conditions of unsteady flow, the user must select a constant discharge as an input to the HEC-RAS model. One approach is to use the daily average discharge, which in many cases, is the only data point available. If more detailed hydrograph data exist, one can select a discharge to represent the period when the ice jam profile is near its maximum but below the point of release. Another approach is to simulate the jam at several discharges within the known ice jamming range. The ice-affected rating curve described in Paragraph 3-12g(1)(*d*) is useful in the selection of ice jam discharges to use in the HEC-RAS simulations.

- Calibration parameters used in the HEC-RAS ice routine include Manning's roughness for ice n_i, ice erosion velocity v_{eros}, ice jam porosity e, and ice accumulation internal strength, expressed as the Mohr-Coulomb Φ angle. Typically ice jam porosity is in the 0.4–0.5 range and Φ is usually held constant at about 45 degrees.

- Ice jam thickness is most sensitive to n_i and v_{eros} . Typical values for n_i for breakup ice jams are in the 0.03–0.1 range and tend to increase with ice jam thickness. HEC-RAS contains an option that automatically relates ice roughness to ice thickness (U.S. Army 2000), but more realistic and stable results can usually be obtained by using fixed ice roughness values. A dilemma exists in that a thicker, smoother ice accumulation can produce the same calculated water surface profile as a thinner, rougher ice jam. For this reason it is important to use reasonable values of ice roughness and check that the resulting HEC-RAS-calculated ice jam thickness also makes sense, based on field observation and experience.

- Ice jam thickness is extremely sensitive to the ice erosion velocity v_{eros} , particularly in the toe region where the ice thickness and water velocities tend to be the greatest. Once the under ice water velocity approaches the user-specified v_{eros}, ice thickness is reduced, increasing under-ice flow depth, such that v_{eros} is not exceeded. Ice pieces are thought to start eroding from the ice jam underside at velocities in the 4–5 ft/s (1.2–1.5 m/s) range, but the ice erosion threshold depends on a number of other factors, such as the ice piece size distribution and under-ice hydraulic radius. In a stable ice jam, the under-ice water velocities are typically in the 2–4 ft/s (0.6–1.2 m/s) range.

One can reason that much higher water velocities are possible in the ice jam toe region because the downstream transport of ice pieces is resisted not only by bank friction, but by direct contact with the channel bed or the piers of an ice control structure.

- The greatest modeling difficulties occur in the ice jam toe region, where natural jams tend to be much thicker than the HEC-RAS-simulated ice jams. This is because the downstream acting forces on the real jam are resisted not only by the bank friction, but by channel obstructions or ice grounding to the bed. Also, when the real jam forms, the momentum loss produces greater ice thicknesses than those predicted by the static force balance used in HEC-RAS. One effective way to artificially thicken the toe of the HEC-RAS-simulated jam is to increase the ice erosion velocity for first one or two cross sections. A v_{eros} value of 10 ft/s (3.1 m/s) serves this purpose, but some trial and error is usually needed to match the observed ice jam profile. This allows a thicker ice accumulation, as flow continuity can be maintained with the high velocity water passing through a smaller cross-sectional area beneath the jam toe. Another approach is to fix ice jam thickness in the toe region instead of calculating ice thickness based on the force balance. Finally, one can artificially thicken the jam toe by assigning very high roughness values to the lower-most cross sections.

(*b*) *Simulation of Candidate ICS Locations*. The simulation of the existing conditions ice jam serves as a baseline for comparison to simulated jams at candidate upstream ICS sites and a jam at the original site with the residual ice supply, as shown in Figure 3-45. For consistency, one should use the same total ice volume and ice jam parameters in simulating alternative ICS sites as used in the existing conditions simulations. Depending on ICS site location, the cumulative pre-breakup ice volume curve is used to estimate the portions of the total ice volume in the ice accumulation at the ICS and at the original ice jam location.

- An ideal ICS site will lie on a relatively flat section of river with an adjacent active floodplain for bypass flow. Active floodplain is defined as overbank area that is inundated fairly frequently. Locating the ICS as close as possible to the downstream ice jam problem area will provide the greatest ice jam flood control benefit as it will retain the greatest portion of the total ice supply.

- Important questions to be answered by the calculations are i) can a stable ice accumulation exist at the ICS under the expected breakup discharge range, ii) is the floodplain adequate to convey relief flow around the jam in the main channel, and iii), will the ICS retain a large enough ice volume to mitigate the downstream ice jam problem?

- The stability of a HEC-RAS simulated ice accumulation can be assessed based on the form of the ice jam thickness profile and the calculated under-ice velocity. Using reasonable ice parameters, indicators of a stable ice accumulation are a relatively uniform ice thickness profile in the jam mid section, and water velocities of about 4 ft/s (1.2 m/s) or lower beneath the ice jam mid section. Calculated under-ice velocities of 5 ft/s (1.5 m/s) or greater in the jam mid-section suggest that the ice accumulation is probably unstable, either because the channel is too steep or the unit discharge* too high. The result will be that the downstream-acting forces of water drag and ice accumulation weight will compress and thicken the jam towards the downstream end, possibly to the point of grounding. At this point, water flow must pass either through the pore space of the jam, or as relief flow around the jam. DynaRICE and the CRREL DEM are capable of modeling the ice thickening, ice erosion, grounding, and porous flow, while HEC-RAS cannot simulate these processes. Beltaos (1993) describes a method for calculating the portion of porous flow through the ice jam as a function of hydraulic gradient, wetted cross-sectional jam area, and a seepage coefficient. For a floating ice jam toe condition, porous flow is typically on the order of 10 percent of the total discharge or less. An approach to modeling a grounded jam with HEC-RAS is to simply block off the main channel and assume that all water except seepage flow bypasses the jam via the floodplain, if one exists. This also provides a means of evaluating the conveyance capacity of the overbank area, another important design parameter.

