CECW-EH

DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

EM 1110-2-1612

Manual
No. 1110-2-1612

30 October 2002

Engineering and Design
ICE ENGINEERING

1. Purpose. This manual, composed of three parts, presents in Part I the current guidance for the planning, design, construction, and operation and maintenance of ice control and ice suppression measures for Corps of Engineers projects; provides in Part II the current guidance for dealing with ice jams and the resultant flooding, including preventive measures; and gives in Part III the current guidance for engineering and operational solutions to ice problems on rivers used for navigation.

2. Applicability. This manual is applicable to all USACE commands having responsibility for civil works design, construction, operations, and maintenance.

3. Distribution statement. Approved for public release, distribution is unlimited.

4. References. Bibliographic material is included at the end of each chapter where necessary.

5. Discussion. All Corps projects subjected to freezing temperatures have ice problems, such as: ice buildup on lock walls, hydropower intakes, and lock approaches; ice accumulation in navigation channels; ice passage over spillways that scours the downstream channels; and ice damage to shore structures and shorelines, etc. Therefore, ice control measures should be considered for both new and existing projects to improve operations and safety in cold regions. In Part I, this manual contains a discussion of ice formation processes, physical properties, and potential solutions to associated problems. Part II considers the problem of ice jams and ice jam flooding, and discusses a broad range of mitigation measures. Part III of this manual addresses the considerations that arise from winter navigation on inland waterways, including the conduct of river ice management studies and the preparation of river ice management plans.

FOR THE COMMANDER:

3 Appendices
(See Table of Contents)

JOSEPH SCHROEDEL
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This manual supersedes EM 1110-2-1612, dated 30 April 1999.

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U.S. Army Corps of Engineers
Washington, DC 20314-1000

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2. Substitute and add the attached pages.

Remove pages	Insert pages
i through vii	i through vii
2-1 through 2-15	2-1 through 2-17
7-1 through 7-10	7-1 through 7-43

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DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
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Engineering and Design
ICE ENGINEERING

1. This change to EM 1110-2-1612, 30 October 2002, replaces the table of contents and Chapter 3.

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i through vii	i through vii
3-1 through 3-73	3-1 through 3-97

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Engineering and Design
ICE ENGINEERING

1. This change to EM 1110-2-1612, 30 October 2002, replaces the table of contents and Chapter 19, and adds Chapter 20.

2. Substitute and add the attached pages.

Remove pages	Insert pages
i through vii	i through vii
19-1 through 19-7	19-1 through 19-7
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ICE ENGINEERING

1. This Change 4 to EM 1110-2-1612, 31 August 2018, replaces the table of contents and Chapter 20.

2. The changed information is annotated as follows.

Section	Page(s)	Paragraphs
Table of Contents	i through viii	n/a
Chapter 20	20-1 through 20-37	20-1 through 20-39

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Change 4

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31 August 18

Engineering and Design
ICE ENGINEERING

TABLE OF CONTENTS

Chapter 1
Introduction

1-1. Purpose

This manual provides a general coverage of the field of ice engineering as it pertains to the responsibilities of the Corps of Engineers. For convenience, it is divided into three parts: first, *Ice Properties, Processes, and Problem Solutions*; second, *Ice Jams and Mitigation Measures*; and third, *Winter Navigation on Inland Waterways.* This manual does not address the environmental impacts of ice.

a. Role.

(1) Part I gives fundamental information about ice and about the hydraulics of ice-affected river flow. It presents current guidance for the planning, design, construction, and operation and maintenance of ice-control and ice-suppression measures for Corps of Engineers projects. It also supplies basic information on selected problems for which ice is a significant engineering factor.

(2) Part II addresses ice jams and related flooding, including prevention and remediation methods. The information presented is intended to be useful to interested parties outside of the Corps of Engineers, as well as within.

(3) Part III gives the current guidance for engineering and operational solutions to ice problems on rivers used for navigation throughout the winter. These solutions can contribute to efficient, cost-effective, reliable, and safe navigation during ice periods. Part III also presents guidance for developing River Ice Management Plans for specific rivers or river systems.

b. Scope.

(1) In Part I, *Ice Properties, Processes, and Problem Solutions*, Chapter 2 discusses ice processes, namely formation, growth, and decay, and the physical and mechanical properties of ice. In Chapter 3 the focus is on techniques for mechanical and thermal ice control in lakes and rivers. Chapter 4 describes methods for modeling the hydraulics of ice-affected rivers and determining the associated water-surface profiles, while Chapter 5 presents approaches for assessing ice-affected stage-frequencies for rivers. Chapter 6 discusses ice-induced forces on riverine, coastal, and offshore structures for inclusion in design considerations. Chapter 7 presents guidance on estimating the effects of ice covers on sediment transport in alluvial channels. Chapter 8 deals with evaluating the bearing capacity of sheet ice for stationary and moving loads as a function of ice thickness and ice conditions. Chapter 9 discusses small-scale ice physical modeling that can be conducted to test concepts for resolving ice problems in all types of water bodies.

(2) In Part II, *Ice Jams and Mitigation Measures*, Chapter 10 presents a general overview of the problem of ice jams and ice jam flooding. Chapter 11 gives a brief review of ice types as a basis for discussing the types of ice jams, their causes, and their prediction. Chapter 12 covers the broad range of methods used to reduce or eliminate ice jam difficulties.

(3) In Part III, *Winter Navigation on Inland Waterways*, Chapter 13 discusses the conduct of a river ice management study, a system-wide approach to solving winter navigation problems. In Chapter 14 the broad range of river ice problems affecting winter navigation is summarized, and guidance for identifying and conducting surveys of these problems is given. Chapter 15 presents river ice forecasting concepts

and methodologies. Systems and techniques for the collection of hydrometeorological data are covered in Chapter 16, including numerical information as well as imagery. Chapter 17 presents basic information regarding navigation in ice, and includes discussion of alternatives for increasing the ease and efficiency of such operations. Chapter 18 addresses structural solutions to ice problems at navigation structures. Lastly, Chapter 19 covers operational solutions to winter navigation problems.

(4) Appendix A, *Glossary*, provides abbreviations and definitions of terms used throughout this manual. Appendix B, *Ice Jam Mitigation Case Studies*, is related to Part II and provides details for many solutions successfully applied to a wide variety of ice jam problems. Appendix C, *Typical River Ice Management Study*, associated with Part III, outlines and organizes the elements necessary to a river ice management study, which would lead to a formal River Ice Management Plan.

1-2. Applicability

This manual is applicable to all USACE commands having civil works design, construction, or operations responsibilities.

1-3. Explanations of Terms

Abbreviations and special terms used in this manual are listed in Appendix A, *Glossary*.

1-4. Ice Impacts on Corps Activities

Figure 1-1 shows the area of North America where temperatures in winter are below freezing over a sufficient length of time for ice to form in rivers, streams, and lakes. Ice in streams and waterways affects Corps projects for navigation, flood control, water supply, and power generation. It can also result in ice jams and lead to flooding at river discharges that would be trouble-free under open-water conditions. During spring breakup, especially, ice may severely damage riprap installations and other riverine structures. Offshore and coastal structures in the Arctic and in subarctic regions, and specifically along the Alaska coastline, need to be designed to withstand the significant forces exerted by sea ice driven by wind or current. Ice in navigable waterways adversely affects many Corps activities and creates the need for specific ice management measures.

a. Ice interference with lock and dam operations. Corps of Engineers navigation projects cannot operate properly when ice accumulates at locks, dams, and related facilities. A few examples illustrate how ice at navigation projects leads to accelerated damage and increased maintenance needs, greater demands on personnel, and more dangerous working conditions. Ice interferes with the movement of lock and dam gates (Figure 1-2) and places added loads on structural components. Lock widths are often not fully usable owing to the accumulation of broken ice in recesses behind miter gates (preventing full gate opening) and the buildup of ice collars on one or both walls of the chamber (Figure 1-3). Broken ice is pushed into lock chambers ahead of tows, sometimes limiting the length of tow that can fit. Floating mooring bitts freeze in place, becoming useless. The passing of ice at dams, while simultaneously trying to maintain navigation pool levels and avoid downstream scour, is often difficult or impossible.

b. Ice effects at flood control projects. Problems at flood control projects are often similar to those at navigation facilities. Dam gates are particularly susceptible to freezing in place because of leaking seals and resulting ice buildup, especially if gates are moved infrequently. Hoisting chains, trunnion arms, etc., may become so loaded with ice as to be too heavy for lifting mechanisms. Personnel

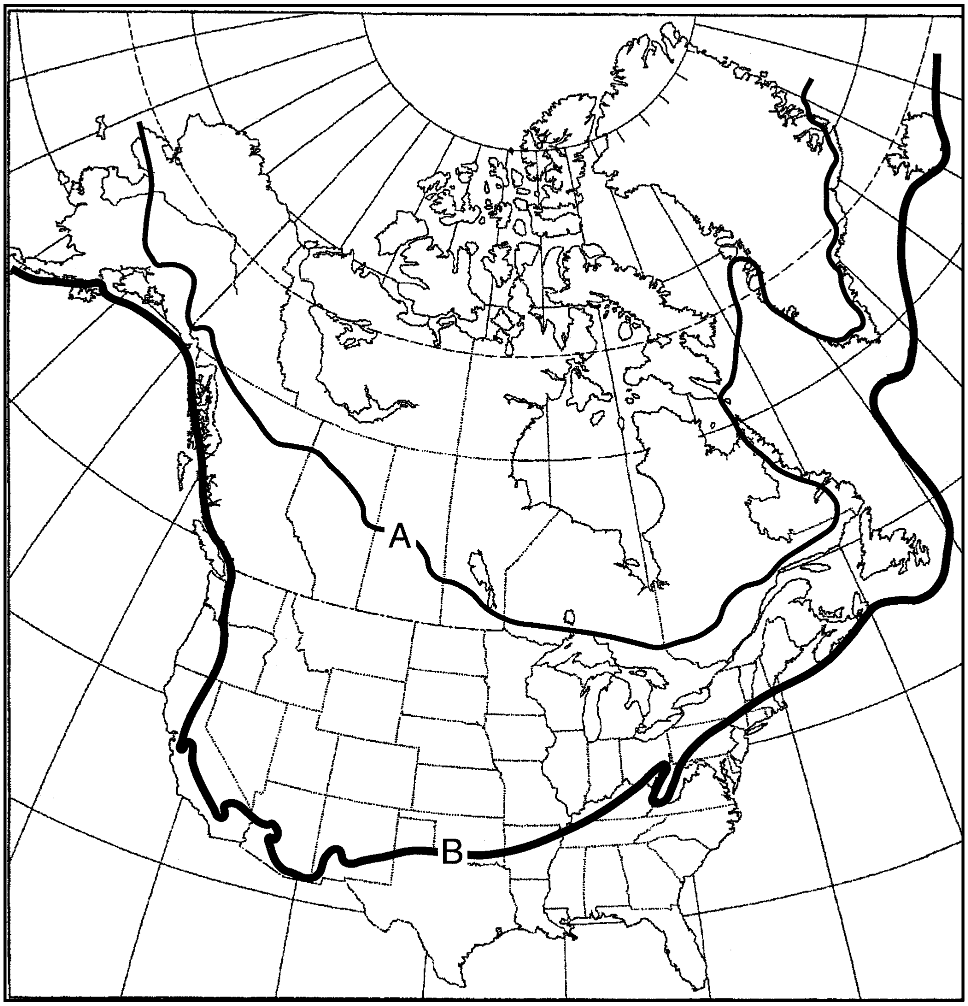

Figure 1-1. Cold regions in North America. *A-line is southernmost boundary of the area where the average temperature of the coldest winter month is -18ºC (0ºF) or less and ice covers navigable waters for at least 180 days of the year; B-line is the southern border of the area where the average temperature of the coldest winter month is between -18 and 0ºC (0 and 32ºF) and ice covers navigable waters for 100–180 days.*

walkways can become dangerously coated with ice from water spray. If not conducted cautiously, water releases from reservoirs may have the effect of dislodging downstream river ice, leading to ice runs, ice jams, and subsequent flooding.

c. Ice effects on water supply and power plants. Frazil ice and brash ice can accumulate on trash racks, thereby blocking water intakes of water supply systems, water intakes at hydropower plants, or cooling water intakes at thermal power plants. Excessively rough ice accumulations may lead to undue head losses in water supply and power canals.

d. Ice effects on river stage. A stationary river ice cover, whether an ice sheet or a jam, introduces an additional boundary and therefore increases energy losses. This translates to an increase in stage compared to open-water conditions for the same discharge. Numerical models for river hydraulics must be able to account for the effects of ice if they are to reliably describe river flows and stages. The

Figure 1-2. Ice accumulation on dam gates

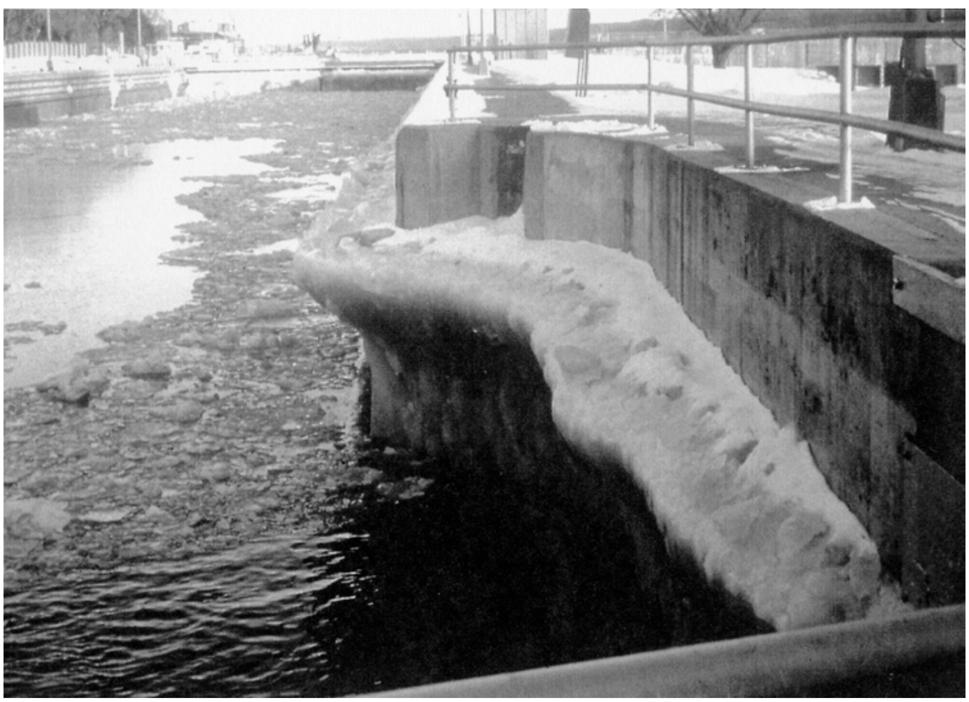

Figure 1-3. Ice collar on lock wall

resistance offered by an ice cover will lead to upstream water storage, resulting in rapid stage rise and possible flooding, and simultaneously will lead to a drop in stage and a discharge deficit downstream from the ice cover. If the stage drop is severe enough, downstream water intakes may become exposed, affecting municipal and industrial water supplies, especially during periods of drought or very low flow.

e. Ice effects on sediment transport and scour. The presence of a floating ice cover roughly doubles the wetted perimeter of a wide channel, which in turn modifies the magnitude and distribution of the velocities and, thus, the boundary and internal shear stresses. For a movable bed channel, an ice cover may, therefore, affect the bed sediment transport and the suspended sediment transport characteristics of the stream and modify the channel geometry and the bed regime. For an abrupt thickening of an ice accumulation, such as the toe of an ice jam, there may be significant bed scour because of the deflection of the flow against the bed. When this happens in the vicinity of a riverine structure, such as a bridge pier, the resulting scour may eventually cause structural failure.

f. Ice-related shore and structure damage. Damage caused by normal ice conditions in ice-prone rivers is often minor. But in more severe ice seasons, scour and ice-force damage to shorelines, pilings, piers, and levees may become significant. Unprotected earth surfaces at shorelines can be severely gouged and eroded. Particularly during ice breakup, ice floes shearing along the riverbank or striking river training structures may severely damage riprap or erode the banks. Public and private riverside structures can be weakened, distorted, or even destroyed.

g. Ice forces on structures. The design of riverine, lake, coastal, and offshore structures to be built in ice-prone areas, such as riprap installations, river training structures, docks, bridge piers, artificial islands, or oil drilling platforms, needs to take into account the potential forces exerted by ice runs at breakup or by large ice floes driven by currents or wind stresses (Figure 1-4). These forces will depend on ice thickness, ice mechanical properties, and the anticipated mode of failure of the ice (crushing, bending, or buckling).

h. Ice jam flooding. River ice jams may contribute to winter and early spring flood damage (Figure 1-5). Ice blockages in main stems and tributaries cause stages to rise and force water out of the channel over the floodplain, even when discharges are low compared to warm-water floods. Ice jam floods, while usually not as extensive as open-water floods, often take place with little or no warning. The factors and relationships that determine the probability of ice jams and ice jam flooding are more complex than those for open-water flooding. This means that the extensive statistical analysis methods applied to normal flooding phenomena are not readily applicable to ice-related occurrences. Many mitigation measures have been developed for preventing or reducing ice jam floods; these methods may be structural or nonstructural, and they may be deployed on a permanent, advance, or emergency basis. Effective Corps emergency management responses depend on fully understanding ice jam phenomena.

i. Ice effects on navigation. Ice-prone rivers in the U.S. directly serve 19 states containing 45% of the Nation's population. These rivers also serve as conduits to eight other river states and connect the U.S. heartland to world markets through the Gulf of Mexico, the St. Lawrence Seaway, and the ports of the Northwest. The principal rivers among these that generally support year-round navigation are the Ohio River (including the Monongahela and Allegheny rivers), the Illinois Waterway, and the Upper Mississippi River from Keokuk, Iowa, downstream to Cairo, Illinois (its junction with the Ohio). Elsewhere, ice formation on the Great Lakes and their connecting channels and in the Upper Mississippi River above Keokuk generally forces the suspension of commercial navigation during most of the winter season. The presence of sheet ice or brash ice in any of these waterways slows navigation considerably (Figure 1-6), may damage the hull or propulsion systems of vessels, and can cause the breakup of tows.

Figure 1-4. Ice action on bridge piers

Figure 1-5. Flooding caused by an ice jam

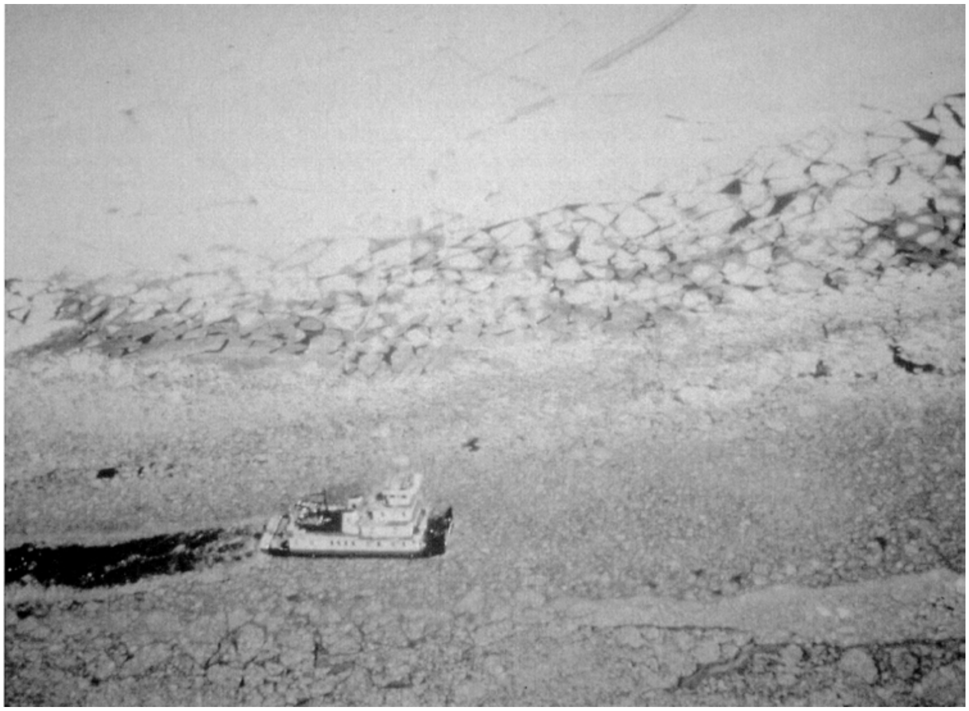

Figure 1-6. Towboat in ice

Broken ice caused by multiple vessel passages may accumulate in navigation channels or under adjacent sheet ice, further exacerbating navigation difficulties. When ice causes navigation to stop or to become significantly curtailed on these waterways, the portions of the local, regional, and national economies dependent on waterborne transportation may be adversely affected.

j. Ice problems for towboat operators. Aside from the obvious effects of ice on the navigation industry, such as increased demands on personnel, accelerated wear and tear on equipment, and increased maintenance requirements for towboats and barges, ice imposes several limitations on tow operations that directly affect the industry's efficiency. The first of these is reduced tow size. The added resistance caused by the heavy ice accumulations means that towboats are not able to push as many barges through the ice as through open water. Thus, for the same operating costs, less tonnage can be moved when ice is extensive. The next limitation is lower travel speeds. Again, this is a function of the extra energy needed to move a tow through ice accumulations, and it varies with the amount of ice in the waterway. And, finally, there are the delays at locks already enumerated, including ice restrictions on usable lock widths dictating narrower tow configurations.

k. Ice effects on industry, commerce, and the general public. When freight is delayed or stopped on ice-prone rivers by adverse ice conditions, the effects are felt by industries served by river transportation. And, as industry is affected, so also are commerce and the general public, since they rely directly or indirectly on industrial payrolls. Ice problems can curtail shipments of fuels, industrial feedstocks, finished goods, road salt, etc. These delays may lead to a range of results, from added transportation costs for alternative shipping modes to industrial plant cutbacks with associated layoffs. Delayed movement of goods leads to the depletion of reserve stockpiles, added inventory carrying costs, and extra labor costs for additional handling of bulk products. Road salt shortages may result in hazardous road conditions. Fuel shortages affect both industry and homes; often when fuel is scarce, industrial cutbacks (and layoffs) are implemented to ensure at least minimum service to hospitals and residences. Major interruptions in industrial raw materials lead to terminating process heating, and this can result in costly shutdown and restarting expenses.