- Table 3-7 lists HEC-RAS-calculated ice–hydraulic parameters for a range of ICS designs, giving an idea of the ice accumulation stability range.

Table 3-7
HEC-RAS-calculated ice-hydraulic parameters for a range of ICS designs.

ISC	Break-up *Q* (cfs)	Bank-full width (ft)	Bank-full depth (ft)	Unit *Q* (cfs/ft)	Average bed slope	Pecent Over-bank flow	Ice thickness (ft)		Under ice depth (ft)		Under ice velocity (ft/s)	
							Toe	Mid-jam	Toe	Mid-jam	Toe	Mid-jam
Cazenovia Creek UC	6000 12,000	150	7	40	0.015	50	6	6–5	4–6	7.5–9	9.3–10	3.0–4.5
Hardwick, VT E	1400	90	4	15	0.002	65	8	4	1	7	7.6	3.1
Salmon R., CT SC	2000	120	8	17	0.002	45	9	6	2.5	6	4.0	2.0
Grasse R. NY CD	8000	375	10	21	0.0001	60	8	4	4	10	3.1	2.5

Notes: UC = under construction, E = existing, SC = scheduled for construction, CD = conceptual design.

- Where HEC-RAS predicts water velocities in the ice jam toe region in excess of 5 ft/s (1.5 m/s), the equivalent prototype ice jams are probably grounded. This observation is based on CRREL physical model tests of the Hardwick and Cazenovia Creek ICSs, as well as the prototype Hardwick ICS, where grounded ice jam toe conditions occurred.

- In cases where the HEC-RAS results predict high under ice water velocities in the mid-jam section (≥ 4 ft/s [1.2 m/s]) or no floodplain is available to bypass relief flow, ice jam stability is questionable and design confidence requires a more sophisticated modeling approach than HEC-RAS. It may be possible to retain ice under these condi-

* Discharge per unit width of river, expressed as cfs/ft or ft^2/s

tions, but a physical model study will probably be needed to assure the desired performance.

- In addition to assessing ice jam stability, the simulations provide an estimate of the conveyance capacity of the floodplain and the flow split between the main channel and the floodplain. The numerical models are also useful for calculating upstream water level rise resulting from the jam at the ICS and the profile of the downstream jam with the reduced ice volume. It is important to realize the preliminary nature and errors associated with these calculations, especially where it concerns issues of upstream lands that may be affected by water level rise from the ICS.

(4) *Pier Design.* At this point, pier design is more experience-based than theoretical. Parameters of pier design include pier spacing, height, width and shape, the most important being spacing. In existing structures, pier spacing ranges from 6 to 20 feet (1.8 to 6.1 meters), with recent designs favoring a gap width of about 12 feet (3.7 meters). The design intent is to maximize the spacing without sacrificing ice retention performance. A wider gap width reduces the number of piers and project cost and also minimizes potential for debris snagging and interference with recreational uses of the river.

(*a*) Experiments by Calkins and Ashton (1975) showed from experiments that, for moving ice with surface concentrations greater than about 30 percent, ice will arch between the piers when the ratio of the average floe diameter and the gap width is about 0.25 or greater. By this relationship, for a concentrated ice run, 3-foot-diameter (1-meter-diameter) floes should arch between piers spaced 12 feet (3.7 meters) apart.

(*b*) A number of pier ICSs are designed so that ice floes ground upstream of the piers in addition to arching. As previously mentioned, it is advantageous to locate an ICS on a flat section of river so that immediately before breakup, a thick competent ice cover exists upstream of the structure. The arriving breakup front pushes these semi-intact sheets and large floes against the piers, arresting the upstream ice run through a combination of grounding and arching.

(*c*) Piers are typically designed to be slightly higher than the top-of-bank height so that the ice accumulation fills the main channel without moving on to and blocking floodplain relief flow. A useful rule of thumb in selecting top-of-pier elevation is that the water surface elevation upstream of the ICS needs to be about 1.5 times the ice thickness above the top of bank to convey ice floes onto the floodplain.

(*d*) Natural levees and trees lining the river bank help contain the ice in the main channel. Lacking trees along the bank, some designs call for lines of posts, boulders, or large concrete weights to help contain the ice in the main channel. Lever et al. (2000) calculated ice forces on ice-retaining posts based on the maximum head differential between the main channel and the floodplain. Typically, the jam thickness and height increase rapidly immediately upstream of the ICS, creating a condition where stage on the floodplain may be greater than the adjacent water surface elevation near the piers. As a result, flow returning from the floodplain to the main channel may wash out ice pieces between the piers, causing partial jam failure. In the Cazenovia Creek design, Lever et al. (2000) solved this with the addition of a 300-foot-long (91.5-meter-long) rock berm along the floodplain margin, extending 150 feet (46 meters) above and below the piers. The crest of the berm is level with the pier tops, which are about 3 feet (1 meter) above top of bank (Figure 3-46).

Figure 3-46. Cazenovia Creek ICS under construction September 2005, showing the rock berm along the right bank.

(*e*) Based on physical model tests at CRREL, actual pier shape is less important than pier spacing and height. In terms of performance, cylindrical piers proved comparable to rectangular piers with rounded noses of the same diameter. Vertical-faced piers were found to perform better than piers with front faces inclined at 45 degrees.

(*f*) The Cazenovia Creek ICS, which is designed to arrest an extremely dynamic ice run, calls for 5-foot-diameter (1.5-meter-diameter) cylindrical piers with12-foot-wide (3.7-meter-wide) gaps. The Salmon River ICS will have 2.5-foot-wide (0.8-meter-wide) rectangular piers with the same gap width. In both cases, the piers rise about 3 feet (1 meter) above top of bank. The Hardwick ICS granite blocks have inclined front faces, 14-foot (4.3-meter) gaps and rise about 1 foot (0.3 meters) above bank height (Tuthill 2005).

(5) *Ice Forces on the Piers*.

(*a*) Ice forces on the piers can be determined through physical model experiments or estimated based on bridge pier design publications. The CRREL DEM (Daly and Hopkins 2001) also predicts ice forces on structures, as does the DynaRICE numerical model. Although a number of ice loading scenarios are possible, maximum ice forces usually result from the initial impact of large floes against the piers (Figure 3-47). Lower but more sustained ice loadings typically follow as ice additional ice accumulates upstream of the piers and the hydrostatic head builds. Once upstream stage exceeds bankfull depth and flow escapes onto the floodplain, the jam may ground to the bed decreasing the ice loading on the piers.

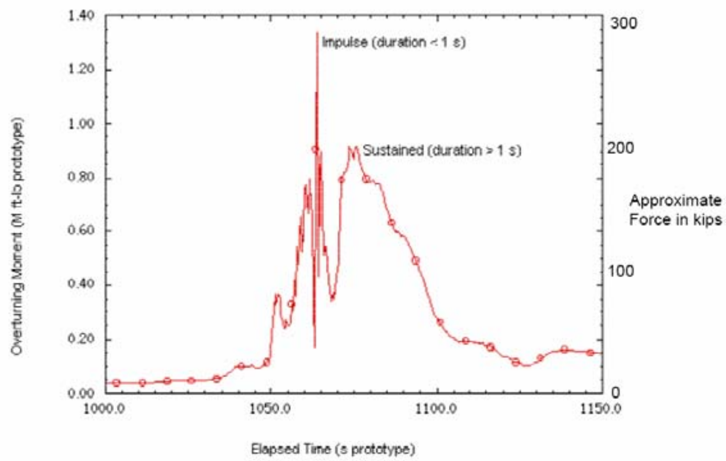


Figure 3-47. Measured moments on a pier, Cazenovia Creek physical model study, from Lever et al. (2000).

(*b*) Lever et al. (2000) analyzed moment and force data from the Cazenovia Creek ICS physical model tests and compared results to a maximum ice loading calculated using the AASHTO code. Lever et al. assigned probabilities to moment and force data from some 20 laboratory experiments, obtaining a 0.001 chance of excedance force of 450 kips (2,001,700 newtons) per pier. Through comparison of measured moment and force data, they calculated an average moment arm of 4.4 feet (1.3 meters) up from the river bed. The average ratio of transverse to downstream moments on the piers was found to be 0.45. The authors then used the AASHTO code to calculate a similar downstream-acting ice force of 400 kips (1,779,289 newtons) per pier, assuming a maximum ice thickness of 2.0 feet (0.6 meters), a floe diameter of 30 feet (9 meters), and an effective ice strength of 220 psi (1517 kilopascals). Based on this analysis, it appears reasonable to calculate ice forces on ICS piers based on AASHTO standards for bridge piers.

(6) *Bed and Bank Protection.*

(*a*) The bed and banks can experience extremely high shear stresses from high water velocities and turbulence caused by an ice accumulation at the ICS. Bed and bank materials may also be disturbed by direct impact of gouging of ice floes as they accumulate at the ICS. Existing methods for calculating bed shear stress under an ice cover include the depth–slope product and drag formulas such as the Darcy Weisbach equation. Beltaos (2001) describes a practical approach for incorporating the effect of ice cover roughness into drag equations for calculating bed shear. More recent experiments (Haines and Zabilansky 2004) and field measurements of hydraulic scour beneath ice jams (Alcoa 2004) indicate that traditional bed shear calculation methods based on average water velocity and flow depth may be un-conservative because they fail to account for the turbulent kinetic energy resulting from a rough ice cover. Because of these uncertainties, a conservative approach might be to calculate the bed shear based average under ice depth and water velocity and roughness factors calculated from Beltaos (2001), then apply a factor of safety of at least 3 where thick ice accumulations and high turbulence are expected.

(*b*) Areas around an ICS that typically experience high bed shear, include the river bed and banks near the piers, and the floodplain margins where bypass flow escapes and re-enters the main channel. The pier foundation design may call for a continuous concrete apron to resist overturning and sliding, which will also serve to prevent bed scour at the pier bases. Lacking a concrete apron, a riprap blanket may be needed around the piers bases. Stone bed and bank protection will also be needed upstream of the piers where the bottom of the ice accumulation is close to the bed or grounded, and downstream where flow jets out through the gaps between the piers. Where large moving ice floes are anticipated, to avoid rock movement, a D100 stone size twice the maximum expected ice thickness for shallow slopes (< 1V : 3H) and three times the ice thickness for steeper slopes (> 1V: 1.5 H) is recommended.