1-5. References

a. Required publications.
None.

b. Related publications.

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Part I: Ice Properties, Processes, and Problem Solutions

CHAPTER 2
Review of Ice Processes and Properties

2-1. Introduction. Each year, ice grows on and disappears from the nation's rivers and lakes in tune with the cycles of nature. Unless the ice causes problems, such as flooding or blocking the arteries of commerce, few people pay more than cursory attention. Because of this, the very great variety of ways in which ice initially forms, grows and accumulates, and finally disappears, are relatively unknown. Ice processes on lakes are different from those on rivers, and for both lakes and rivers, the size of the water body affects which processes take place. Ice owes its existence to the thermal process of heat transfer, but its evolution is greatly influenced by physical and mechanical processes. Thus, this chapter introduces the wide variety of ice formation, evolution, and destruction mechanisms, and identifies the principal thermal, physical, and mechanical properties that govern them.

2-2. Physical Properties of Ice and Fresh Water

a. Water Properties. In ice engineering, ice is most often encountered in contact with liquid water. Therefore, it is important to be aware of the physical properties of water to fully understand the interaction of ice and water. The physical properties of greatest importance are density and specific heat.

(1) *Density*. One of the most important physical properties of water affecting the interaction of ice and water is density (mass per unit volume). The density of water is temperature-dependent. The changes in water density with temperature are relatively small over the normal range of water temperature, but these small changes can have large-scale results. The primary example of this is the *thermal stratification* of lakes and reservoirs. The density change of water in response to temperature is unusual compared to almost all other substances—the density of water does not increase continuously with decreasing temperature, but has a density maximum at 4°C (39.2°F). A further temperature decrease causes the density of water to decrease. This density maximum has a profound effect on the thermal stratification of lakes and reservoirs in winter. The density of water as a function of temperature is reasonably well described by the following formula (Heggen 1983)

$$\rho = 1000 - 1.9549\times10^{-2}\,|\theta - 4|^{1.68}$$

where ρ is the density of water in kilograms per cubic meter (kg/m^3), and θ is the temperature in degrees Celsius. In English units the equation is

$$\rho = 62.4 - 4.5441\times10^{-4}\,|\,\theta - 39.2|^{1.68}$$

where ρ is the density of water in pounds per cubic foot and θ is the temperature in degrees Fahrenheit. At 0°C (32°F), the density of water is 999.87 kg/m^3 (62.42 lb/ft^3).

(2) *Specific Heat*. Specific heat is a measure of the quantity of heat required to raise the temperature of one unit mass of fluid one unit degree under constant pressure. The specific heat of water is much larger than the specific heat of most materials. As a result, a relatively large amount of heat must be added to or extracted from water to change its temperature. The specific heat of water as a function of temperature is described by the following formula (Heggen 1983)

$$C_p = 4174.9 + 1.6659\,(e^{r/10.6} + e^{-r/10.6})$$

where $r = 34.5 - \theta$ for $\theta < 35.5°C$, θ being the temperature in degrees Celsius, and C_p is the specific heat in joules per kilogram per degree Celsius (J/kg °C). In English units

$$C_p = 0.9979 + 3.9793\times10^{-4}\,(e^{r/19.08} + e^{-r/19.08})$$

where $r = 94.10 - \theta$ for $\theta < 94°F$, θ being the temperature in degrees Fahrenheit, and C_p is the specific heat in British Thermal Units per pound per degree Fahrenheit (Btu/lb °F). At 0°C (32°F), C_p = 4217.7 J/kg °C (1.0074 Btu/lb °F).

(3) *Density Stratification in Natural Water Bodies*. Stratification describes the process that results from differences in density and temperature occurring in a vertical section of a lake or reservoir. These differences exist because lighter fluids "float" on top of denser, heavier fluids. In summer the temperature of the water in the lake or reservoir will be much greater than 4°C (39°F), and warmer water will float on top of colder, denser water. As a result, in summer the water near the surface will be warmer than the water found at depth. In the winter months, when the temperature of the water in the lake or reservoir is at 4°C (39°F) or less, the less dense water will be the colder water and will float on top of the warmer, denser water, which has a temperature closer to 4°C (39°F). As a result, in winter the water near the surface will be colder than the water found at depth. This warmer water found at depth in lakes and reservoirs forms a "thermal reserve." If available in sufficient quantities, this reserve can be used to melt ice at the water surface by bringing up the denser, warmer water using bubblers (see Chapter 4) or mechanical diffusers.

(4) *Mixing*. The density difference between 0 and 4°C (32 and 39°F) is small, and it does not take much mixing action to overcome the stratification. Turbulence is a very effective mixer. All rivers, streams, and channels with any appreciable flow velocity are turbulent and, therefore, will be well-mixed vertically and will exhibit virtually no stratification. Therefore, there is almost no thermal reserve located at depth in flowing rivers, streams, or channels that can be exploited for melting ice. Lakes and reservoirs may be well-mixed to some depth owing to the turbulence created by wind. Ponds and shallow lakes may be well-mixed throughout their entire depth during times when there are strong winds blowing. The presence of an intact ice cover will generally protect the water below from the influence of the wind and promote stratification.

b. Properties of Freshwater Ice. To understand and analyze the effects of ice on waterways and reservoirs, familiarity with certain properties is necessary. The important physical properties of ice given here are density and specific heat capacity. The thermal properties also included are the thermal conductivity, latent heat, and thermal expansion of ice.

(1) *Density*. The density of freshwater ice is 916.8 kg/m^3 at 0°C (57.2 lb/ft^3 at 32°F). Like most materials, ice becomes denser with decreasing temperature (at –30°C [–22°F], the density of ice is about 920.6 kg/m^3 [57.4 lb/ft^3]). The density of ice is affected by the presence of impurities, with the two most common "impurities" being air bubbles and unfrozen water. The presence of air bubbles tends to reduce the density, and unfrozen water tends to increase the density. Unfortunately, for ice found on natural water bodies, little can be said about the amount of these "impurities" without resorting to direct and somewhat difficult measurements. As a result, for engineering calculations, the approximation of 915–917 kg/m^3 (57.1–57.2 lb/ft^3) for the density of ice is probably adequate.

(2) *Specific Heat Capacity*. The specific heat of ice as a function of temperature is described by the following equation (Ashton 1986)

$$C_p = 2114 + 7.789\theta$$

where θ is the temperature in degrees Celsius, and C_p is the specific heat in joules per kilogram per degree Celsius (J/kg ºC). In English units

$$C_p = 0.505 + 0.001860\theta$$

where θ is the temperature in degrees Fahrenheit, and C_p is the specific heat in British Thermal Units per pound per degree Fahrenheit (Btu/lb ºF). At 0ºC (32ºF), the specific heat of ice C_p = 2114 J/kg ºC (0.505 Btu/lb ºF).

(3) *Thermal Conductivity*. Thermal conductivity describes the ability of ice to transmit heat under a unit temperature gradient. The temperature dependence of thermal conductivity is described by

$$k_i = 2.21 - 0.011\theta$$

where k_i is the thermal conductivity in watts per meter per degree Celsius (W/m °C) and θ is the temperature in degrees Celsius. In English units

$$k_i = 1.27 - 0.0061\,(\theta - 32)$$

where k_i is the thermal conductivity in British Thermal Units feet per hour per square foot per degree Fahrenheit (Btu ft/[hr ft^2 °F]) and θ is the temperature in degrees Fahrenheit. The thermal conductivity of ice is greater than that of concrete (0.81–1.40 W/m °C {0.47–0.81 Btu ft/[hr ft^2 °F]}) and wood (0.14–0.21 W/m °C {0.08–0.12 Btu ft/[hr ft^2 °F]}) but much less than that of metal (for example, copper 388 [224], aluminum 209 [120], and steel 49 [3]). Ice is a not a great insulator, but it is not much of a heat conductor either. The thermal conductivity of ice is significantly influenced by air bubbles and the inclusion of unfrozen water. As with the density determination, the amount of both of these impurities in ice in natural water bodies is usually not known, and as a result, their influence is usually ignored.

(4) *Latent Heat*. Pure water freezes at 0°C (32°F) under standard atmospheric pressure. When water freezes, 333.4 J/g (143.3 Btu/lb) of latent heat is released. This is a substantial amount of heat, especially when compared to the 4.217 J/g (1.813 Btu/lb) it takes to change the temperature of water 1°C (1.8°F). Table 2-1 shows the amount of heat required to melt ice per unit mass and volume.

Table 2-1
Heat Requirements to Melt Ice

gram	333.4 J/g
kilogram	3.33×10^5 J/Kg
pound	143.3 Btu/lb
cubic meter	3.06×10^8 J/m^3
cubic foot	8196.8 Btu/ft^3

(5) *Thermal Expansion*. Thermal expansion represents the change in length, area or volume of a sheet of ice due to an increase in temperature. For linear expansion the following equation can be used to determine the increase in length:

$$\Delta L = \alpha L_o \Delta T$$

where α is the thermal expansion coefficient, equal to 50×10^{-6} °C^{-1} (30×10^{-6} °F^{-1}). ΔL is the change of length and L_o is the initial length in meters (feet). ΔT is the change in temperature in degrees Celsius (Fahrenheit). For a change in area, the coefficient becomes 2α, and for a change in volume, the coefficient increases by a factor of 3.

2-3. Mechanical Properties of Freshwater Ice. Mechanical properties are important parameters that control the forces that ice may exert upon structures and the deformation of ice under load. Ice is a complex material whose behavior under load can range from brittle to ductile, depending on its structure, the rate of load application, temperature, and, in the case of sea ice, salinity or brine content. Because of these factors, the values of ice properties also vary with the measurement techniques and conditions. Only a brief summary of the mechanical properties of freshwater ice is presented below. The reader interested in ice rheology and ice mechanics should consult more specialized texts such as Pounder (1965), Michel (1978), or Ashton (1986).

a. Ice Strength. Strength is defined as the maximum stress that a test specimen can support immediately before failure. Its value will thus depend on the mode of failure (e.g., bending or flexure, crushing or compression, shear), the type of failure (namely brittle or ductile), the presence of flaws in the ice, and, as already mentioned, the test technique. In the following, only brittle failure will be considered, because it corresponds to the relatively high loading rate more commonly associated with ice impacts on structures when driven by water flow or wind.

(1) B*ending or Flexural Strength*. The ice bending or flexural strength is the maximum stress that an ice sheet or ice floe can withstand when subjected to a vertical load at the edge of the ice sheet, e.g., when riding up an inclined slope or striking an inclined bridge pier. A number of studies have measured ice flexural strength (Frankenstein 1968, Lavrov 1969, Gow 1977). From these, the expected bending strength of competent, columnar freshwater ice ranges from a low of 0.5 MPa (70 psi). for relatively large specimens tested by the cantilever beam method. to a high of 1.2 MPa (170 psi) for small, simple beam specimens. This range of values also reflects differences in results obtained depending on whether the tests were conducted with the top of the ice under tension or the bottom of the ice under tension, and the corresponding variation in crystal size.

(2) *Crushing or Compressive Strength*. The ice compressive strength is the maximum stress before failure that ice can withstand when subjected to in-plane loads, i.e., normal to the ice floe thickness, as when being pushed against a vertical surface or bridge pier. The main factors that affect the crushing strength of ice are the crystal size, the rate of loading (strain rate), and the ice temperature. On the average, for columnar ice and snow or frazil ice at about –10°C (14°F) and in the brittle range of failure, i.e., for relatively high rate of loading, the crushing strength is in the range of 8 to 10 MPa (1.1 to 1.5 kpsi). Michel (1978) gives the following formula for estimating the ice crushing strength

$$\sigma = 9.4 \times 10^5 \left(d^{-1/2} + 3 \left| \theta \right|^{0.78} \right) \qquad (2\text{-}1)$$

where σ = crushing strength (Pascals)
d = crystal size (centimeters)
θ = temperature (degrees Celsius).

(3) *Breakthrough Loads*. The bearing capacity of ice is discussed in some detail in Chapter 8. For short-term duration loads, the allowable load P that a floating ice sheet can support is proportional to the square of the ice thickness h, that is

$$P = A h^2. \qquad (2\text{-}2)$$

For most practical purposes, the value for A can be taken as 1/100 when P is expressed in metric tons (1000 kg) and h in centimeters (A can be taken as 1 when P is expressed in meganewtons and h in meters), and for P in tons and h in inches, then A can be taken as 1/16.

b. Elastic Modulus. The elastic modulus E describes the relationship between stress and strain. For the case of ice, the elastic modulus has been found to depend on the ice temperature, crystal structure, and the rate of stress application. Also, creep in ice can occur soon, especially at high stress levels, requiring that strain be measured "extremely quickly after the application of the stress" (Ashton 1986). As for the other mechanical properties of ice, the measured values of the elastic modulus also depend on the measurement techniques. As a result, estimates of the elastic modulus can range widely, and values estimated or measured in the field for the elastic modulus of intact freshwater ice range from about 0.4 to 9.8 GPa (55 to 1350 kpsi). The elastic modulus of ice grown in large laboratory tanks ranges from about 4.3 to 8.3 GPa (600 to 1150 kpsi), whereas the elastic modulus of small laboratory specimens is typically higher. Values for extensively cracked or deteriorated ice may be much lower.

c. Characteristic Length. The characteristic length L_c of a floating ice sheet is a measure of the extent of the zone of deformation when the ice is subjected to a vertical load. It also governs the initial size of ice floes resulting from the breakup of a sheet ice cover. This parameter is expressed in terms of the ice thickness h and modulus of elasticity E by

$$L_c = \left[\frac{E h^3}{12\gamma\left(1-\nu^2\right)} \right]^{1/4} \tag{2-3}$$

where γ is the specific weight of water and ν is the Poisson's ratio of ice, usually taken equal to 0.3. From elastic analysis, the radius of the area of deformation is approximately equal to 3 characteristic lengths. Field measurements (Sodhi et al. 1985) have shown that the characteristic length of competent freshwater ice is about 15 to 20 times the ice thickness, with the higher ratio corresponding to cold ice, and the lower values for warm ice in late winter or early spring.

d. Field Measurements. There is no simple, reliable method to measure the compressive strength of ice in the field. It is often necessary to collect ice samples for testing in the laboratory under controlled conditions. The flexural strength and the elastic modulus can, on the other hand, be measured in the field with a minimum of equipment (IAHR 1980) using one of the techniques described below.

(1) *Cantilever Beam*. A cantilever beam of length L (= 5 to 8 h) and width B ($\cong$ 2 h) is cut in the ice sheet (Figure 2-1a). A load P is applied to the tip of the beam and the corresponding deflection δ is measured. The elastic modulus E is given by

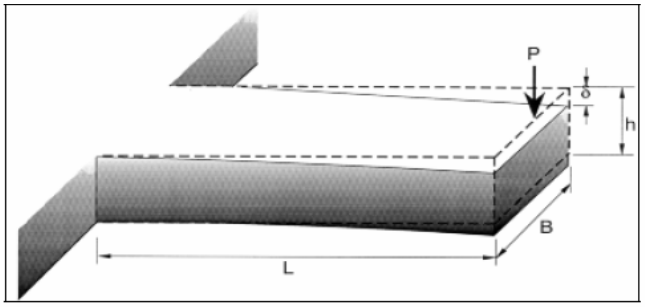
$$E = \frac{4}{B}\left(\frac{L}{h}\right)^2 \frac{P}{\delta}. \tag{2-4a}$$

If P' is the failure load of the cantilever beam, the flexural strength is calculated by

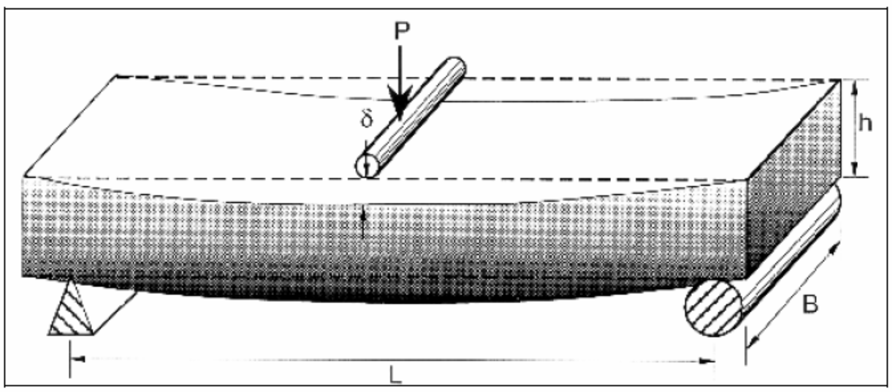
$$\sigma_b = 6\frac{P'L}{B h^2}. \tag{2-4b}$$

To make the results as reliable as possible, the saw cuts at the root of the cantilever beam should be rounded to avoid local stress concentration and resulting early failure of the beam.

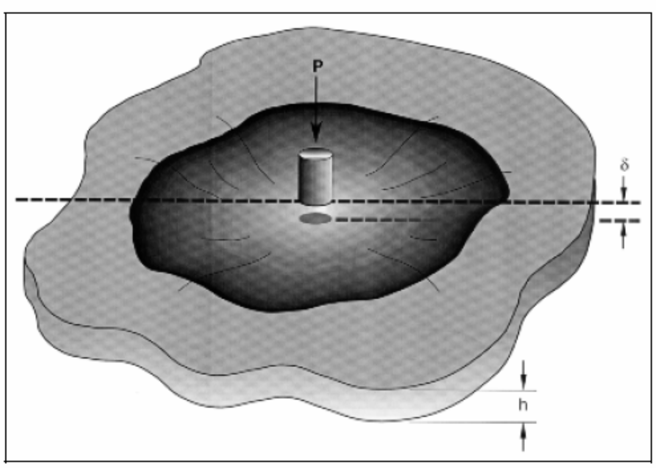
(2) *Simple Beam*. A beam of length *L* and width *B* cut from the ice sheet is placed on two supports and loaded in the beam center with a load *P* that yields a deflection (Figure 2-1b). The corresponding value of the elastic modulus is



a. Cantilever beam method.



b. Simple beam method.



c. Plate deflection method.

Figure 2-1. Determination of the mechanical properties of ice.

$$E = \frac{P}{4B\delta}\left(\frac{L}{h}\right)^3. \tag{2-5a}$$

The flexural strength is obtained for the maximum load at failure P' by

$$\sigma_b = \frac{3P'L}{2Bh^2}. \tag{2-5b}$$

(3) *Plate Loading*. The characteristic length L_c of ice can be directly measured by loading an ice sheet with a load P (e.g., a drum that can be filled with water from a safe distance away) and measuring the corresponding plate deflection δ as near the edge of load application as possible, as shown in Figure 2-1c.

$$L_c = \sqrt{\frac{P}{8\gamma\delta}} \tag{2-6}$$

where γ is the specific weight of water. For equation 2-6 to be valid, the ratio of the radius a of the load area to the characteristic length should not exceed 0.2, i.e.

$$\frac{a}{L_c} \approx \frac{a}{17h} \le 0.2. \tag{2-7}$$

2-4. Frazil Ice. Frazil ice is formed in turbulent, supercooled water. Supercooled water is at a temperature below its equilibrium freezing point; for pure water the freezing point is, by definition, 0°C (32°F) at atmospheric pressure. Supercooling takes place in lakes and rivers at locations where the water is turbulent, where the water surface is not covered by ice, and when the air temperature is less than 0°C (32°F) by a significant amount (usually an air temperature of –8°C (18°F) or lower is required). The requirement for open water can be understood by noting that, if the water surface is covered with ice, the temperature at the ice/water interface must be at the equilibrium freezing point, and all heat transfer from the water would stop when the water cooled to 0°C (32°F). As a result, the formation of frazil is always associated with open water. The level of supercooling should not be overestimated; it will usually not exceed several hundredths of a degree Celsius, and in no case will it exceed 0.1°C (0.18°F). As a result, supercooling is detectable only with laboratory-grade thermometers. Frazil ice appears first as small crystals (0.1 mm to several millimeters, 0.004 in. to one or two tenths of an inch) that are distributed more or less uniformly throughout the region of turbulence. In rivers, for example, this is likely to be throughout the entire depth. Each crystal starts out as a perfect disk, whose major diameter is 10 to 12 times its thickness. This disk shape is the form by which frazil is chiefly known, but, with time, frazil ice evolves through a number of processes to form larger and larger ice masses. Eventually, it will become a stationary, floating ice cover that may be many kilometers (miles) long.

a. Frazil Ice Formation. During the formation stage, the initial frazil ice crystals are created. Formation is characterized by supercooled water, turbulent flow, the rapid growth of disk-shaped crystals, and the creation of new crystals by secondary nucleation (explained below). The length scales of the ice associated with this stage range from several micrometers to perhaps a few millimeters (i.e., between a hundredth and a tenth of an inch). This stage usually takes place during cold periods when the heat loss from the open water surface is intense.

(1) *Nucleation*. It is now known that the frazil crystals do not "spontaneously" appear through nucleation in the water column. Nucleation is a general term, referring to the formation of a new phase of a substance from a parent phase. In our case, the parent phase is obviously water, and the new phase that is appearing is, of course, ice. We know now that frazil ice crystals are formed from s*eed crystals*, which are ice crystals introduced from outside the natural water body. Seed crystals can come from a number of different sources: vapor evaporating from the water surface, upon encountering cold air, can sublimate into ice crystals, which fall back onto the water surface and are entrained by the turbulent motion of the flow; small water droplets generated by breaking waves, bubbles bursting at the water surface, and splashing; snow and sleet. But seed crystals are not the whole story.

(2) *Secondary Nucleation*. It is observed that once a very few seed crystals are introduced into turbulent supercooled water, very quickly many new crystals are created through *secondary nucleation*. Collisions of existing crystals with hard surfaces (including other crystals) is thought to be the main mechanism through which new frazil ice crystals are formed. These new crystals can then further increase the rate of secondary nucleation with a multiplicative effect. Because the frazil ice crystals are suspended in supercooled water they are also growing in size. The water temperature will dynamically reflect the balance of the latent heat released by the growing crystals and the heat transfer from the water surface. Eventually, the rate of latent heat released is enough to return the water temperature to the ice–water equilibrium temperature (0°C [32°F]).

b. Frazil Ice Evolution and Transport. Frazil ice evolves and is transported after it forms. Frazil evolves in form largely from the individual crystals joining together to form larger masses. The evolution of frazil is characterized by water more or less at the equilibrium temperature, and frazil in the form of *flocs*, *anchor ice,* and *floes*. The length scales of the ice associated with this stage range from several millimeters to many meters (i.e., a fraction of an inch to tens of feet). The frazil is largely moving under the influence of the flow velocity of the river or stream, generally at the surface. After cold nights, it is typical to see *frazil slush*, formed of frazil flocs, moving along at the water surface of northern rivers and streams. This ice may travel long distances, moving for many days and may eventually form large moving floes. Eventually, frazil can form stationary, floating ice covers that may be quite large and last for the entire winter season. These ice covers are formed by a variety of mechanisms, depending on what form the frazil ice takes when it arrives at the stationary ice cover, and on the hydraulic conditions at the cover's leading edge. These floating covers can become very thick, especially in the (relatively rare) cases where a *hanging dam* forms. Frazil ice may be deposited on or eroded from the underside of the cover throughout the winter. The crystal structure of ice covers formed from frazil ice reflects its origin, and the ice crystals tend to be small and randomly oriented.

c. Problems Caused by Frazil Ice. There are a number of problems that can be caused by frazil ice. If areas of streams or channels remain open for long periods during cold weather, large amounts of frazil ice can be formed, carried downstream by the flow velocity, and eventually deposited in a relatively slow velocity reach of the river to form a *freezeup ice jam*. Freezeup ice jams can block substantial portions of the river cross section. This blockage may raise upstream water levels enough to cause flooding, or may serve as the site of a *breakup ice jam* later in the winter season. Upstream water levels may also be raised if large amounts of frazil ice are deposited on the channel bottom as *anchor ice* to form *anchor ice dams*. Anchor ice dams are relatively rare and usually occur in steep, shallow rivers and streams. Water intakes can experience significant problems with frazil ice if they are operated when the water is supercooled. The crystals in the supercooled water will be growing in size and will stick to any object they contact—including intake trash racks—as long as these objects are at a temperature below freezing. Given the effective heat transfer rates provided by flowing water, any object in the water that is not heated will quickly be at the temperature of the supercooled water and will accumulate frazil. Sufficient frazil can accumulate on the trash rack to effectively block it and completely stop the flow of water into the intake, often with severe consequences.

d. Control of Frazil Ice. An intact, stable ice cover will always prevent the production of frazil ice by "insulating" the water surface and preventing the large heat loss rates responsible for supercooled water. If an ice cover can be successfully created and kept in place over a reach of a river that is normally open during periods of cold weather, frazil ice problems can be completely avoided or substantially reduced. The techniques for creating and maintaining a stable ice cover are described in Chapter 4. Another technique for preventing supercooled water is to mix "warm" water with the supercooled water and raise the water temperature to the ice–water equilibrium temperature, or slightly above. This technique is especially effective near water intakes, where the quantity of warm water required can be modest. Finally, if the actual production of frazil ice cannot be controlled, mechanical removal of the frazil, using techniques described elsewhere in this manual, may be the only recourse.

2-5. Thermal Ice Growth

a. Static Ice Formation. Ice formation on water in which the flow velocity plays no role is called static ice formation. This includes ice formed on lakes and ponds during periods of low winds, and on rivers and streams in which the flow velocity is approximately 0.3 m/s (1 ft/s) or less. Static ice formation starts in a very thin layer of supercooled water at the water surface and is probably initiated by the introduction of seed crystals. The ice grows at the ice/water interface as a result of heat transfer upwards from the interface, through the ice, to the atmosphere. Ice grows in hexagonal crystals with three "a" axes of symmetry in what is called the basal plane, and one "c" axis perpendicular to the basal plane. The orientation of the ice crystals in a static ice cover can vary, depending on the initial formation process. Often, ice crystals in a static ice cover look like pencils with the "c" axes as the leads, and are called *columnar*. Because the impurities in the water are "pushed" to the boundaries of columnar crystals during growth, a relatively high concentration of impurities is trapped between the crystal boundaries. Owing to the trapped impurities, melting begins at the crystal boundaries during warm periods and a phenomenon called *candle ice* often develops. In candle ice, innumerable single crystals are no longer frozen together, but rather are leaning on each other for support. A small impact, such as wave, or well placed kick, can collapse the entire mass. Another form of ice found during static ice growth results from the presence of a snow cover on the ice and is called *snow ice*. Snow ice is formed when the weight of a snow cover on the ice sheet is sufficient to depress the ice and cause water to flood up through cracks and saturate the lower layers of the snow. Snow ice is granular, opaque, and white, and has small, randomly oriented crystals.

b. Thermal Balance of Ice Covers. The thermal balance of ice covers is found by summing all the modes of heat transfer between the ice cover and the atmosphere, and between the ice cover and the water below (Ashton 1986). One important aspect of the thermal heat balance is the heat input through solar radiation (sunlight), especially in the spring, when the hours of daylight are increasing. The ratio of the reflected sunlight to the incident sunlight is defined as the *albedo* of the surface. (An albedo of unity indicates all of the solar radiation is reflected, while an albedo of zero means all of the radiant energy is absorbed.) Ice covers that look "white" tend to have high albedos. For example, an ice surface covered with fresh snow can have an albedo of 0.9; ice covers composed of snow ice can have albedos as high as 0.6 to 0.8. In contrast to this, ice covers that are composed of clear columnar ice ("black" ice) may have albedo values as low as 0.2. An attractive and relatively easy way to modify the thermal balance of ice, especially to promote the melting and weakening of the ice cover to reduce the threat of ice jam flooding, is to decrease its albedo by applying a dark material or *dust* to the top surface to increase the absorption of solar radiation. Depending on the type of dust used and amount applied, the albedo can be reduced to 0.15 or 0.2.

c. Estimating Thermal Ice Growth. Predicting the thickness of a natural ice cover attributable to thermal growth is a classic problem of ice engineering. The differential equation describing the thermal growth rate can be formulated by assuming the following:

- That the ice is a homogenous, horizontal layer.
- That the ice is growing only at its horizontal interface with the water.
- That the thermal conditions in the ice are quasi-steady.
- That the heat flux from the water is negligible.
- That the heat fluxes are in the vertical direction only.
- That the heat loss rate from the ice surface to the atmosphere is a linear function of the temperature difference between the ice surface and the air.

Under these assumptions, the heat transfer rate through the ice cover to the atmosphere is equivalent to that of a steady heat flux through a composite slab. The thermal growth rate of the ice is found as

$$\frac{\mathrm{d}h}{\mathrm{d}t} = \frac{1}{\rho\lambda}\frac{\left(T_\mathrm{m} - T_\mathrm{a}\right)}{\left(\dfrac{h}{k_\mathrm{i}} + \dfrac{1}{H_\mathrm{ia}}\right)} \tag{2-8}$$

where h = ice thickness
T_m = temperature at the water/ice interface (assumed to be the ice–water equilibrium temperature, or 0°C [32°F])
t = time
T_a = air temperature
k_i = thermal conductivity of the ice
H_{ia} = heat transfer coefficient from the ice surface to the atmosphere
ρ = ice density
λ = ice latent heat.

Although Equation 2-8 is nonlinear, it is readily solved to yield the following "standard" model of ice thickness as a function of air temperature

$$h_j = \sqrt{(B + h_k)^2 + 2A(U_j - U_k)} - B \tag{2-9}$$

where h_j = calculated ice thickness on day j
h_k = ice thickness on day k, either observed or calculated (note that $j > k$, meaning that day j occurs after day k).

$$A = \frac{k_i}{\rho\lambda}$$

$$B = \frac{k_i}{H_{ia}}$$

$$U_j = \sum_{i=1}^{j} (T_m - T_{ai})$$

$$U_k = \sum_{i=1}^{k} (T_m - T_{ai})$$

U_j = Accumulated Freezing Degree-Days (AFDDs) recorded between the onset of freezeup (day 1) and day j
U_k = AFDDs recorded between the onset of freezeup and day k (note that $U_j > U_k$).

If the heat conduction through the ice cover is the controlling rate in the overall energy flux, then B can be ignored and if the initial ice thickness is assumed to be zero, then the classic result is found

$$h_j = \alpha\sqrt{U_j} \tag{2-10}$$

where

$$\alpha = \sqrt{\frac{2k_i}{\rho\lambda}}$$

Typical values for α are presented in Table 2-2. In this case the ice thickness is proportional to the square root of the accumulated freezing degree-days.

Table 2-2
Typical Values of α (after Michel 1971)

Ice Cover Condition	*α* *	*α* †
Windy lake w/no snow	2.7	0.80
Average lake with snow	1.7–2.4	0.50–0.70
Average river with snow	1.4–1.7	0.40–0.50
Sheltered small river	0.7–1.4	0.20–0.40

* AFDD calculated using degrees Celsius. The ice thickness is in centimeters.
† AFDD calculated using degrees Fahrenheit. The ice thickness is in inches.

d. Remarks. It is not surprising that for natural ice covers, the assumptions upon which the standard model is based may not always hold true, and other processes, not included in the standard model, may also influence the thermal growth rate of the ice. For example, the presence of snow on the ice cover may influence the heat transfer rate from the ice surface to the atmosphere. In theory, this influence could be accounted for in the standard model if the snow depth and the snow thermal conductivity were known. The ice surface may also be flooded if the weight of the accumulated snow is greater than the buoyant force of the ice cover. This will cause part of the snow to become saturated by water flowing upwards through cracks in the ice. This saturated snow is able to freeze relatively rapidly, forming snow ice. In addition, the heat flux from the ice surface to the atmosphere is composed of several modes of heat transfer, including shortwave radiation, long wave radiation, evaporation, and sensible heat loss. The actual heat transfer rate is only approximated by the relationship included in the standard model. As a result, H_{ia}, the heat transfer coefficient, may not be a constant but may vary with the meteorological conditions. Given all this, however, the standard model represented by Equation 2-10 still represents a good, practical model of ice growth. To go beyond the standard model requires an extensive data collection, and, to date, there has been no indication that the additional effort would be rewarded by a more accurate model.

2-6. Dynamic Ice Cover Formation. When an ice cover's growth is dominated by the interaction between the transported ice pieces and the flowing water, the cover is said to form dynamically. This is the counterpart of the thermal formation and growth described earlier. Almost all river ice covers are formed dynamically. All ice covers that form in this way progress upstream from an initiation point as ice is brought to the leading upstream edge of the ice cover by the flow of the river. Many different and separate processes may occur at the leading edge, depending on the hydraulic flow conditions, and the form of the arriving ice. The various processes at the leading edge are described in a general way in the following.

a. Bridging. At very low flow velocities and relatively high concentrations of surface ice, it may be possible for the ice cover to spontaneously arch across the open width of the channel and stop moving. It is generally not possible to predict where these bridging locations will be without historical knowledge. To assure the initiation of an ice cover at a specific location, ice control booms or hydraulic control structures, or both, may be necessary.

b. Juxtaposition. At relatively low flow velocities, ice floes arriving at the leading edge may simply come to a stop and not underturn. In this way the ice cover will progress upstream by juxtaposition. The maximum flow velocity at which juxtaposition happens depends on the floe geometry and the channel depth. Generally, ice control booms will function properly only if juxtaposition of the arriving ice is possible.

c. Underturning of Floes. At higher flow velocities, the arriving floes may not be stable but may instead underturn. If the flow velocity is not too high, these underturned floes will remain at the leading edge of the ice cover.

d. Ice Cover Shoving. Shoving in the ice cover can happen over a wide range of flow velocities. The cover collapses in the downstream direction and becomes thicker if the forces acting on it exceed its ability to withstand those forces. The strength of an ice cover formed from many separate pieces of ice is directly proportional to its thickness. When shoving takes place, the strength of the ice cover is increased. An ice cover may repeatedly shove and thicken as it progresses upstream. If the ice cover is treated as a "granular" material, its strength characteristics and final thickness can be estimated.

e. Under-ice Transport of Floes. At relatively high flow velocities, the ice floes arriving at the leading edge of the ice cover may be underturned and transported under the ice cover for considerable distances. At this point, further upstream progression may be halted until the deposition of the floes somewhere downstream of the leading edge reduces the channel conveyance sufficiently to cause the upstream water levels to rise and the flow velocities at the leading edge to be reduced.

f. No Ice Cover Progression. The ice cover will stop progressing upstream if the flow velocities at the leading edge remain too high. In this case open water will remain upstream of the leading edge throughout the winter season. This will result in the production of frazil ice in the open water area all winter, which may lead to the formation of freezeup jams or other problems downstream.

2-7. Ice Cover Breakup. Breakup transforms a completely ice-covered river into an open river. Two example forms bracket the types of breakup commonly found throughout most of North America. At one extreme is *thermal meltout*. During an ideal thermal meltout, the river ice cover deteriorates through warming and the absorption of solar radiation and melts in place, with no increase in flow and little or no ice movement. At the other extreme is the more complex and less understood *mechanical breakup*. Mechanical breakup requires no deterioration of the ice cover but rather results from the increase of flow entering the river. The increase in flow induces stresses in the cover, and the stresses in turn cause cracks and the ultimate fragmentation of the ice cover into pieces that are transported by the channel flow. Ice jams take place at locations where the ice fragments stop. Severe and sudden flooding can result when these ice jams form or when they release. Actual breakups take place most often during warming periods, when the ice cover strength deteriorates to some degree and the flow entering the river increases because of snowmelt or precipitation. Therefore, most river ice breakups actually fall somewhere in-between the extremes of thermal meltout and mechanical breakup. As a general rule, the closer a breakup is to being a mechanical breakup, the more dramatic and dangerous it is because of the increase in flow and the large volume of fragmented ice produced.

a. Thermal Meltout. Every river in North America will experience a thermal meltout every spring unless a mechanical breakup occurs first. Thermal meltouts will not take place at all points on a river simultaneously, but will occur at different locations at different rates, depending on the latitude, local climate, and ice exposure. Thermal meltouts happen because of heat transfer into the ice cover by convection to its underside from the water, by convection from the warm air to its top, and radiation, both longwave (infrared) and shortwave (sunlight). The transfer of heat from the water to the underside of the ice cover can be very substantial, especially if there is open water upstream that provides an area in which the flowing water can absorb heat from the atmosphere. In almost all cases, the albedo of open water areas will be much less than the albedo of the ice cover. As a result, the open water areas will absorb more solar radiation than ice-covered areas. When the flowing water passes under the ice cover, a portion of the extra heat provided by this lower albedo will be available to melt its underside. Generally, the albedo of snow on the ice surface or snow ice will be quite large and little solar radiation will penetrate the ice cover. The creation of meltwater on the surface will drastically lower the albedo and help the ice absorb sunlight. The ice cover can also deteriorate internally without much of a loss of thickness if solar radiation is able to penetrate it. The absorbed solar radiation causes melting in the interior of the ice that results in a loss of structural integrity of the cover, as described previously in Paragraph 2-5a. This is most likely to happen if the ice cover is composed of columnar crystals. Fine-grained ice covers, composed of snow ice or frazil ice, are much less susceptible to internal deterioration through absorption of solar radiation.

b. Mechanical Ice Cover Breakup. Breakup does not happen simultaneously everywhere along a river network. Often breakup occurs first on smaller tributaries, and then proceeds haphazardly to the main stem rivers. This can result in severe ice jams at the confluence of tributaries and the main stems. Breakup can progress upstream or downstream, depending on the local weather. Generally, if it progresses upstream, fewer ice jams will result than if it progresses downstream. Every breakup is different, but there are a few broad similarities in the sequence of a breakup that can be described. The mechanical breakup always occurs in response to an increase in flow in the river, with a corresponding increase in stage.

(1) *Formation of Shore Cracks*. Shore cracks are longitudinal cracks running parallel to the banks of the rivers. Shore cracks form when the magnitude of the water level change in the river channel exceeds a limit determined by the material properties of the ice, the ice thickness, channel width, and the type of attachment of the ice cover to the channel bank (hinged or fixed). Only a small increase or decrease in discharge is necessary to cause shore cracks, and they are usually common soon after runoff into a river has begun to increase. The presence of shore cracks does not necessarily indicate the immediate onset of breakup. They may be present throughout the winter season.

(2) C*racking of the Ice Sheet into Individual Floes*. Transverse cracks (across the channel) will appear soon after the river stage has begun to increase. The first cracks will generally create relatively large ice floes, a river-width wide, and many river-widths long, but sometimes the ice covers are immediately broken into much smaller floes. The actual mechanisms responsible for creating the individual floes have not yet been positively identified.

(3) *Movement of Floes*. As the stage continues to increase, the ice floes will begin to move. If the floes are relatively large, they may be kept from movement by geometric constraints, such as sharp bends, constrictions, the presence of bridge piers, etc., until a substantial increase in stage is reached. If the floes are relatively small, and there are no constraints, they may begin to move after a small stage increase. As a rule of thumb, the stage must rise 1-½ to 3 times the ice thickness before the ice moves. Once the floes begin moving, they are quickly reduced in size, eventually arriving at a size that is roughly 4 to 6 times the ice thickness.