(7) *Extreme Events Failure Modes and Ice Jam Melt-out.* Any structure placed in a river will be subject to a wide range of natural conditions and, in some instances, the ICS may fail to retain ice. At the low end of the range, the ice will need to reach a minimum thickness before the average piece size is large enough to arch or ground at the piers. An early season ice release of thin ice through the structure is not of great concern as an ice run composed of small pieces is unlikely to form a serious jam at the ice jam problem area downstream of the ICS. Based on New England rivers, severe ice jams are uncommon for ice thicknesses less than about 8 inches (20 centimeters) while severe ice jams are associated with pre-breakup ice thicknesses of 1 foot (0.3 meters) or more. Lever and Gooch (2005) discusses the relationship between ice floe thickness and the reliability of the Hardwick, Vermont, ICS since its construction in 1994.

(*a*) In many regions such as northeastern U.S., the peak annual discharge can occur at any time of the year and ice breakup may occur during the peak flow event. Where this is a possibility, the structure must be designed to retain ice during a worst-case flow event without a catastrophic release. Physical model tests or comparisons to similar existing ICS may be used to assess the structure's ice retention capability at the expected maximum flows.

(*b*) Depending on the form of the extreme event hydrograph, it may be possible to demonstrate that the ice jam melts out before the hydrograph peaks. This occurs as a result of the rapid heat exchange attributable to the high water discharge and the slightly above-freezing water temperatures typical of the breakup period. Lever et al. (2000) analyzes progressive washout and melting during a hypothetical extreme discharge event on Cazenovia Creek, estimating the ice volume lost to melting per degree Fahrenheit above freezing to be about 1 percent of the water discharge rate. The authors developed a maximum upstream water surface profile by superimposing a series of HEC-RAS simulations with progressively increasing discharge and decreasing ice volume.

Table 3-8
Breakup ICS Design Procedure

1. Characterize of existing ice regime and ice jam problem
    - Research historical ice events
    - Inspect study area for evidence of past ice action and jams
    - Analyze hydro-meteorological data related to ice breakup
        - Calculate maximum pre-breakup ice thickness based on air temperature data
        - Relate hydrograph data, to nature of ice breakup severe ice events
        - Construct ice-affected rating curve for project reach
    - Estimate frequency and severity of past ice jam events
    - Determine "worst-case" ice event for use in ICS design
        - Identify probable ice source reach and estimate en-route ice losses
        - Estimate maximum probable ice supply

2. Select ICS location
    - Seek site with favorable hydraulic conditions:
        - Can a stable ice accumulation exist upstream of piers for expected discharge range?
        - Will under-ice water velocities exceed the ice erosion threshold?
        - Will ice run from upstream impact a sheet ice cover upstream of piers, or open water?
    - Consider channel morphology at the ICS, and upstream and downstream:
        - Does site provide overbank relief flow around jam in main channel?
        - Does upstream reach provide sufficient upstream ice storage?
        - Will ICS retain sufficient ice volume to alleviate downstream ice jam problem?
        - To what degree will stage rise from the ICS affect upstream properties?

3. Model ice accumulations under existing conditions and with ICS alternatives.
    - Select modeling approach based on problem complexity, scale, uncertainty and resources:
        - One-dimensional steady state hydraulic equations with equilibrium ice jam theory
        - HEC-RAS 1-D, gradually varied flow model with wide jam ice routine (and similar)
        - DynaRICE 2-D, dynamic, ice-hydraulic model
        - CRREL discrete element model with ADH hydrodynamics
        - Physical hydraulic model with plastic or real ice
    - Calibrate model to existing-conditions "worst case" ice event
    - Simulate ice accumulations for range of ICS site alternatives, considering:
        - Ice accumulation stability
        - Under ice erosion
        - Relief channel capacity
        - Upstream ice storage capacity
        - Upstream water level rise
        - Effect of upstream ice retention on downstream ice jam problem

Table 3-8 (cont'd).
Breakup ICS Design Procedure

4. Structural Design
    - Pier spacing and height:
        - Select pier spacing based on existing designs such that ice accumulation arches or grounds upstream of piers
        - Select pier height such that ice remains in main channel allowing water flow to escape to floodplain
    - Ensure that relief flow channel remains ice-free.
        - Natural levees, trees, boulders, piers etc. to retain ice in main channel
    - Estimate ice forces and moments on piers based on:
        - AASHTO bridge design code
        - Existing ICS designs
        - CRREL DEM or DynaRICE numerical model force outputs
        - Measured data from physical ice-hydraulic models with instrumented piers
    - Estimate shear forces and design bed and bank protection based on:
        - Classic 1-D shear and drag equations and
        - Beltaos (2001) to incorporate effect of ice cover roughness
        - Recognize added shear resulting from turbulence and apply a significant factor of safety.
        - Consider potential for direct impact by ice floes and size armor stone according to (Sodhi et al., 1996)
    - Consider extreme events and possible failure modes
        - Ice bleed-out and blowouts at piers
        - Progressive ice accumulation melt-out scenarios as flow increases (Lever, 2000)
        - With regard to potential failure modes, err on the conservative side:
            - Ensure that ICS project does not introduce a greater hazard than the original problem that you are trying to solve.

h. Summary. This Paragraph outlines basic steps involved with the design of breakup ice control structures and Table 3-8 provides a checklist summarizing these steps. A range of breakup ICS types are described with a focus on the design of pier ICS with floodplain flow relief, as these structures are currently the most economical and reliable, with the least environmental impact. Design steps include characterization of the existing ice regime based on a review of historical ice events, collection of hydrometeorological data and a field inspection of the river for past ice jam evidence. ICS site selection must consider local hydraulic and geomorphologic conditions, upstream effects, and potential benefits in terms of reducing the downstream ice jam problem. Available calculation and modeling methods are discussed with an emphasis on the use of the HEC-RAS model to evaluate important design parameters such as under-ice erosion and ice jam stability. Important aspects of pier design such as spacing and height are discussed along with methods for estimating ice forces on the piers. Calculation methods for bed and bank shear forces are outlined for use in the design of bed protection, and ICS failure modes discussed. Background publications and more sophisticated ice–hydraulic models are referenced. Finally, Tuthill (2005) summarizes the recent performance of breakup ISCs.