(4) *Formation of Ice Jams*. Ice jams form when the moving ice floes reach a location in the river where its ice transport capacity is exceeded. This is most likely at places where an intact ice cover remains, the slope of the river decreases, a geometric constraint exists, etc. At these locations, the ice stops moving and jams. This type of ice jam is a *breakup ice jam*. Ice jams substantially reduce the channel flow conveyance. As a result, water levels upstream of an ice jam can rise substantially and quickly, causing flooding and transporting ice into the flood plain. The probable maximum thickness and roughness of ice jams can be estimated and used to estimate the probable flood stages (see Chapter 3).

2-8. References

a. Required Publications.

None.

b. Related Publications.

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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.

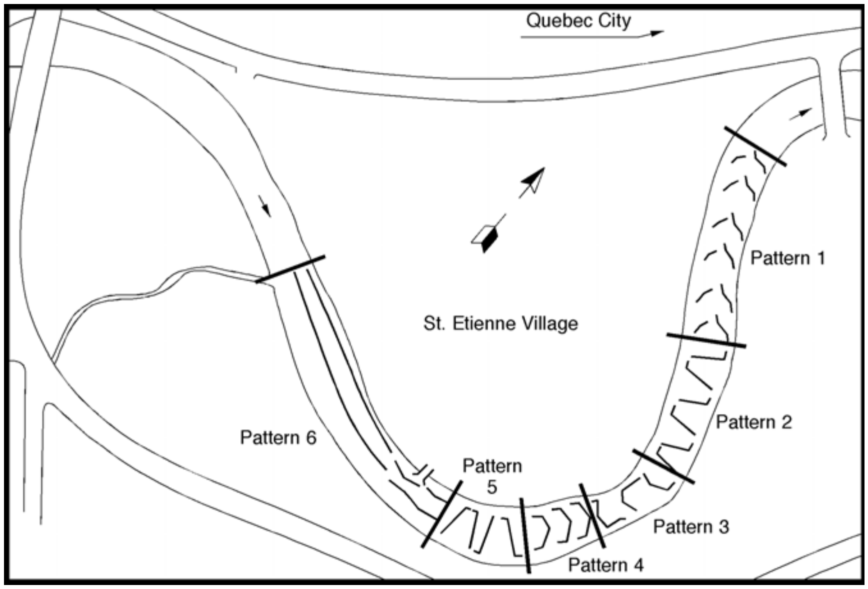


Figure 3-1. Trench patterns cut in the Beaurivarge River, Canada (after Jolicoeur et al. 1984).

(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.

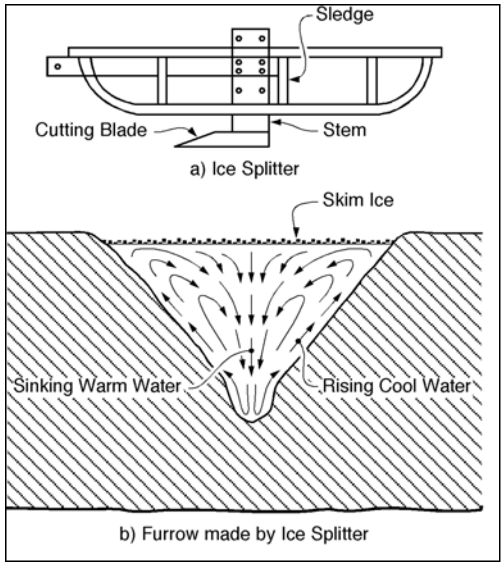


Figure 3-4. Ice channeling plow developed by Tyskin (1970).

(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.

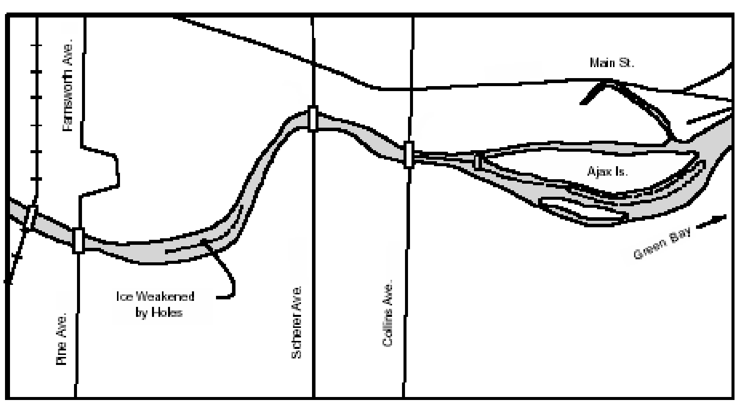
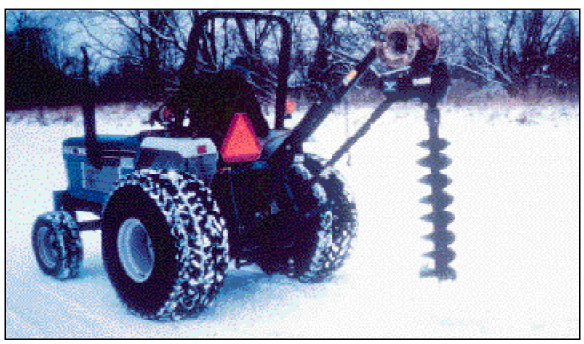


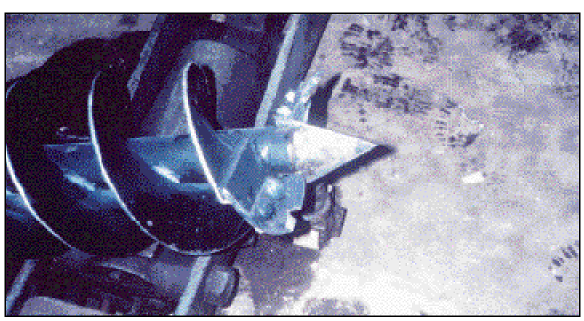
Figure 3-5. Hole drilling operations on the Oconto River at Oconto, Wisconsin.

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.

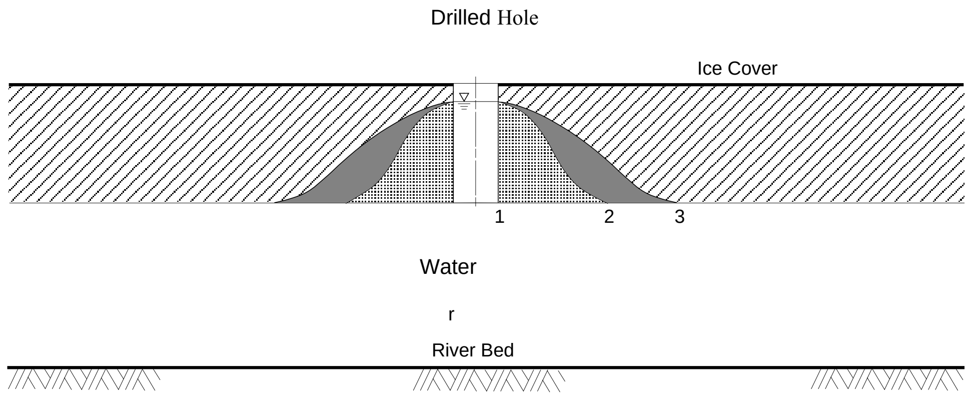


Figure 3-8. Typical observed ice profile around a hole drilled in ice with water flowing by it. The original hole is shown in profile 1. Profiles 2 and 3 show the progressive melting of the ice away from the hole (after Haehnel 1996).

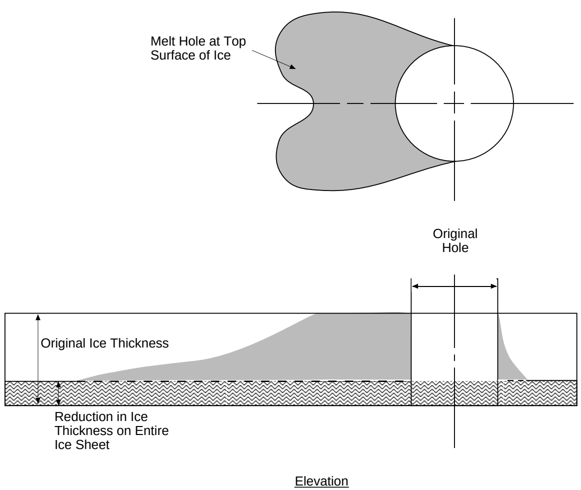


Figure 3-9. Observed melt pattern around a 2.54-centimeter-diameter (1-inch) hole drilled through a floating ice cover in a refrigerated flume.

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

$$W_{opt} = 21t^3 \tag{3-2}$$

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

$$W_{opt} = 1.4t^3 \tag{3-3}$$

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

$$D = 15t. \tag{3-4}$$

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

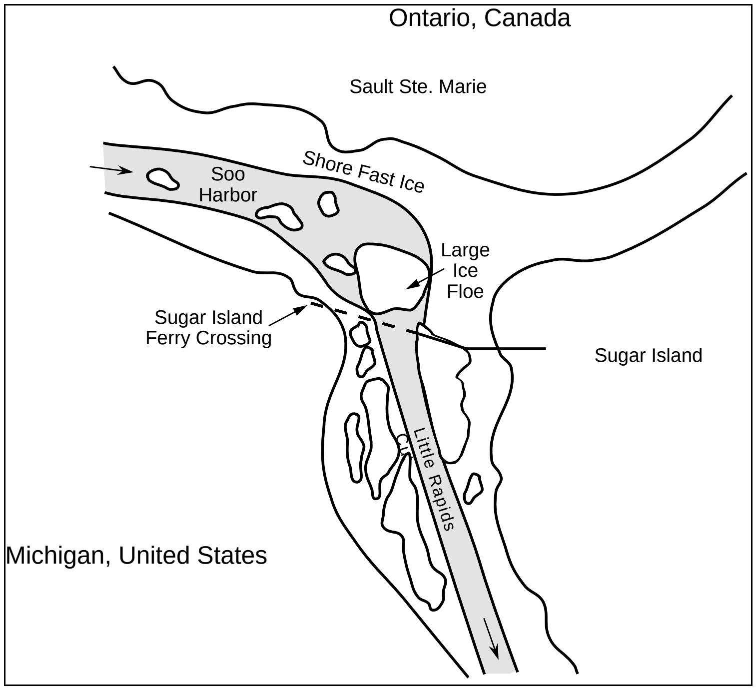
reduced to 6000 to 7500 m^2/hr (64,600 to 80,700 ft^2/hr). In brash ice (e.g., refrozen ship tracks), the AST-002 broke ice at a rate of about 42,000 m^2/hr (452,000 ft^2/hr).

(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).

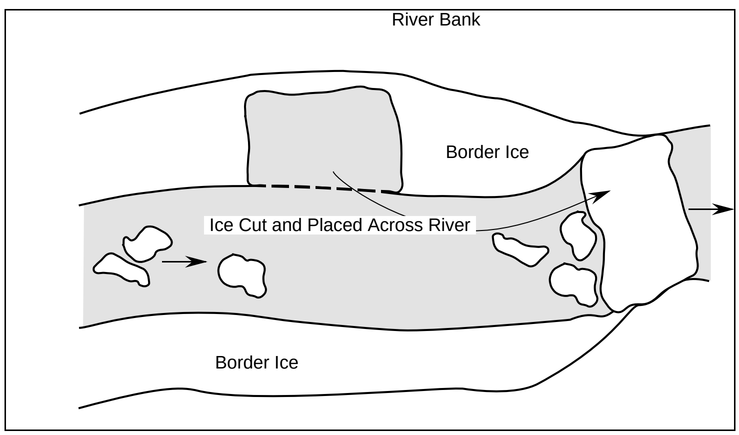
Figure 3-11. Breaking ice with an amphibious excavator on the Aroostook River, Ft. Fairfield, Maine.

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.

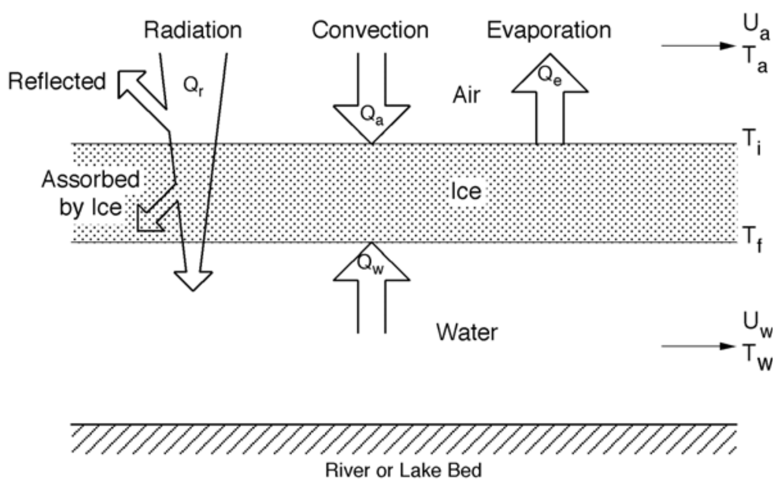


Figure 3-13. Various sources of thermal energy available for deteriorating and melting an ice cover. Q refers to the heat flux, U is velocity, and T is temperature.

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).

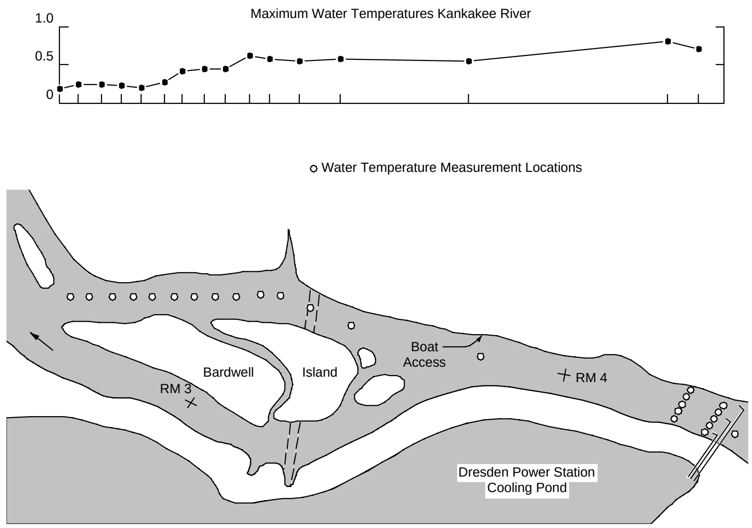


Figure 3-14. Siphons used to route warm water from the Dresden Power Station cooling pond for melting ice in the Kankakee River, Wilmington, Illinois. The plot shows the water temperature at various river sections downstream of the siphon outlets during operation on 18 January 1988.

(*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).

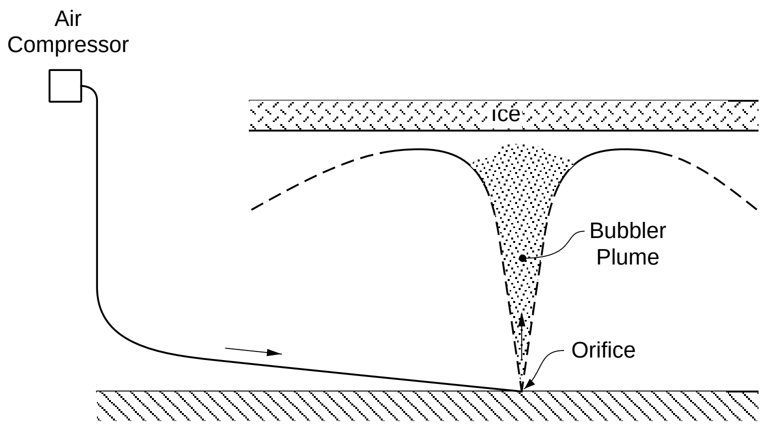


Figure 3-15. Schematic of a typical bubbler system.

(*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).

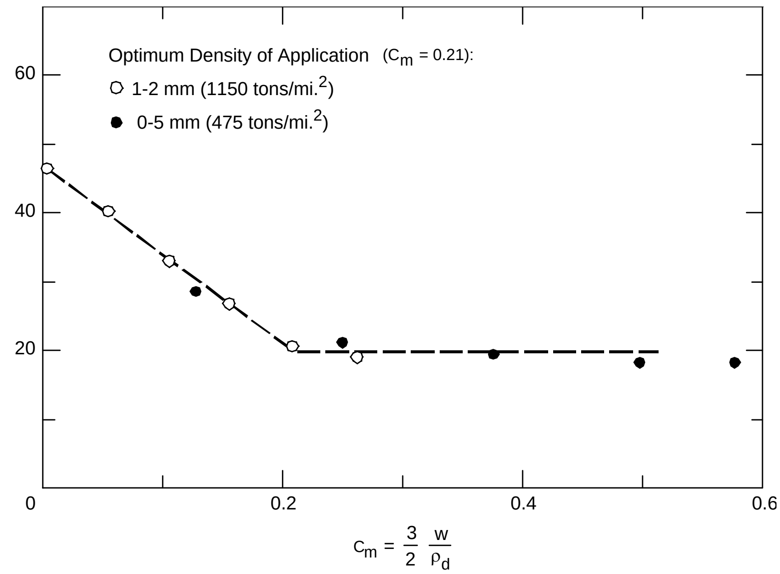


Figure 3-16. Albedo as a function of application density for Ottawa Valley crushed limestone applied to an ice surface (after Williams and Gold 1963).

(*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 ($/m^2)	Cost ($/ft^2)	Application rate (m^2/hr)	Application rate (ft^2/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 herringbone 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 icebreakers, 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.

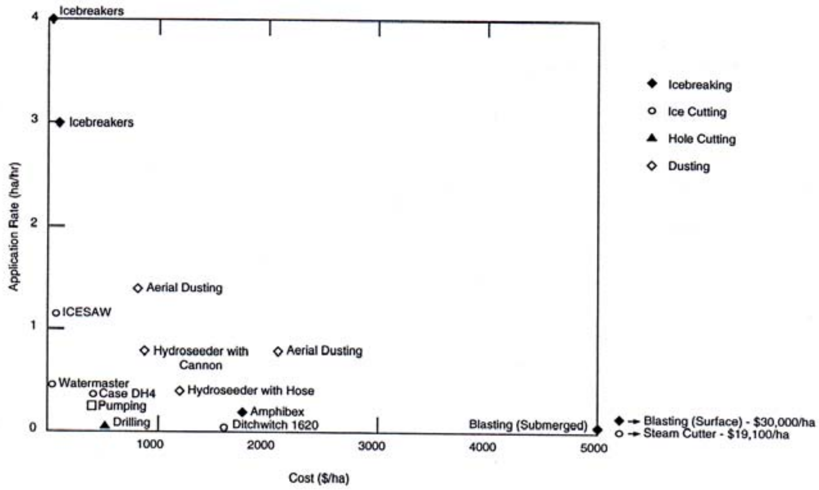


Figure 3-19. Cost and performance data for various methods of ice control. (1 ha= 10,000 m^2 = 107,640 ft^2)

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).

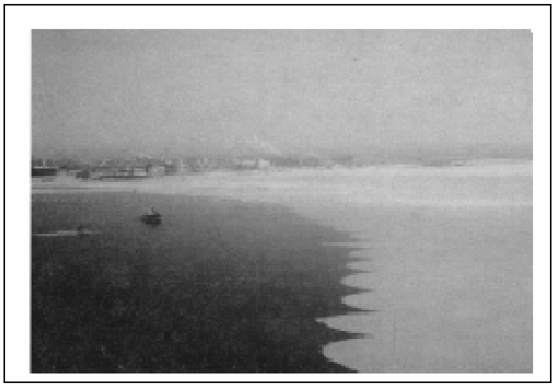


Figure 3-20. Lake Erie ice boom.

(*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.

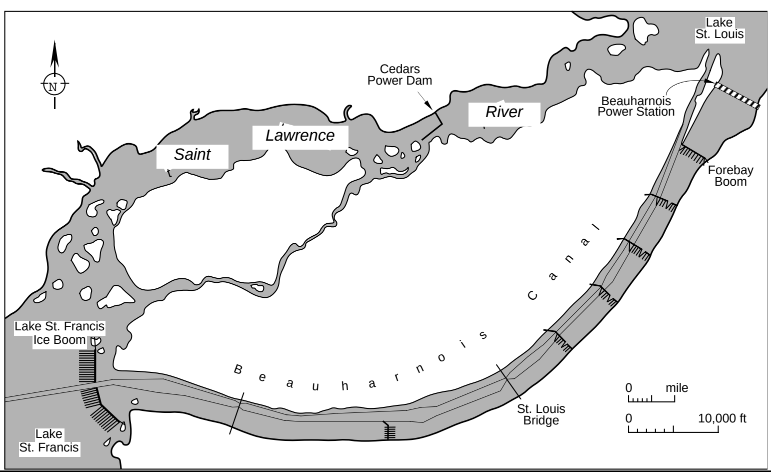


Figure 3-21. Locations of ice booms on the Beauharnois Canal.

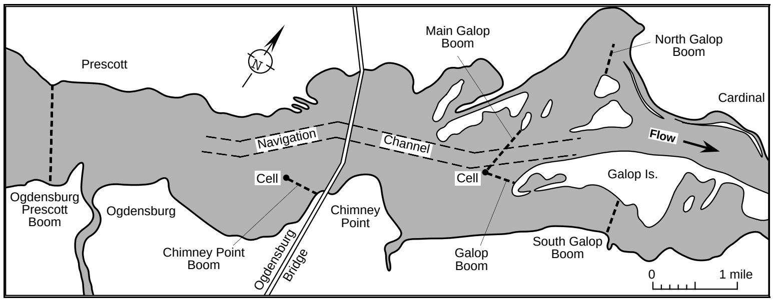
(2) *Ice Control for Hydropower.*

(*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.

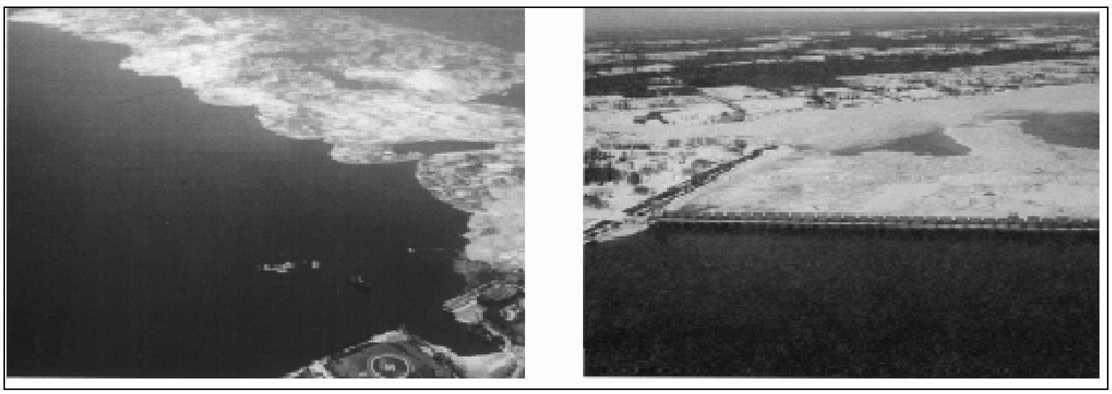
(*b*) Downstream of the Lake St. Francis boom, a series of six steel pontoon booms on the Beauharnois Canal promote the rapid formation of an ice cover, upstream of the power station (Figure 3-21). Rapid ice cover progression depends on flow reductions during the 7- to 14-day formation period. Because 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.

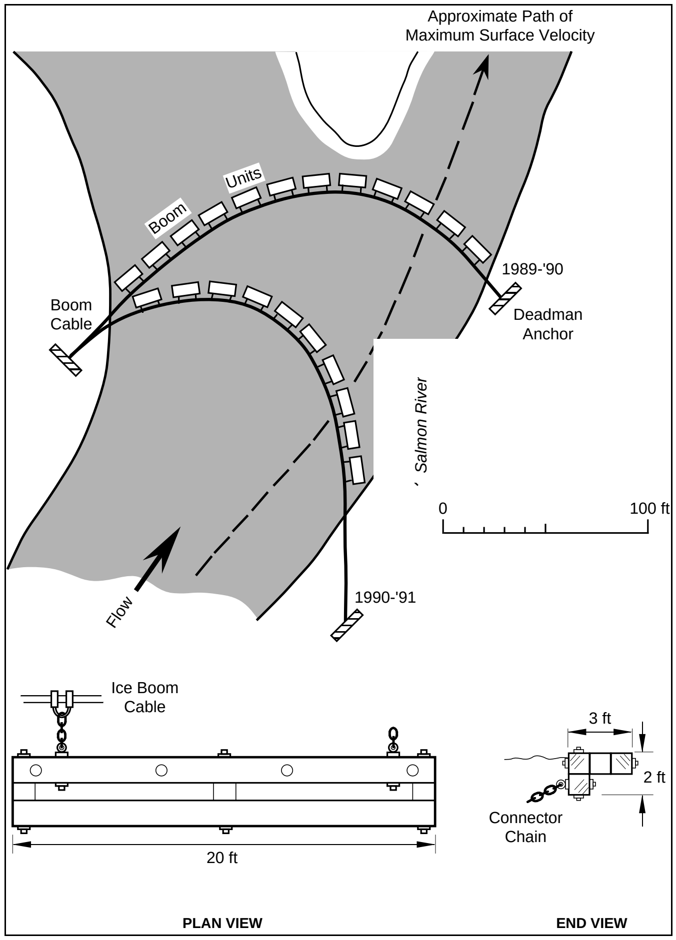


Figure 3-24. Two boom configurations tested at Salmon, Idaho.

(*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).

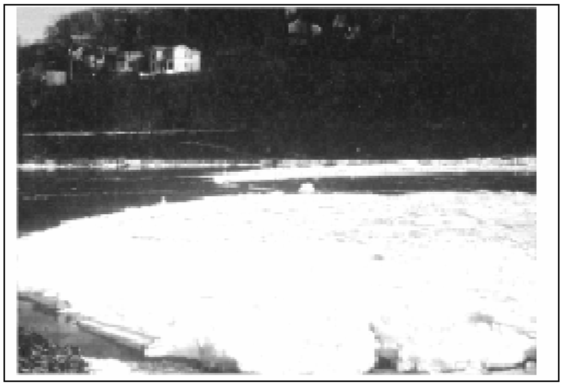


Figure 3-25. Allegheny River ice boom.

(*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.

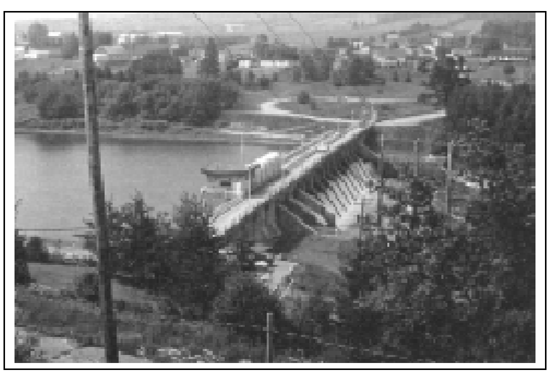
(*a*) As mentioned earlier, the majority of sheet ice retention methods are successful only under the hydraulic conditions of relatively low energy slope, low water surface velocity, and low Froude number. By raising the upstream water level, groins, weirs, and dams may create conditions favorable for 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.

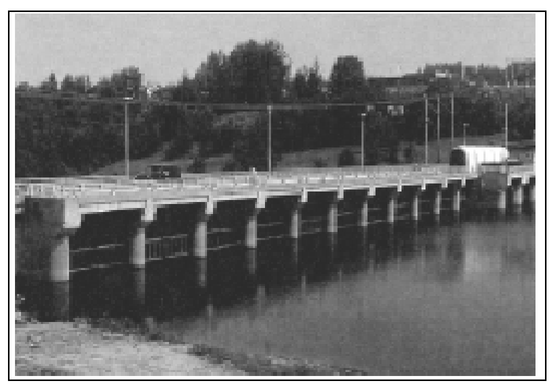
(*c*) A system of groins, used in conjunction with booms, promotes ice cover formation upstream of the hydrostation at Hestefoss in northern Norway (Kanavin 1970, Perham 1983). On the Burntwood River of the Churchill River Diversion Project, Manitoba Hydro uses two opposing groins, or wing dikes, to 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.

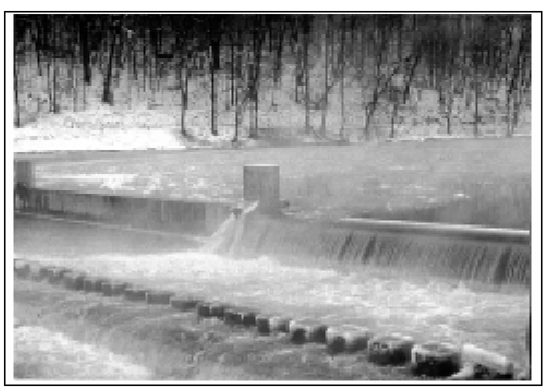
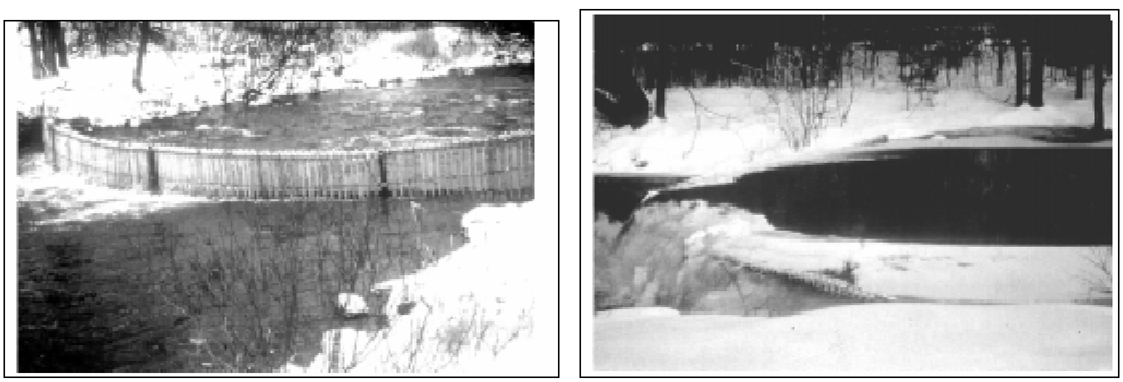


Figure 3-28. Ice control weir on Oil Creek, upstream of Oil City, Pennsylvania.

(*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.

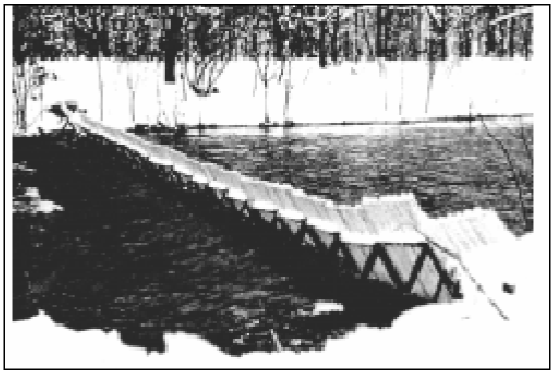
(6) *Removable Weirs.* Experimental tension weirs placed in small rivers have successfully created pools and ice covers for the purpose of limiting frazil production. Researchers at CRREL initially used a structure consisting of vertical wood 2×4s attached to top and bottom cables, referred to as a fence 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.

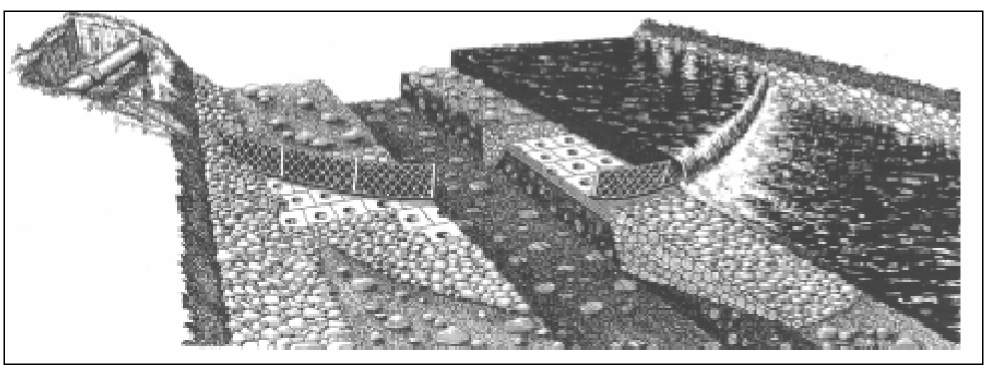


a. 24 December 1991.

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.

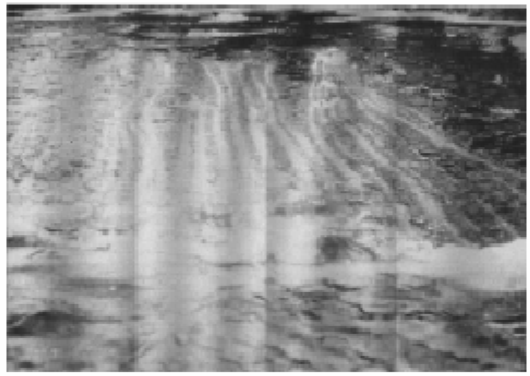


Figure 3-32. Frazil collector lines being tested on the Mascoma River, 1981. The view is looking upstream. Frazil accumulates on the individual lines, which are floating near the surface.

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).

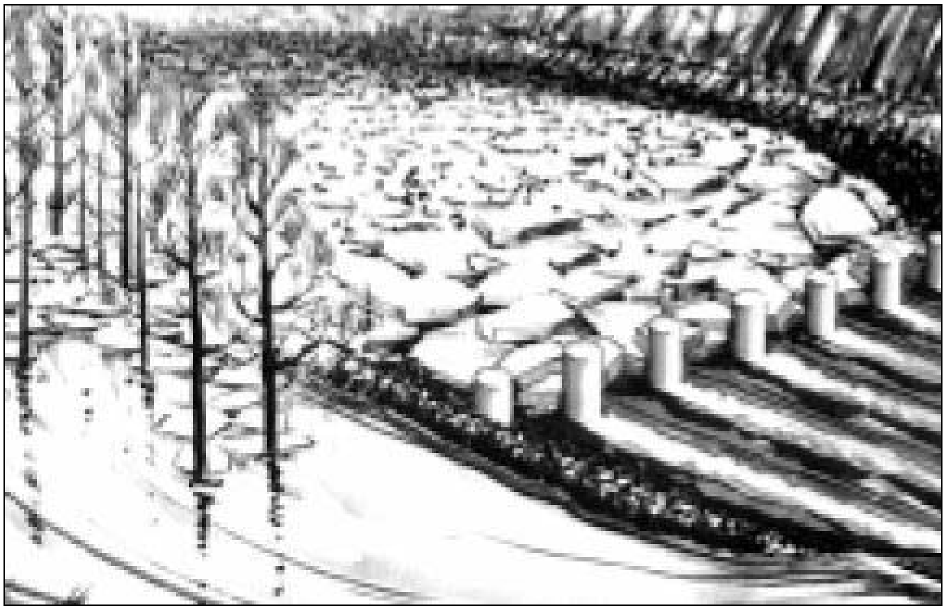


Figure 3-35. Conceptual drawing of Cazenovia Creek ICS.

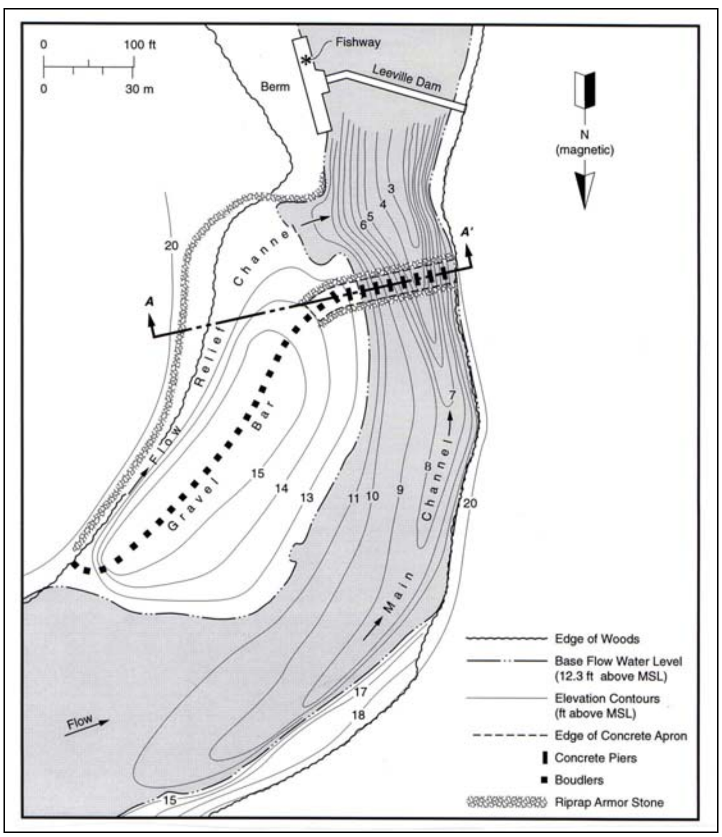


Figure 3-36. Plan view of the Salmon River ICS.

(*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.

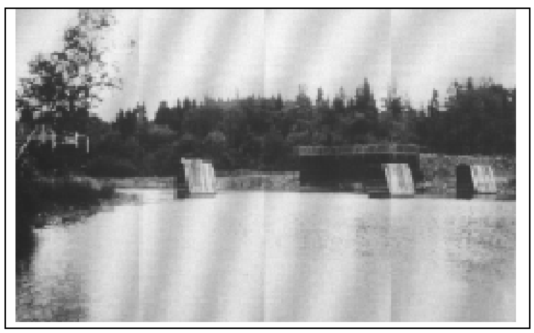


Figure 3-38. Rock-filled timber cribs upstream of the dam at Cherryfield, Maine.

(*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.

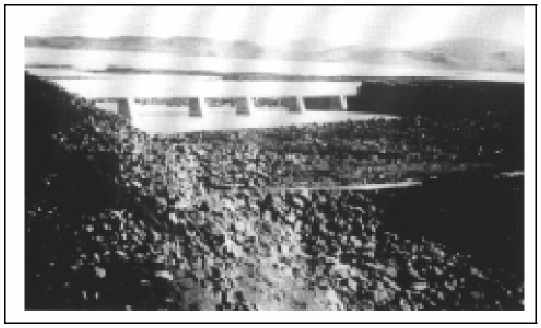


Figure 3-39. Spillway barrier at the outlet of the Sigalda Reservoir in Iceland.

(*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.

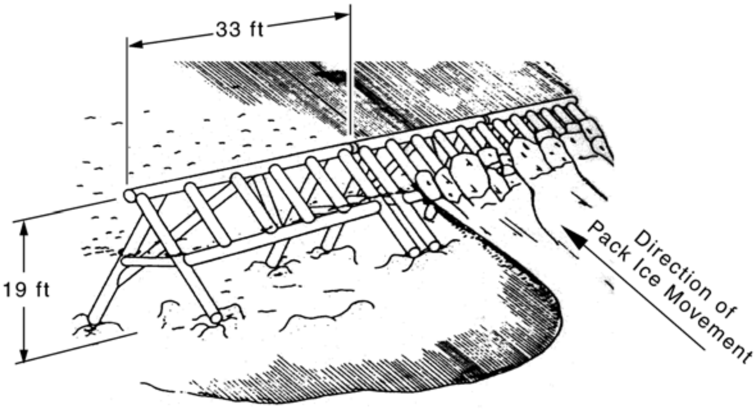


Figure 3-40. Pack ice barrier, Saroma Lagoon, Sea of Okhotsk. The direction of ice movement is from lower right to upper left. (After Yamaguchi et al. 1988.)

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.