3-13. Ice Diversion Structures. This final group contains ice control structures whose main purpose is ice diversion. The goal of this type of ice control is often to prevent ice from entering and blocking hydropower intakes. To this end, special structures such as shear booms may be used to direct ice past the forebay area while diverting the water flow from beneath the ice. In the absence of hydropower, an ice diversion structure may guide frazil and floes away from lock entrances or toward gates capable of flushing ice past dams. Ice control at hydropower intakes is well developed in northern Europe and Iceland. Preventing ice from entering locks and flushing ice past dams is a major issue on waterways that carry winter navigation in the U.S.

a. Ice Diversion at Hydropower Intakes in Northern Europe. At the Burfell power plant in Iceland, the discharge of frazil and solid ice may be as great as 55% of the total winter ice and water flow of 3500 cfs (100 m^3/s). In addition, the river carries a significant sand bedload. The three-level intake structure, shown in Figure 3-47, consists of an upper-level ice sluice and an under sluice for sand, allowing relatively ice- and sediment-free flow to enter the diversion canal leading to the intakes. In addition, a rock-filled jetty and an excavated basin in front of the ice sluice further reduce the ice quantities entering the diversion canal (Carstens 1992).

(1) Perham (1983) described a fixed concrete shear boom at the head of the intake canal to the Hraunyjafoss power plant, located downstream of the Sigalda Reservoir in Iceland. Constructed in 1981, the boom extends to a depth of 4 meters (13 feet) and prevents frazil from entering the power canal. The frazil is not sluiced over the adjacent spillway but kept in the reservoir to promote ice cover formation. The boom does not provide a complete solution, however, because the surface velocity in the 1000-meter-long (3300-foot-long) canal is too great for an ice cover to form. As a result, frazil accumulates at the trash racks located at the canal's downstream end (Freysteinsson and Benediktsson 1994).

(2) At the power dam at Rygene, Norway, a 1.5- × 8-meter (5- × 26-foot) ice flushing gate, located 12 meters (40 feet) upstream of the intakes, performed poorly, until a redesign located a new ice sluice gate immediately adjacent to a submerged intake. The ice-flushing capacity was also increased at the power plant at Fiskumfoss, Norway, again by locating a new ice-flushing gate as close to the intakes as possible. At the Burfell, Rygene, and Fiskumfoss power stations, physical model studies helped optimize the design of the ice diversion structures upstream of the intakes (Carstens 1992).

(3) In contrast, the intake on the Orkla River, at Bjorset, Norway, has performed poorly, experiencing severe frazil problems. Flow is diverted beneath a shear wall, upstream of a control weir, to enter an 11-kilometer-long (7-mile-long) rock tunnel. Frazil accumulates on the trash racks, tunnel walls, and even at the downstream surge tank. The intake's poor performance may result in part from its location 150 meters (500 feet) upstream of the control weir.