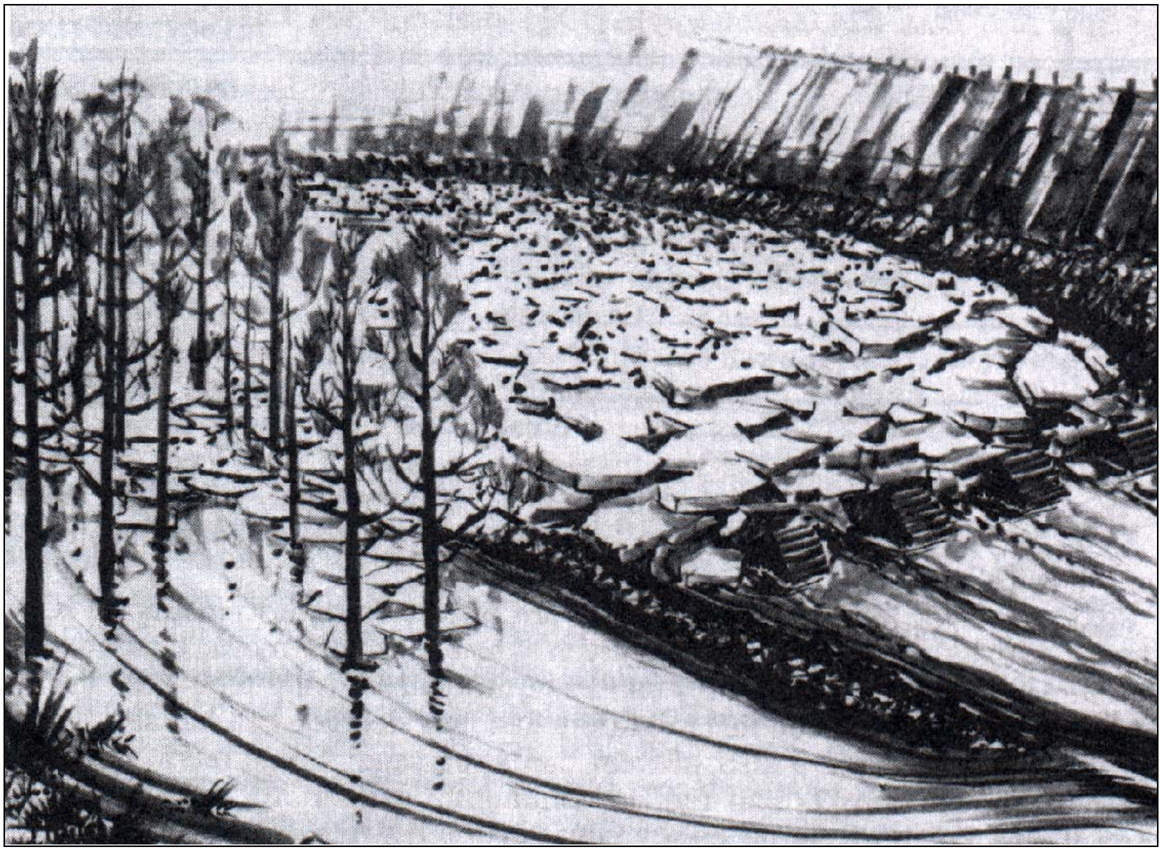


Figure 3-41. Concept drawing of the Hardwick, Vermont, ICS, which retains the breakup ice run behind boulders in the main channel while relief flow bypasses the structure via the floodplain.

(2) *Pier ICS without Floodplain Relief Flow*. A limitation of pier ICS designs with overbank 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.

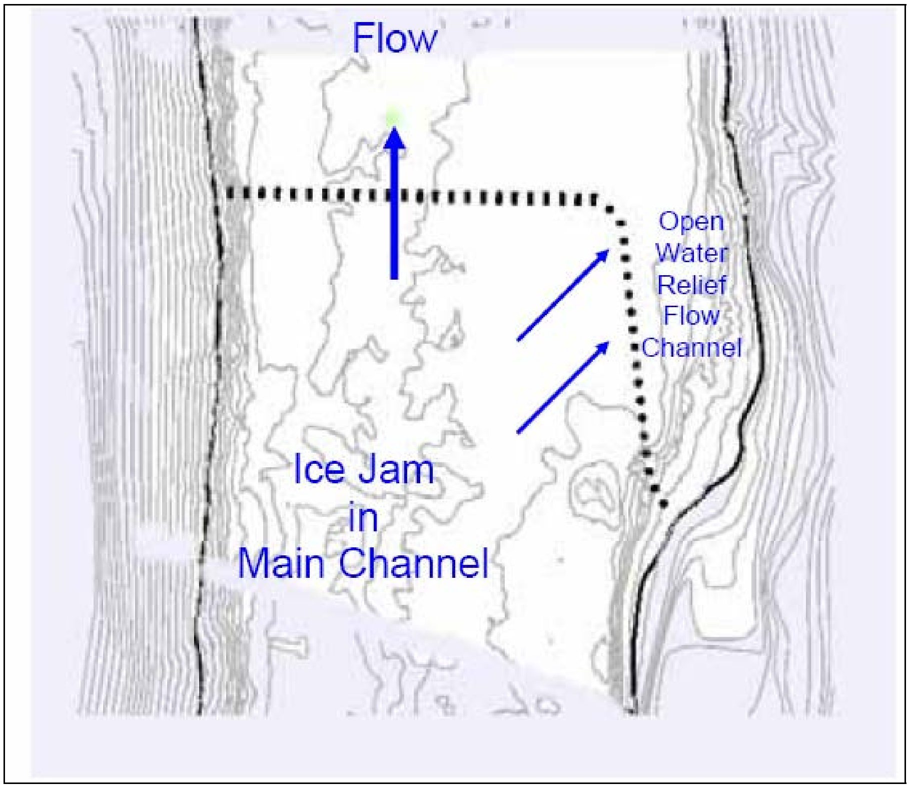


Figure 3-42. Example of pier ICS with in-channel relief flow.

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.

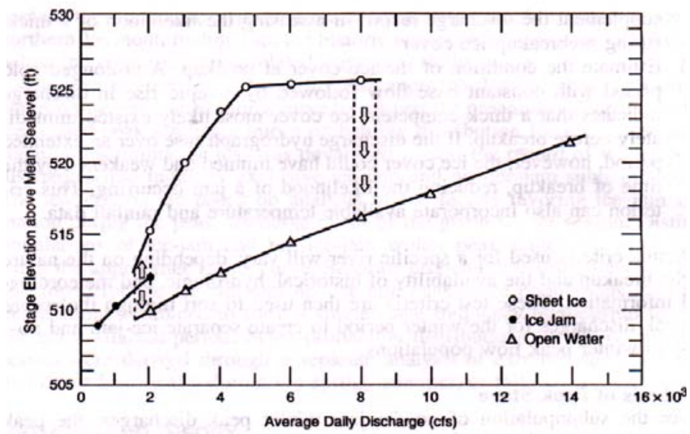


Figure 3-43. Ice-affected rating curve for the 1992 Montpelier ice jam.

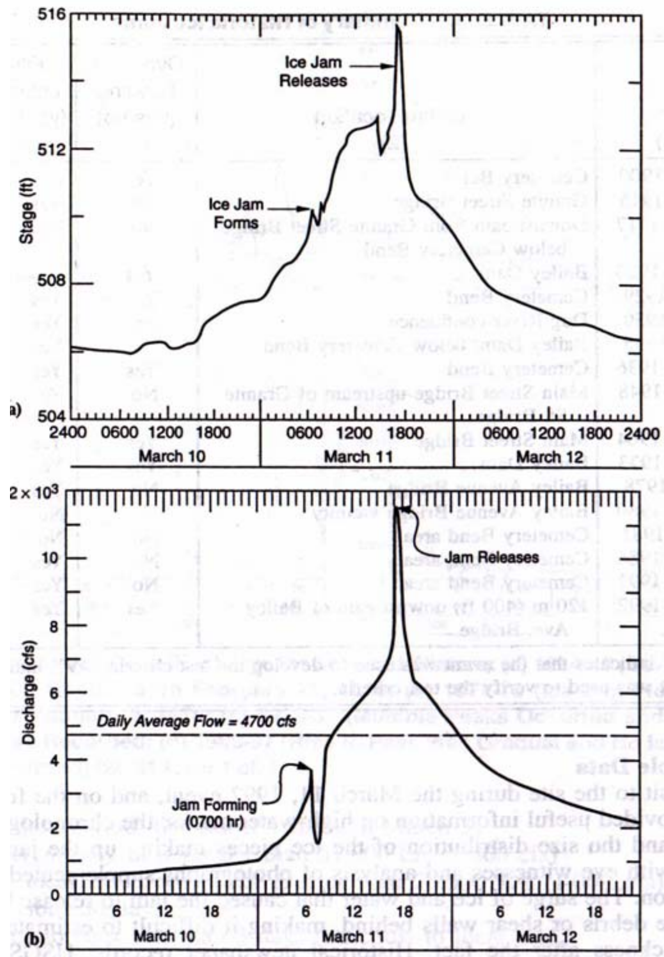


Figure 3-44. Stage and discharge hydrographs for the Winooski River showing the formation and release of the 1992 ice jam at Montpelier, Vermont.

(*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.

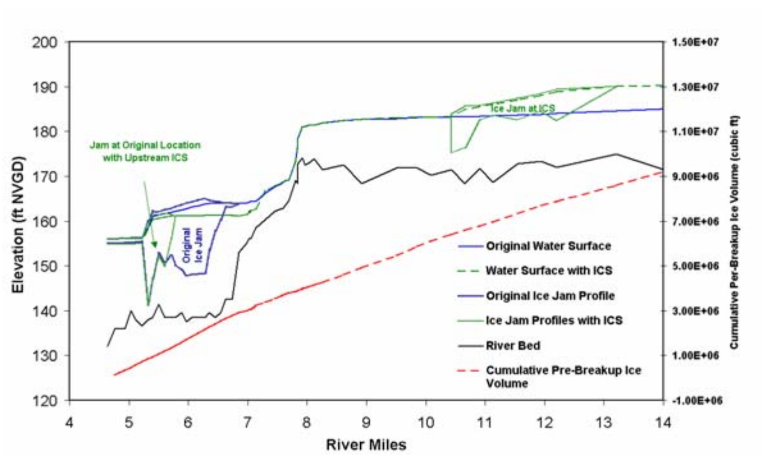


Figure 3-45. HEC-RAS simulations of existing-conditions ice jam compared to ice jam profiles resulting from upstream ice retention. The cumulative pre-breakup ice volume is also shown.

(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.

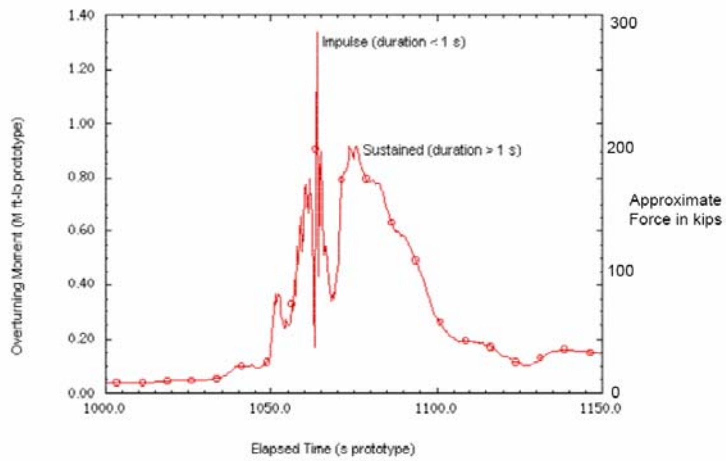


Figure 3-47. Measured moments on a pier, Cazenovia Creek physical model study, from Lever et al. (2000).

(*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.

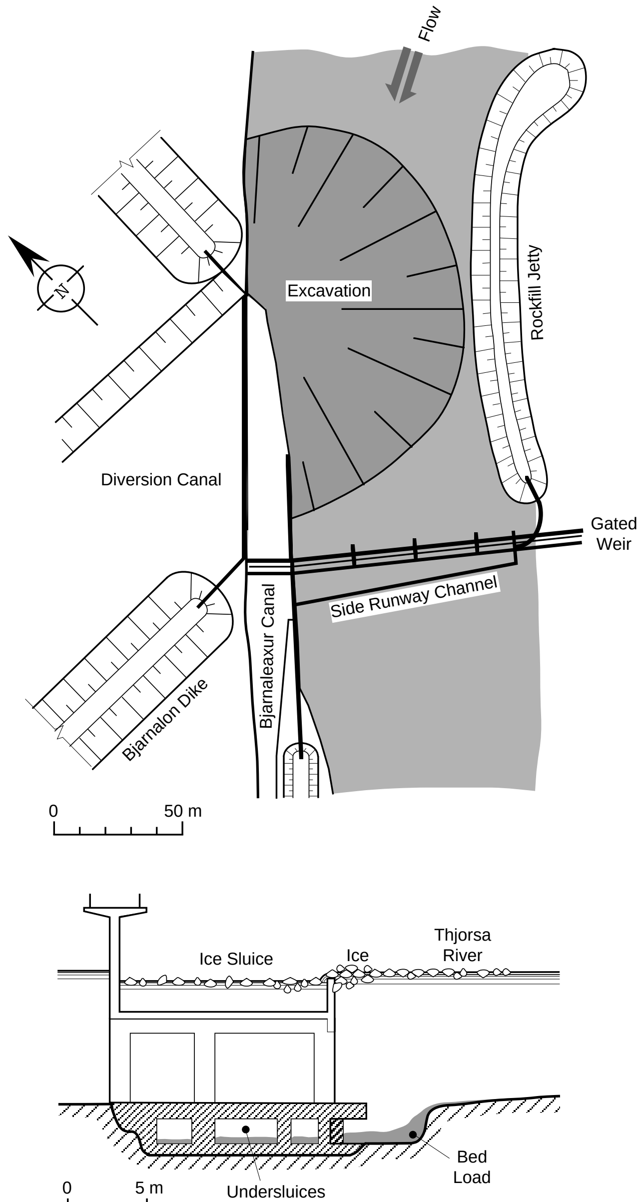


Figure 3-47. Ice sluice at the intake to the Burfell Power Station, Iceland. (After Carstens 1992.)

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.

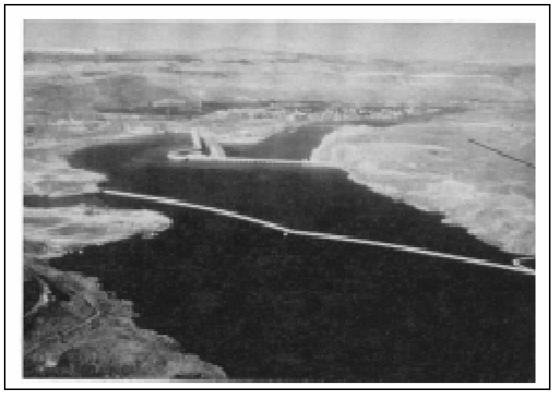


Figure 3-48. Chief Joseph shear boom on the Columbia River at Bridgeport, Washington.

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

						Breakup
		Freeze-up				
			Fixed			
		Removable				
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.

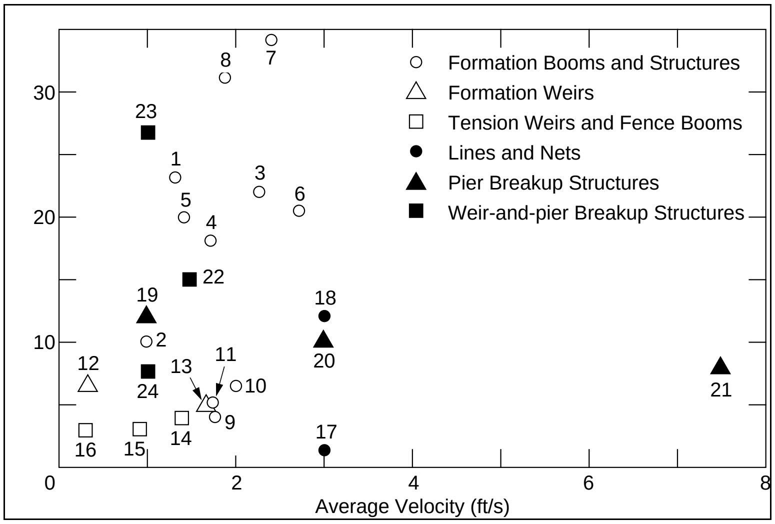


Figure 3-49. Depth vs. average velocity for various types of ice control structures. The numbers correspond to the list in Table 3-10.

(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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Chapter 4
Hydraulic Computations and Modeling of Ice-Covered Rivers

4-1. Introduction

This chapter describes the general concepts for numerical modeling of the hydraulics of ice-covered channels and contains background material and the equations used. The calculation of the hydraulics of rivers for open water conditions (i.e., water-surface profiles) has a long history and well established procedures. One of the complications imposed by ice on rivers is the difficulty of calculating the hydraulic parameters of interest when the flow is affected by an ice cover or an ice jam. Section I of this chapter presents the general principles and equations for modeling river ice covers. Over 30 years ago, the Corps of Engineers' Hydrologic Engineering Center (HEC) formulated the first version of the program known as HEC-2 for calculating the hydraulics of open-channel flow (U.S. Army 1990). In an effort to model the effect of an ice cover, a utility program called ICETHK was developed at CRREL to be used in conjunction with HEC-2. Section II of this chapter describes the ICETHK model. More recently, the HEC-RAS model (for River Analysis System) was developed by the Hydrologic Engineering Center as a replacement for HEC-2. HEC and CRREL collaborated to include river ice as an integral part of the structure of the new model. As such, HEC-RAS overcomes several limitations that exist in ICETHK, and it applies to a wider variety of river ice situations. The ice-handling characteristics of HEC-RAS are described in Section III.

a. ICETHK. ICETHK is a useful engineering tool, since many flood studies and hydraulic design projects require the calculation of ice-affected stages. Before the development of ICETHK, the calculation of ice-affected backwater profiles using HEC-2 was painstaking, requiring many iterations. The model has two strong points. First, ICETHK is used in conjunction with HEC-2, the most commonly used backwater model in the United States, and river geometry data in the HEC-2 format are widely available. Second, ICETHK is designed to help the user understand ice jam processes and is relatively easy to use. The original ICETHK model has been supplanted by an improved ice routine in HEC-RAS, but it is described in this chapter for those who may continue to find it useful and because of its strong association with the well-established HEC-2 model.

b. HEC-RAS. The HEC-RAS model of river hydraulics contains code that enables the user to model ice-covered channels at two levels. The first level applies to an ice cover with known geometry. In this case, the user specifies the ice cover thickness and roughness at each cross section. Different ice cover thicknesses and roughnesses can be specified for the main channel and for each overbank, and both the thickness and roughness can vary along the channel. The second level addresses a wide-river ice jam. In this case, the ice thickness is determined by an ice jam force balance. The ice jam can be confined to the main channel or can include both the main channel and the overbanks. The material properties of the wide-river jam can be selected by the user and can vary from cross section to cross section. The user can specify the hydraulic roughness of the ice jam, or HEC-RAS will estimate the hydraulic roughness on the basis of empirical data.

Section I
Modeling River Ice Covers

4-2. General

The common formation of ice covers on rivers during the cold winter months arises in a variety of ways. How an ice cover forms depends on the channel flow conditions and the amount and type of ice generated. In most cases, river ice covers float in hydrostatic equilibrium because they react both elastically and plastically (the plastic response being termed *creep*) to changes in water level. The thickness and roughness of ice covers can vary significantly along the channel and even across the channel. A stationary, floating ice cover creates an additional fixed boundary with an associated hydraulic roughness. An ice cover also makes a portion of the channel cross-sectional area unavailable for flow, i.e., that part occupied by the ice. The net result is generally to reduce the channel conveyance, largely by increasing the wetted perimeter and reducing the hydraulic radius of a channel, but also by modifying the effective channel roughness and reducing the channel flow area.

4-3. Modeling Ice Covers with Known Geometry

The conveyance of a channel or any subdivision of an ice-covered channel, K_i, can be estimated using the Manning equation:

$$K_i = \frac{1.486}{n_c} A_i R_i^{2/3} \tag{4-1}$$

where

n_c = composite roughness

A_i = flow area beneath the ice cover

R_i = hydraulic radius modified to account for the presence of ice.

The composite roughness of an ice-covered river channel can be estimated using the Belokon-Sabaneev equation as

$$n_c = \left(\frac{n_b^{3/2} + n_i^{3/2}}{2} \right) \tag{4-2}$$

where

n_b = roughness value for the bed

n_i = roughness value for the ice.

The hydraulic radius of an ice-covered channel is found as

$$R_i = \frac{A_i}{P_b + B_i} \tag{4-3}$$

where

P_b = wetted perimeter associated with the channel bottom and sideslopes

B_i = width of the underside of the ice cover.

It is interesting to estimate the influence that an ice cover can have on the channel conveyance. For example, if a channel is roughly rectangular in shape and much wider than it is deep, then its hydraulic radius will be approximately cut in half by the presence of an ice cover. Assuming that the flow area remains constant, we see that the addition of an ice cover, having a roughness equivalent to the bed roughness, reduces conveyance by 37 percent.

4-4. Modeling Wide-River Ice Jams

The wide-river ice jam is probably the most common type of river ice jam (Figure 4-1). In this type, all stresses acting on the jam are ultimately transmitted to the channel banks. The stresses are estimated using the ice-jam force balance equation:

$$\frac{d\overline{\sigma}_x t}{dx} + \frac{2\tau_b t}{B} = \rho' g S_w + \tau_i \tag{4-4}$$

where

$\overline{\sigma}_x$ = longitudinal stress (along stream direction)

t = the accumulation thickness

τ_b = shear resistance of the banks

B = accumulation width

ρ' = ice density

g = acceleration of gravity

S_w = water surface slope

τ_i = shear stress applied to the underside of the ice by the flowing water.

This equation balances changes in the longitudinal stress in the ice cover and the stress acting on the banks with the two external forces acting on the jam, namely the gravitational force attributable to the slope of the water surface and the shear stress of the flowing water on the jam underside.

a. Assumptions. Two assumptions are implicit in this force balance equation: that $\bar{\sigma}_x$, t, and τ_i are constant across the width, and that none of the longitudinal stress is transferred to the channel banks through changes in stream width or horizontal bends in the plan form of the river. In addition, the stresses acting on the jam can be related to the mean vertical stress using the passive pressure concept from soil mechanics, and the mean vertical stress results only from the hydrostatic forces acting in the vertical direction. In the present case, we also assume that there is no cohesion between individual pieces of ice, a reasonable assumption for ice jams formed during river ice breakup.

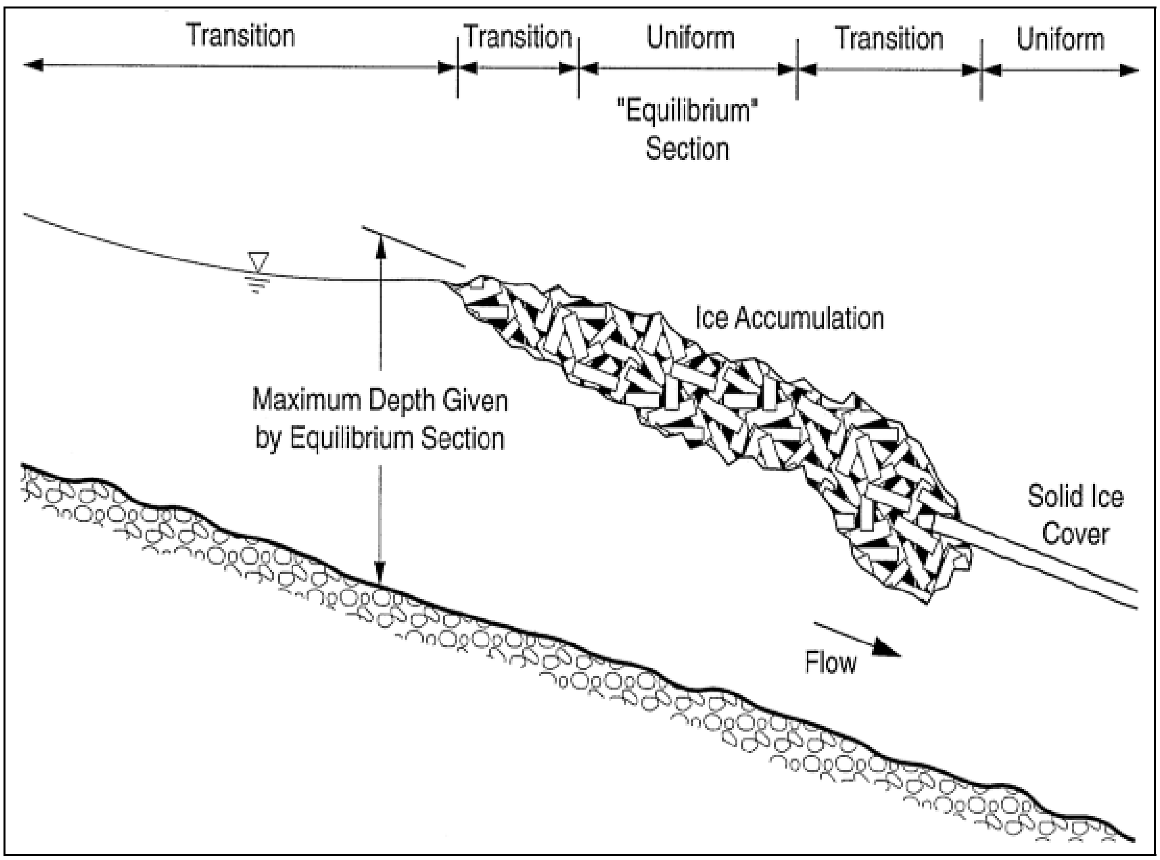

Figure 4-1. Schematic profile of a wide-river ice jam. *Note that the ICETHK model applies to the "equilibrium section" of the jam where ice thickness and flow are relatively uniform. HEC-RAS applies to the entire jam except grounded portions, if any.*

(1) In this light, the vertical stress, $\bar{\sigma}_z$, is

$$\bar{\sigma}_z = \gamma_e t \tag{4-5a}$$

in which

$$\gamma_e = \frac{1}{2}\rho' g(1-s)(1-e) \tag{4-5b}$$

where

e = ice jam porosity (assumed to be the same above and below the water surface)

s = specific gravity of ice.

(2) The longitudinal stress is then

$$\bar{\sigma}_x = k_x \bar{\sigma}_x \tag{4-6}$$

where

$k_x = \tan^2 (45° + \phi/2)$

ϕ = angle of internal friction of the ice jam.

(3) The lateral stress perpendicular to the banks can also be related to the longitudinal stress as

$$\bar{\sigma}_y = k_1 \bar{\sigma}_x \tag{4-7}$$

where

k_1 = coefficient of lateral thrust.

(4) Finally, the shear stress acting on the bank can be related to the lateral stress

$$\tau_b = k_o \bar{\sigma}_y \tag{4-8}$$

where

$k_o = \tan \phi$.

b. Reformulation of the force balance equation. Using the above expressions, we can restate the ice-jam force balance as

$$\frac{dt}{dx} = \frac{1}{2k_x\gamma_e}\left(\rho' g S_w + \frac{\tau_i}{t}\right)\frac{k_o k_1 t}{B} = F \tag{4-9}$$

where

F = shorthand description of the force balance equation.

4-5. Roughness of the Ice Accumulation

Ice roughness can be calculated as a function of ice thickness or as a function of ice piece size. Existing field data show that thick jams are typically made up of larger ice pieces and are hydraulically rougher than thin jams. Relationships based on Nezhikhovskiy's (1964) data relate Manning's n for the ice cover to the ice accumulation thickness. The relationships take the form of a similar equation by Beltaos (1983). Nezhikhovskiy's data were measured in wide canals, 2–3 meters (6.6–9.8 feet deep), for ice floes, dense slush, and loose slush.

a. Thick breakup jams. For breakup ice jams with ice accumulations greater than 0.46 meters (1.5 feet) thick:

$$n_{\mathrm{i}} = 0.0588\left(\frac{H}{2}\right)^{-0.23} t_{\mathrm{i}}^{0.40} = 0.0690 H^{-0.23} t_{\mathrm{i}}^{0.40} \qquad (4\text{-}10)$$

where

H = total water depth

t_{i} = measured thickness of the ice accumulation.

b. Thin breakup jams. A second relationship for breakup ice jams applies to ice accumulations less than 0.46 meters (1.5 feet) thick:

$$n_{\mathrm{i}} = 0.0506\left(\frac{H}{2}\right)^{-0.23} t_{\mathrm{i}}^{0.77} = 0.0593 H^{-0.23} t_{\mathrm{i}}^{0.77} \qquad (4\text{-}11)$$

c. Freezeup jams. A third relationship predicts the roughness of a freezeup ice jam:

$$n_{\mathrm{i}} = 0.0249\left(\frac{H}{2}\right)^{-0.23} t_{\mathrm{i}}^{0.54} = 0.0292 H^{-0.23} t_{\mathrm{i}}^{0.54} \qquad (4\text{-}12)$$

d. Roughness summary. Nezhikhovskiy's data and the curves produced by these three equations are plotted in Figure 4-2.

4-6. Limitations of Ice Modeling

Although there are a number of limitations that arise from the assumptions required to solve the ice-jam force balance in practical situations, the models have produced good results in a number of applications. There are two general classes of limitations: those associated with the circumstances of the jam formation, and those describing the material properties of the jam.

a. Limitations attributable to circumstances of jam formation. Both HEC-RAS and ICETHK assume one-dimensional, gradually varied, steady flow. This may be in error when the ice jam formed during a surge or other transient flow event. However, the extent to which the ice jam is influenced by the unsteady flow cannot be estimated at this time. Neither HEC-RAS nor ICETHK can estimate where an ice jam will occur. This information must be entered by the user.

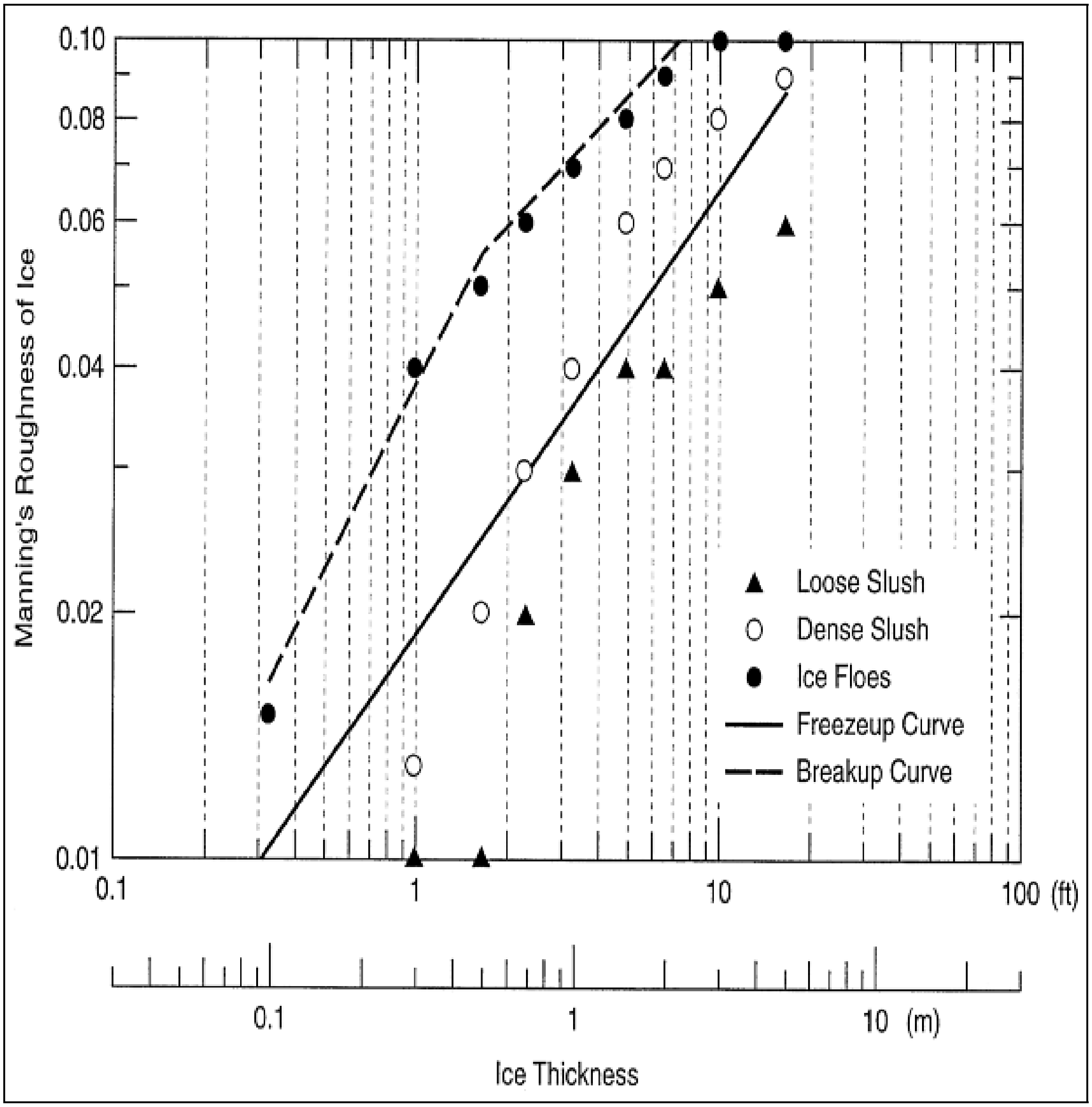

Figure 4-2. Nezhikovskiy's ice roughness values. *The data are plotted in log-log format with the ice-thickness versus ice-roughness relationships used in the ICETHK model.*

b. Limitations attributable to jam material properties description. The collection of ice floes that make up the jam are assumed to be a granular material with known properties. The determination of these properties requires that the ice jam be floating in hydrostatic equilibrium. The result is that grounded ice jams, where the ice jam is resting fully or partially on the channel bottom, cannot be well described by this approach. This may have the largest influence at the downstream end or “toe” of the jam in the calculated results. However, it has generally been found that this description produces “reasonable” results in the toe area.

Section II
The ICETHK Model

4-7. General

ICETHK is an ice utility program that is used in conjunction the HEC-2 backwater model to simulate an equilibrium ice jam profile (Tuthill et al. 1998). ICETHK uses the results of hydraulic calculations from HEC-2, with an ice cover, to produce new estimates of ice thickness and ice roughness for the reach of river being modeled. HEC-2 is then used to recalculate the hydraulic conditions with the updated ice values from the previous ICETHK run. The HEC-2 and ICETHK iteration cycles continue until the change in ice thickness between successive iterations is acceptably small.

4-8. Ice Covers with Known Geometry

The utility program ICETHK cannot be used to model ice covers with known geometry (i.e., the ice cover thickness and roughness are known at every cross section). If the ice cover geometry is known, this information can be entered into HEC-2 directly using the IC card. The reader is referred to the HEC-2 Manual (U.S. Army 1990) for this information.

4-9. Equilibrium Ice Jam Theory and ICETHK

a. Definition of an equilibrium ice jam. ICETHK treats each reach between adjacent cross sections as individual equilibrium reaches. The equilibrium form of Equation 4-9 above can be found by setting the differential term with respect to *x*, the longitudinal distance, to zero. Equilibrium ice jam theory assumes that the downstream forces on the ice cover are resisted by the accumulation’s internal strength and bank shear. In this case it is assumed that the downstream forces are the water drag on the ice accumulation’s underside and the downstream component of the ice accumulation’s weight. The ice accumulation’s ability to transfer these downstream forces to the banks depends on its internal strength and thickness, and the model’s governing equations determine the minimum ice thickness at which this force balance can occur.

b. Ice thickness calculation. ICETHK calculates ice thickness by three processes: juxtaposition, wide-river jam, and thinning by erosion. In this manual, only the wide-river ice jam will be discussed. In this case the wide-river jam can be simplified to a quadratic algebraic equation to reflect the ice jam forces in an equilibrium reach.

$$\mu\left(1-\frac{\rho'}{\rho}\right)\rho' g t^2 - \left(g\rho' S_f B - 2_{c_t}\right)t - \tau_i B = 0 \qquad (4\text{-}13)$$

where

μ = coefficient relating the internal strength of the accumulation, ranging from 0.8 to 1.3

ρ, ρ' = densities of water and ice, respectively

g = acceleration due to gravity

t = thickness of the ice accumulation

S_f = friction slope (assumed equal to the water surface slope)

B = channel width at bottom of ice cover

C_i = cohesion factor for ice can range from zero for breakup jams to 958 Pa (20 lb/ft^2) for freezeup jams

τ_i = shear force on underside of accumulation, approximated by $\rho\, g(y_i/2)\, S_f$, where y_i = under-ice depth.

This quadratic equation can be solved directly.

4-10. Ice in Overbank Areas

Once flow depth in the floodplain reaches a threshold value, ice thickness in the overbank areas is determined by the same steps and equations as the channel ice thickness. The threshold flood-plain depth is defined by a specified factor times the ice thickness before breakup. The use of the same calculation method to calculate ice thickness in the overbank area (i.e., the same method as is used for the main channel area) relies on the assumption that the ice-on-ice shear between the channel and floodplain ice is approximately equivalent to the bank shear of a jam remaining in the channel.

4-11. Structure and Operation of ICETHK

ICETHK is designed as a utility program for HEC-2. Figure 4-3 shows the program's overall structure and the interaction between ICETHK and HEC-2. Square-cornered boxes signify ICETHK programs and subprograms, while boxes with rounded corners indicate external input and output files. Overall, the structure is fairly simple: ICETHK reads hydraulic data from a HEC-2 output file. Then the thickness and roughness of the equilibrium ice accumulation are calculated. If water current velocity is greater than the threshold velocity for thinning, thinning of the ice accumulation is calculated, as previously described. If juxtaposition is possible, thickening from juxtaposition is found. The shoving thickness of the accumulation is then calculated, and the greater of the shoving and juxtaposition thicknesses is selected. The thickness of the initial (parent) ice cover is used as a minimum. This means that the cover cannot thin beyond the parent ice thickness. It also means that, if a solution is not possible by juxtaposition or shoving, the parent ice thickness will be used. Next, the ice roughness is calculated as a function of accumulation thickness. If floodplain flow depth is greater than a user-defined threshold value, the process described for the main channel is repeated to calculate ice thickness in the overbank areas. Finally, the resulting ice data are inserted into the original HEC-2 input file, creating a new input file.

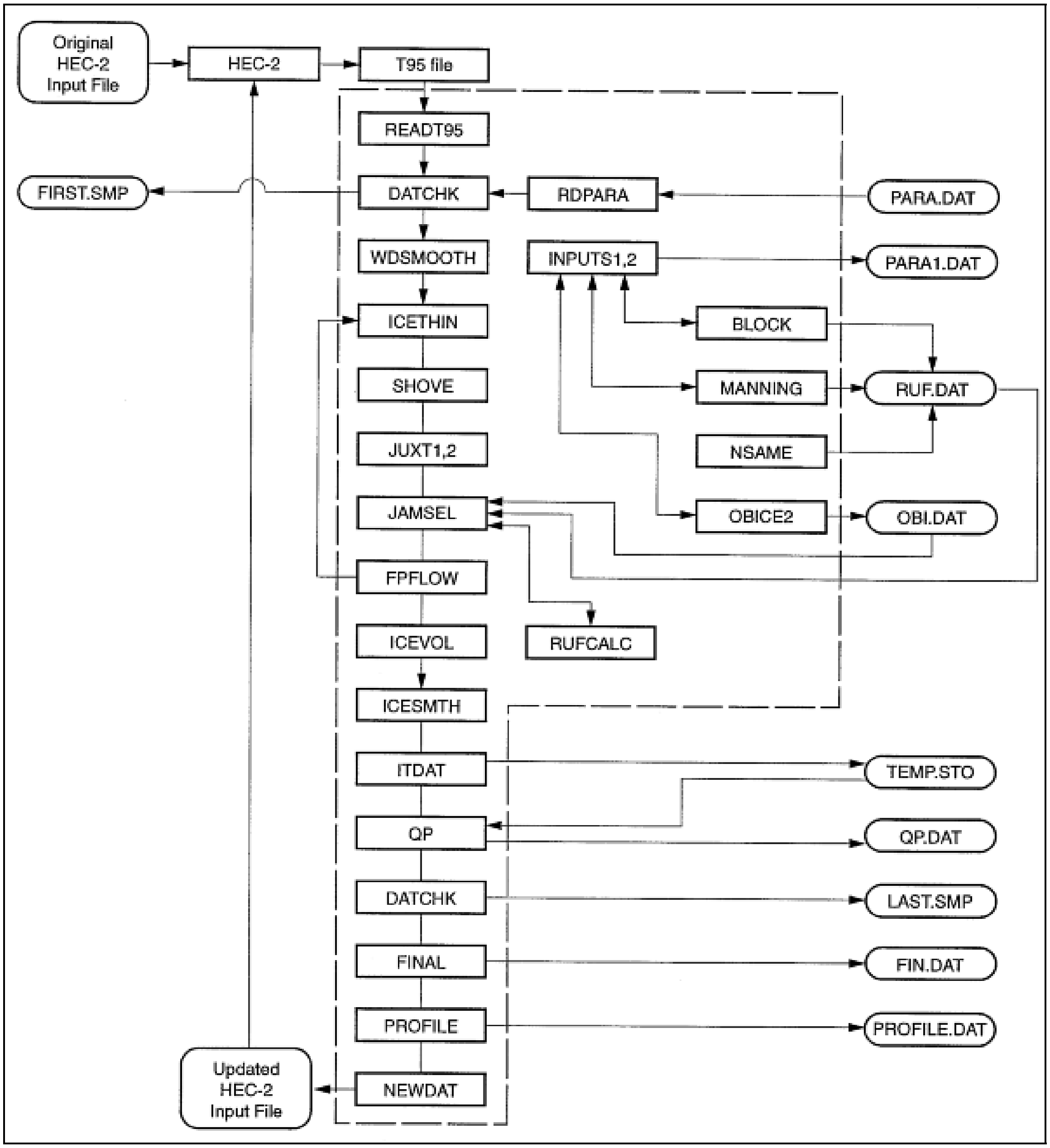

Figure 4-3. Structure of the ICETHK model. *Square-cornered boxes indicate programs and subprograms. ICETHK subprograms lie within the large dashed line box. External files (both input and output) are indicated by round-cornered boxes*

Section III
The HEC-RAS Model

4-12. General

HEC-RAS allows the user to model ice-covered channels at two levels. The first level is an ice cover with known geometry. In this case, the user specifies the ice cover thickness and roughness at each cross section. Different ice cover thicknesses and roughnesses can be specified for the main channel and for each overbank and both can vary along the channel. The second level is a wide-river ice jam. In this case, the ice jam thickness is determined at each section by balancing the forces on it. The ice jam can be confined to the main channel or can include both the main channel and the overbanks. The material properties of the wide-river jam can be selected by the user and can vary from cross section to cross section. The user can specify the hydraulic roughness of the ice jam or HEC-RAS will estimate the hydraulic roughness on the basis of empirical data. Published documentation (U.S. Army 1998a, 1998b, 1998c) should be consulted for a fuller discussion of HEC-RAS.