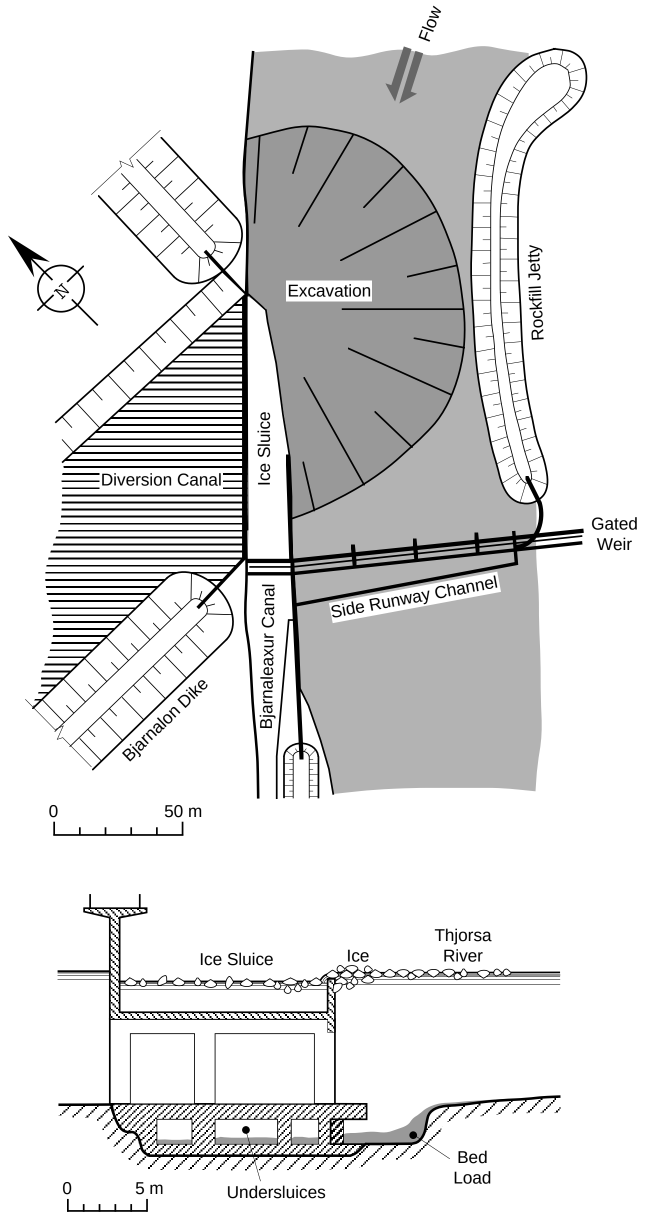


Figure 3-47. Ice sluice at the intake to the Burfell Power Station, Iceland. (After Carstens 1992.)

b. Floating Shear Booms Upstream of Dams. Many shear booms designed to divert debris to collection sites along the shore upstream of dams are also effective for ice. In addition, any structure designed to capture or divert debris in cold regions must consider ice forces in the design. The shear boom upstream of the Chief Joseph Dam, a large-scale structure of this type, successfully diverts debris and ice from the forebay area (Figure 3-48). Located on the Columbia River at Bridgeport, Washington, this 915-meter-long (3000-foot-long) boom consists of 228 government-surplus mooring floats, 1.8 meters (6 feet) in diameter by 3.7 meters (12 feet) long. Each float contains 2.5 tons (2268 kg) of concrete ballast. Perham (1983) and Appendix B give examples of cross-sectional geometry of various types of shear booms. The estimated maximum design load of 103 tons (93,420 kg) on the 1-centimeter-diameter (2.5-inch-diameter) main cable on the Chief Joseph boom is expected to result from wind and wave loading.

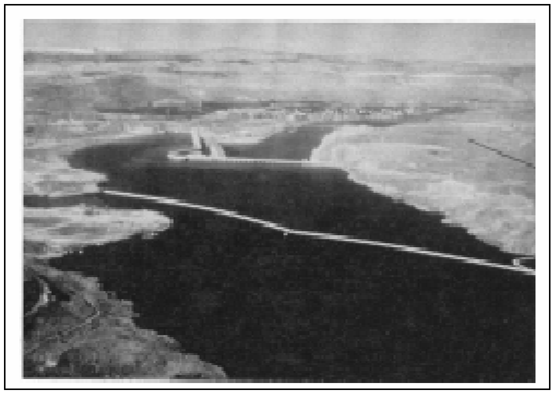


Figure 3-48. Chief Joseph shear boom on the Columbia River at Bridgeport, Washington.

c. Analysis. This review of existing structures brings together information on a wide range of ice control structures, assessing their performance. This Paragraph examines how well existing methods (as well as relatively untried ones) apply to a range of confluence ice situations. In addition, a range of existing ice control structures will be examined with respect to channel depth and average velocity. Structural methods to help form and retain sheet ice are well developed and relatively well understood. Floating booms, the most common structure type in this group, do not significantly alter the existing hydraulic conditions, and their environmental impact is minimal. Their initial capital cost is low, and applications are possible in very deep channels. A floating boom solution applies to a relatively narrow range of hydraulic conditions, however, and reliability can be limited, as seen in the ice runs that override the Lake Erie boom. The selection of ice boom design to date has been based on a combination of theory, experience, physical model studies, and availability and cost of construction materials. The relationship between a boom unit's cross-sectional geometry and its capture efficiency is not that well understood, however. Recent applications of note are the formation booms installed on the Salmon River in Idaho and the Allegheny River at Oil City, Pennsylvania. In both cases the booms caused ice covers to form at locations where the hydraulic conditions were previously thought to be unfavorable. The future may see reduced installation and removal costs through the further development of sink-and-float booms. Efforts are now underway to increase ice boom capture efficiency. These designs might lead to successful ice retention at surface velocities well above the currently accepted maximum of 2.3 ft/s (0.70 m/s). Finally, floating boom technology might be further developed for the purpose of breakup ice control.

(1) Compared to sheet ice retention, breakup ice control methods are less developed and less well understood. Dams and fixed weirs are effective and time-tested breakup ice control methods, and the ice-hydraulic design aspects involved are fairly straightforward. The object is to create upstream hydraulic conditions of sufficiently low slope and low surface velocity to al-

low the formation of a stable, floating ice accumulation, with relief flow passing underneath the ice and over the weir crest. Properly designed, weirs and dams retain breakup ice runs with great reliability. As an added benefit, dams may serve as freezeup ice control structures by promoting ice cover formation early in the season, thereby reducing frazil production. Major drawbacks are their high capital cost, the obstacles presented to navigation and fish migration, and upstream sedimentation. An example of a successful ice control weir is the structure on the Ste. Anne River in St. Raymond, Quebec. As a further drawback, permitting for new dam construction at present is difficult in the U.S. There may be some potential for ice control using inflatable dams, however.

(2) The greatest development potential in the field of breakup ice control lies in pier structures. A grounded jam forming behind the piers creates an impoundment, allowing the formation of a stable floating ice accumulation upstream. Relief flow is typically routed around the grounded portion of the jam via some type of channel in the overbank area. In the non-ice-jam case, these structures do not cause a rise in water level, so they do not create a barrier to migrating fish or cause upstream sedimentation. Their capital cost is lower than for an equivalent weir structure. Being relatively new technology, the ice and hydraulic design aspects are tricky and not that well understood, so their reliability may be less than for a weir. Scour and debris clogging are also potential problems. A successful example is the pier structure built on the Credit River at Mississauga, Ontario. Future directions might be to scale the current small river applications up to larger rivers or to develop removable frames or collapsible piers that do not interfere with navigation. Application of pier ice control structures to moveable-bed rivers also presents a major challenge.

(3) Recent innovations in freezeup ice control include the development of fence booms, tension weirs, and ice nets. Though limited in their range of application, these methods are extremely inexpensive and easy to deploy. An example of a recent success is the ice fence located upstream of a small hydro station on the island of Hokkaido in Japan. Ice nets caused the formation of an ice cover upstream of the Stornorrfors power station on the Ume river in Sweden, with surface velocities in the 3-ft/s (0.91-m/s) range, well above the accepted maximum for booms of 2.3 ft/s (0.70 m/s). The ice nets have the additional advantage of no depth limitation. Perhaps the nets could be used upstream of booms in borderline formation situations. Some adaptation of the ice net could possibly be used to stabilize and retain shore ice at locations downstream of peaking hydro dams as well.

d. Applicability of Structural Ice Control Methods to River Confluence Situations. Table 3-9 ranks the applicability of selected structural ice control methods to five confluence situations. For simplicity, only the five major structure categories are considered. The structure types are grouped according to function, i.e., freezeup and breakup. They are further categorized as removable or fixed, and are floating booms, shear booms, man-made islands, weirs and dams, and piers and boulders. Floating booms, man-made islands, and weirs and dams apply well to relatively low velocity confluences where a stable ice cover is desired. Careful location of formation booms upstream of large river–large river confluences may reduce the ice supply to the main stem and the severity of ice jam problems. Although never tried at a confluence, shear booms are not without potential. Perhaps floating ice could be diverted towards the shore or onto floodplains for storage, or directed away from navigation channels and fleeting areas on large rivers.

Weirs and dams get high rankings in nearly all categories when dealing with both breakup and freezeup ice problems. Finally, piers apply potentially to many confluence ice control situations, although, to date, they have been tested only on small to medium-sized rivers.

Table 3-9
Applicability of Structural Ice Control Methods to River Confluence Situations

		Freeze-up				Breakup
		Removable		Fixed		
Confluence situation	Example	Floating booms	Shear booms	Man-made islands	Weirs and dams	Piers and boulders
Large river–Large river	Mississippi–Missouri	3*	3*	3*	5	4*
Small river–Large river	Oil Creek–Allegheny R.	5	1*	0	5	5*
Large lake–Large river	Lake Erie–Upper Niagara R.	5	1*	4	0	4*
Large river–Large lake	St. Lawrence R.–Lake St. Peter	5	1*	5	4	3*
Small river–Lake	Czech Rivers–Reservoirs	0	0	0	4	5

* Indicates potential application, but not tried.
Scale:
0 (not applicable) 1 2 3 4 5 (highly applicable)

e. Channel Depth and Water Current Velocity at Selected Structures. Figure 3-49 and Table 3-10 give the range of river depths and velocities that existing structures handle. The structures are divided into six groups according to type and function: formation booms, formation weirs, tension weirs, lines and nets, pier breakup structures, and weir and pier combinations. For methods that significantly raise the water level, such as weirs and piers, velocities and depths are given for the pool upstream of the structure. Formation booms, the most common type of ice control structure, have the greatest range of application, particularly in terms of depth, working at a maximum possible velocity of about 0.76 m/s (2.5 ft/s). The depth ranges from 1–1.5 meters (4–5 feet) for shallow pool-riffle rivers to 14 meters (45 feet) for some booms on major waterways. Slightly higher velocities are reported for the St. Marys River boom, which retains predominantly brash and floes rather than frazil. The Montreal Harbor ICS and the Lake St. Peter ice islands, with similar hydraulic conditions, fall into the same field as the formation booms.

(1) Formation weirs, like booms, promote ice cover growth during freezeup, and their velocity range is similar to formation booms. Formation weirs such as the Israel River and Oil Creek structures, with velocities in the 0.09- to 0.51-m/s (0.3- to 1.7-ft/s) range, are limited to shallower rivers because of cost. Tension weirs built to date (including the Japanese ice fence) are even more limited in terms of depth but are comparable to fixed weirs in terms of approach flow velocity. Although experimental at this point, frazil collector lines and nets are relatively unconstrained by depth and appear to exceed the velocity range of formation booms and weirs, promoting ice cover growth with velocities in the 0.9-m/s (3-ft/s) range.

Table 3-10
Channel Depth and Water Current Velocity at Selected Structures

	Depth (ft)			Velocity (ft/s)			Depth (ft)			Velocity (m/s)		
Structure	**Low**	**High**	**Avg**	**Low**	**High**	**Avg**	**Low**	**High**	**Avg**	**Low**	**High**	**Avg**
Formation booms and structures												
1 Ice islands, Lake St. Peter	21	25	23	1	1.6	1.3	6.4	7.6	7.0	0.3	0.5	0.4
2 Booms at Lanoraie and Lavaltrie	—	—	10	—	—	1	—	—	3.0	—	—	0.3
3 Montreal Harbor ICS	—	—	22	2	2.5	2.25	—	—	6.7	0.6	0.8	0.7
4 Lake Erie boom	—	—	18	1.4	2	1.7	—	—	5.5	0.4	0.6	0.5
5 Lake St. Francis boom	—	—	20	—	—	1.4	—	—	6.1	—	—	0.4
6 St. Marys River boom	10	31	20.5	—	—	2.7	3.0	9.4	6.2	—	—	0.8
7 Beauharnois Canal booms	—	—	34	—	—	2.4	—	—	10.4	—	—	0.7
8 International Section booms	17	45	31	0.95	2.75	1.85	5.2	13.7	9.4	0.3	0.8	0.6
9 Salmon boom	2	6	4	1	2.5	1.75	0.6	1.8	1.2	0.3	0.8	0.5
10 Allegheny boom	—	—	6.4	—	—	2	—	—	2.0	—	—	0.6
11 North Platte boom	—	—	5	—	—	1.7	—	—	1.5	—	—	0.5
Formation weirs												
12 Israel River weir	—	—	6.5	—	—	0.33	—	—	2.0	—	—	0.1
13 Oil Creek weir	—	—	5	1.5	1.8	1.65	—	—	1.5	0.5	0.5	0.5
Tension weirs and fence booms												
14 Mascoma River fence boom	—	—	4	—	—	1.4	—	—	1.2	—	—	0.4
15 Japanese ice fence	—	—	3	—	—	0.9	—	—	0.9	—	—	0.3
16 Union Village tension weir	—	—	3	—	—	0.3	—	—	0.9	—	—	0.1
Lines and nets												
17 Frazil collector lines	1	4	2.5	2.4	3.6	3	0.3	1.2	0.8	0.7	1.1	0.9
18 Swedish ice nets	—	—	12	—	—	3	—	—	3.7	—	—	0.9
Pier break-up												
19 Credit River piers	—	—	12	—	—	1	—	—	3.7	—	—	0.3
20 Hardwick granite blocks	—	—	10	—	—	3	—	—	3.0	—	—	0.9
21 Mohawk River ice breakers	—	—	8	5	10	7.5			2.4	1.5	3.0	2.3
Weir and pier												
22 St. Raymond weir with piers	—	—	15	1	2	1.5	—	—	4.6	0.3	0.6	0.5
23 Ice control dam at St. Georges	—	—	27	—	—	1	—	—	8.2	—	—	0.3
24 Narragaugus River structure	—	—	7.5	—	—	1	—	—	2.3	—	—	0.3

(2) Of the two groups of breakup structures, weirs with piers are the more conservative, with approach velocities in the 0.3- to 0.46-m/s (1.0- to 1.5-ft/s) range. In addition, the weir breakup structures do not depend solely on arching and the formation of a grounded jam to impound flow and reduce the approach velocity. Note that, even at the peak discharges associated with breakup, the approach velocity is quite comparable to the surface velocities upstream of the formation boom group, indicating that the design of these breakup ice control weirs is quite conservative. The breakup structures that rely on piers alone to form a grounded jam appear less conservative in terms of approach velocity. At an extreme breakup flow, the calculated approach velocity for the recently completed Hardwick granite block structure is in the 0.91-m/s (3-ft/s) range. The experimental structure performed well during its first winter of testing, however. Estimated velocities at the Colebrook, N.H., icebreaker blocks are high, 1.5–3.0 m/s (5–10 ft/s),

and the adjacent floodplain conveyance area is limited. It is, therefore, not surprising that the structure fails to retain the breakup ice run.

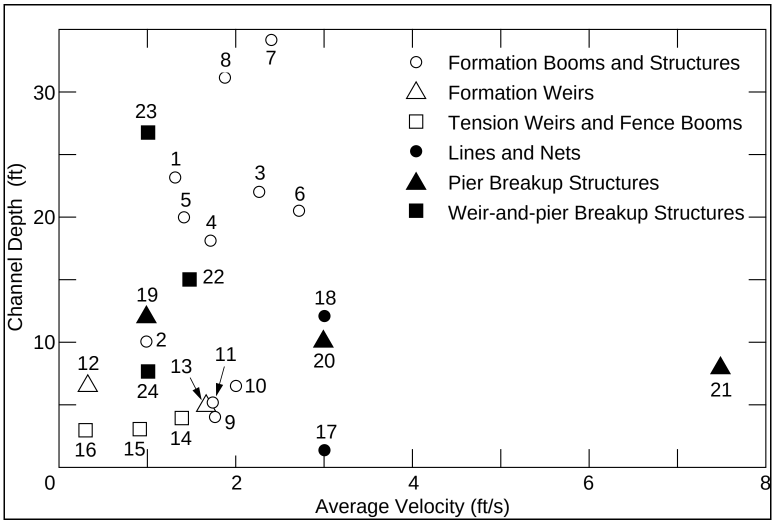


Figure 3-49. Depth vs. average velocity for various types of ice control structures. The numbers correspond to the list in Table 3-10.

(3) The range of possible approach velocities for successful ice retention is relatively narrow. Figure 3-49 shows the practical upper limit for all groups of structures to be in the vicinity of 0.91 m/s (3 ft/s). In addition, there is considerable overlap in the velocity ranges of the formation boom, formation weir, pier breakup, and weir-and-pier breakup structure groups. For the formation boom and frazil lines and nets groups, the velocity must fall into the range of less than or equal to 0.91 m/s (3 ft/s) under natural conditions. The remaining four groups rely on some structural means of raising the water level to meet the velocity criteria, however.

3-14. References

a. Required Publications.

None.

b. Related Publications.

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