4-13. Ice Covers with Known Geometry

Separate ice thicknesses and roughnesses can be used in HEC-RAS for the main channel and each overbank, providing the ability to have three separate ice thicknesses and ice roughnesses at each cross section. The ice thickness in the main channel and each overbank can also be set to zero. The ice cover geometry can change from section to section along the channel. The suggested range of *n* values for river ice covers is listed in Table 4-1.

Table 4-1
The Suggested Range of Manning's *n* Values for a Single Layer of Ice and for Ice Jams

Single Ice Layer

Type of Ice	*Condition*	*Manning* n *Value*
Sheet ice	Smooth	0.008 to 0.012
	Rippled ice	0.01 to 0.03
	Fragmented single layer	0.015 to 0.025
Frazil ice	New, 0.3-0.9 m (1–3 ft) thick	0.01 to 0.03
	0.9–1.5 m (3–5 ft) thick	0.03 to 0.06
	Aged	0.01 to 0.02

Ice Jams

Thickness m (ft)	*Manning's* n *Value*		
	Loose Frazil	*Frozen Frazil*	*Sheet Ice*
0.1 (0.3)	--	--	0.015
0.3 (1.0)	0.01	0.013	0.04
0.5 (1.7)	0.01	0.02	0.05
0.7 (2.3)	0.02	0.03	0.06
1.0 (3.3)	0.03	0.04	0.08
1.5 (5.0)	0.03	0.06	0.09
2.0 (6.5)	0.04	0.07	0.09
3.0 (10.0)	0.05	0.08	0.10
5.0 (16.5)	0.06	0.09	--

4-14. Ice Jam Thickness Calculation

HEC-RAS estimates the ice jam thickness using Equation 4-9 above. No assumptions are made with respect to there being an equilibrium reach or not. As a result, the entire equation is solved, including the differential term with respect to x, the longitudinal length along the channel.

a. Force balance. To evaluate the force balance equation, the under-ice shear stress must be estimated. The under-ice shear stress is

$$\tau_i = \rho g R_{ic} S_f \tag{4-14}$$

where

R_{ic} = hydraulic radius associated with the ice cover

S_f = friction slope of the flow.

b. Hydraulic radius. The value of R_{ic} can be estimated as

$$R_{ic} = \left(\frac{n_t}{n_c}\right)^{3/2} R_i \tag{4-15}$$

c. Roughness. The hydraulic roughness of an ice jam can be estimated using the empirical relationships derived from the data of Nezhikovskiy (1964). These are the relationships described in paragraph 4-5. Note that only the relationships for breakup ice covers are available.

4-15. Solution Procedure

The ice jam force balance equation is solved using an approach analogous to the standard step method. In this, the ice thickness at each cross section is found, starting from a known ice thickness at the upstream end of the ice jam. The ice thickness at the next downstream section is assumed and the value of F found. The ice jam thickness at this downstream cross section, t_{ds}, is then computed as

$$t_{ds} = t_{us} + \overline{F}L \tag{4-16}$$

where

t_{us} = thickness at the upstream section

L = distance between sections

$F = (F_{us} + F_{ds})/2$

The assumed value and computed value of t_{ds} are then compared. The new assumed value of the downstream ice jam thickness is set equal to the old assumed value plus 33 percent of the difference between the assumed and computed value. This *local relaxation* is necessary to ensure that the ice jam calculations converge smoothly to a fixed value at each cross section. A maximum of 25 iterations is allowed for convergence. The above steps are repeated until the values converge to within 0.03 meters (0.1 foot) or to a user-defined tolerance.

a. Tests for reasonableness. After the ice thickness is calculated at a section, the following tests are made:

- The ice thickness cannot completely block the river cross section. At least 0.30 meters (1.0 foot) must remain between the bottom of the ice and the minimum elevation in the channel available for flow.

- The water velocity beneath the ice cover must be less than 1.5 m/s (5 ft/s) or a user-defined maximum velocity. If the flow velocity beneath the ice jam at a section is greater than this, the ice thickness is reduced to produce a flow velocity of approximately 1.5 m/s (5 ft/s) or the user-defined maximum water velocity.

- The ice jam thickness cannot be less than the thickness supplied by the user. If the calculated ice thickness is less than this value, it is set equal to the user-supplied thickness.

b. Simultaneous solution scheme. It is necessary to solve the force-balance equation and the energy equation simultaneously for the wide-river ice jam. However, difficulties arise because the energy equation is solved using the standard step method, starting from the downstream end of the channel and proceeding upstream, while the force-balance equation is solved starting from the upstream end and proceeding downstream. The energy equation can only be solved in the upstream direction because ice covers and wide-river jams exist only under conditions of subcritical flow. To overcome this incompatibility and to solve both the energy and the ice jam force-balance equations, the following solution scheme was adopted.

(1) A first guess of the ice jam thickness is provided by the user to start this scheme. The energy equation is then solved using the standard step method starting at the downstream end. Next, the ice jam force-balance equation is solved from the upstream to the downstream end of the channel. The energy equation and ice jam force-balance equation are solved alternately until the ice jam thicknesses and water surface elevations converge to fixed values at each cross section. This is *global convergence*.

(2) Global convergence occurs when the water surface elevation at any cross section changes less than 0.02 meters (0.06 feet), or a user-supplied tolerance, and the ice jam thickness at any section changes less than 0.03 meters (0.1 foot), or a user-supplied tolerance, between successive solutions of the ice jam force-balance equation. A total of 50 iterations (or a user-defined maximum number) is allowed for convergence. Between iterations of the energy equation, the ice jam thickness at each section is allowed to vary by only 25 percent of the calculated change. This *global relaxation* is necessary to ensure that the entire water surface profile converges smoothly to a final profile.

4-16. References

a .Required publications.

None.

b. Related publications.

Beltaos 1983
Beltaos, S. 1983. "River Ice Jams: Theory, Case Studies, and Applications," *Journal of Hydraulic Engineering*, American Society of Civil Engineers, Vol. 109, No. 10, pp. 1338–1359.

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Nezhikovskiy, R.A. 1964. "Coefficient of Roughness of Bottom Surfaces of Slush Ice Cover," *Soviet Hydrology, Selected Papers*, No. 2, pp. 127–150.

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Tuthill, A.M., J. L. Wuebben, and J. G. Gagnon. 1998. *ICETHK Users Manual, Version 1*, Special Report 98-11, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

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U.S. Army 1990. *HEC-2 Water Surface Profiles*, Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, California.

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U.S. Army 1998a. *HEC-RAS River Analysis System: Hydraulic Reference Manual*, Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, California, June.

U.S. Army 1998b
U.S. Army 1998b. *HEC-RAS River Analysis System: Users Manual*, Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, California, June.

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U.S. Army 1998c. *HEC-RAS River Analysis System: Application Guide*, Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, California, June.

Chapter 5
Ice-Affected Stage-Frequency Analysis

5-1. Introduction

The purpose of this chapter is to provide techniques for the determination of stage-frequency distributions for rivers subject to periods of ice. Such analyses can be important for projects dealing with ice-affected flooding, clearance for bridges or hydraulic structures, tailwater elevations for hydroelectric plants, water intake elevations, and shore protection design. In contrast to open-water flooding, where high water levels directly result from excessive water discharge, ice-affected flooding results from added resistance to flow and blockage of flow caused by accumulations of ice. Water discharge during ice-induced flooding is typically low relative to open-water floods. Consequently, a flood-frequency analysis based on peak annual discharges will often miss most, if not all, ice-affected events, even though the stages may be among the highest on record. Thus, ice-induced flooding must be analyzed in terms of stage frequency, which is primarily influenced by the ice regime.

5-2. Ice Effects on River Stage and Flooding

The formation of an ice cover or ice jam on a river roughly doubles the wetted perimeter of a wide channel. The added resistance to flow, along with the reduction in flow area caused by the ice, results in higher stages than a comparable open-water discharge would produce. This is particularly true for the case of ice jams, which can cause flood stages comparable to rare open-water events, despite discharge exceedance probabilities on the order of 0.5 or greater. These accumulations include freezeup jams, formed by the collection of pieces of floating ice during the periods of relatively steady flow experienced when the ice cover initially forms early in the winter season, as well as breakup jams, which form during the often highly unsteady flow conditions when the ice cover breaks up because of a significant rainfall event, snow melt, or other increase in runoff.

a. Ice jam flow profiles. Most ice jams are the result of ice moving downstream until it encounters an intact downstream ice cover, or other surface obstruction. Figure 5-1 illustrates the longitudinal profile of a typical fully developed jam. Downstream from the jam, the flow may be uniform (at least in a reach-averaged sense). At the downstream end, or toe, of the jam, the ice accumulation results in a gradually varied flow profile in the transition reach, as water depth increases toward the deeper normal-flow depth associated with the thicker, rougher ice conditions. If the ice jam is long enough, a fully developed or equilibrium-jam reach may form, in which ice and flow conditions are relatively uniform. From the upstream end, or head, of the jam, flow depths again transition toward the lower uniform-flow depth associated with the open-water conditions upstream.

b. Ice jam data. Ice-related flooding tends to be local and highly site specific. While ice jams may be relatively common at a given site, they cannot be predicted with certainty in any given year, and may be totally absent at other sites nearby, even along the same river. Without prior field observations, it is generally difficult to predict where, or even if, jams will form along a river. Thus, ice-affected frequency analysis emphasizes historical data, even though they may be scarcer and less reliable than the open-water data. The available information may range from detailed hydrographic records to observations by local residents. At a minimum, it is necessary to have some information on where, when, and with what frequency ice events happen. The types of available data will determine the form and reliability of the frequency analysis that can be conducted.

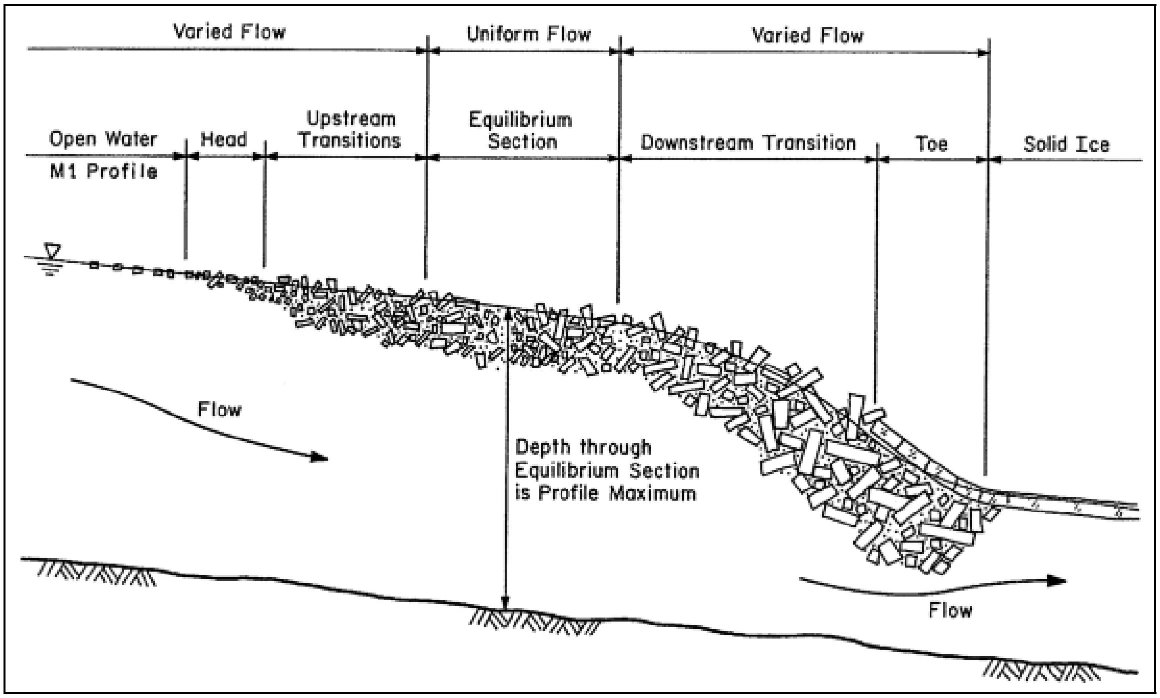

Figure 5-1. Typical ice jam profile

5-3. Data Sources

Ice jam floods often occur when flow rates are relatively low, perhaps no more than a 0.5-exceedance-probability discharge, and water levels are normally high only in the vicinity of the ice and in a backwater zone upstream. Their relatively small geographic extent (perhaps a few river miles or kilometers) and short duration (from a few hours to a few days for breakup events) make it unlikely that detailed field information will have been gathered at most sites. Even in cases where hydrographic gaging records exist for a site, the potential for gage freezeup because of cold weather, ice effects on the gage rating curve, the location of the gage relative to the ice accumulation, or direct ice action on the gage can reduce their reliability for ice events. Because ice jams are site-specific, it is generally not possible to transpose stage data from other sites along the river. Hence, it is often necessary to resort to other sources of data, sources that are often overlooked or regarded as unreliable for analysis of open-water flooding. Sources of historical data might include:

- USGS or Corps gaging station reports or files.
- Corps District or Area Office files.
- State and local water resources and Civil Defense offices.

- Prior flood insurance studies.
- Historical societies, museums, town offices, libraries.
- Newspapers, books, photographs.
- Interviews with local residents.
- Environmental indicators, such as tree scars, structural markings or damage, and vegetation trim lines.

5-4. Form of Frequency Analysis

To analyze ice-influenced flood frequency, mixed populations must be considered. Depending on the objectives of the overall project, it may be necessary to split the sample population into two or more subsets, such as open water, freezeup, solid ice cover, and breakup. Separate frequency distributions could be derived for any population subset, but in most cases a single, annual flood-frequency distribution is desired. As described by Morris (1982), this could be derived in two ways. If the annual frequency curve is derived directly from annual peak data that have not been segregated, it is called a *mixed-population frequency curve*. If the annual frequency curve is derived from two or more frequency curves developed from separate populations, it is called a *combined-population frequency curve*. The combined-population approach should be used when frequency curves derived from mixed populations exhibit sudden breaks in curvature (Morris 1982). These sudden breaks are often caused by several large events that depart from the trend of the remainder of the data and may arise from hurricane events in a normal rainfall series, rainfall events in a snowmelt dominated series, or, in the present case, ice-influenced flooding. Details on mixed-population analysis can be found in Morris (1982) and in a publication of the Interagency Advisory Committee on Water Data (U.S. Geological Survey 1982).

a. Mixed-population frequency analysis. When determining the stage-frequency distribution for a mixed population, one must first tabulate the annual peak stage for each year of record. These annual peaks are then ranked in descending order of severity, and the exceedance probability, in terms of plotting position, is determined for each event. There are several plotting-position equations that can be used, perhaps the most common of which is the Weibull equation:

$$P = m/N + 1 \qquad (5\text{-}1)$$

where

P = exceedance probability corresponding to the event of rank m

m = rank of the event

N = total number of events.

(1) The Weibull equation was developed so that the exceedance probability associated with the highest ranked event would be correct, on the average. Another commonly used

plotting-position equation, which is an approximation of the Beard, or median, plotting-position equation (Morris 1982), is

$$P = m - 0.3/N + 0.4. \qquad (5\text{-}2)$$

The median plotting-position equation was developed so that the exceedance probability associated with the largest event would have an equal chance of being too high or too low.

(2) Once the plotting positions have been determined, the exceedance probability and stage coordinates are plotted on the appropriate probability paper. An analytical frequency curve may then be calculated using a selected probability distribution. The Interagency Advisory Committee on Water Data (U.S. Geological Survey 1982) recommends that the log-Pearson type III distribution, with a weighted skew coefficient, be used to model annual peak discharges. However, the interagency committee's conclusions and generalized skew coefficient map were based on annual peak data that were not segregated according to causal factors. Morris (1982) suggests that, unless the annual series in a number of stations clearly contain non-zero skew coefficients, one should use the log-normal distribution. Further, it is not clear what form of distribution ice-affected stages should follow. In view of these uncertainties, it is suggested here that the log-normal distribution be used, owing to its simplicity, with all stages referenced to the zero-discharge stage. However, since ice-affected stages are primarily governed by the ice regime and its interaction with channel geometry, extrapolation beyond the range of observed data is risky. Because discharges are normally low for ice events, the frequency curve can become highly nonlinear as flow enters the floodplain. Further, as discharge increases, a point will be reached where no stationary ice accumulation is possible and a discontinuous distribution of stages can occur as the dominant factor governing stage reverts from ice processes to water discharge. As such, it is normally sufficient to graphically fit a curve through data plotted on log-normal paper. The upper limits on ice-affected stages are discussed later.

b. Combined-population frequency analysis. For a combined-population frequency analysis, the annual peaks for each subpopulation must be tabulated similarly to the way described above for the mixed-population case.

(1) The first step is to identify the significant causal factors and determine a method for separating events into subsets. One option is to separate data populations by season (such as open water, ice covered, freezeup jamming, and breakup jamming). Such seasons must be based on different hydrometeorological conditions and not be arbitrary periods, such as calendar months. However, if the data are separated into too many subsets, one or more of the subsets may contain a few large events and many small ones (Morris 1982). This causes the frequency curves of these subsets to be unreasonably steep, and a combined annual curve will predict unreasonably high magnitudes for extreme events.

(2) The procedure for combining multiple frequency curves developed from independent annual series can be expressed in general form as

$$P_c = 1 - (1 - P_1)\,(1 - P_2) \ldots (1 - P_n) \qquad (5\text{-}3)$$

$$= 1 - \pi_{i=1}^{n}(1 - P_i) \tag{5-4}$$

where

P_c = exceedance probability of the combined-population frequency curve for the selected discharge

$P_1, P_2, ... P_n$ = exceedance probabilities associated with selected discharge from curve numbers 1, 2,through n

n = number of frequency curves to be combined.

If only two curves are combined, this reduces to

$$P_c = P_1 + P_2 - (P_1)(P_2) \tag{5-5}$$

These equations assume that each of the frequency curves used to develop a combined curve is independent, a valid assumption when combining open-water and ice-influenced events.

5-5. Approaches for Developing Ranked Data Tabulations

The discussion above has assumed that annual peak data were available for each population to be analyzed. In this paragraph, we consider how the ranked data tabulations can be developed, given the variability in data quantity and quality mentioned previously. There are two general approaches. The first is a direct analysis of historical data. The second is an indirect analysis based on data synthesized from estimates of discharge and an understanding of ice jam mechanics. The latter method is significantly more difficult than it is for the case of open-water flooding, but at the same time is typically more necessary because of the likelihood that few or no historical ice-affected data will be available. Further, it is the only feasible approach if the ice regime has changed or will be changed as a result of project construction that makes historical data obsolete. Frequently, the best approach is to use a combination of the direct and indirect methodologies.

a. Direct approach. If reliable hydrometric data are available at the site, and the desired product is a combined-frequency analysis of the open-water and ice-covered flows, the analysis is relatively straightforward. The maximum open-water and ice-covered stages should be tabulated for each water year. The two event types are independent because they have different causes (water quantity versus ice processes) and are not mutually exclusive (an open-water flood can occur in the same year as an ice-affected flood). Each of these populations can then be analyzed using standard techniques, as discussed earlier. If the desired subpopulation is ice jam events, however, a variation in technique is required, since ice jams do not typically form every year at a given site.

(1) Morris (1982) discusses several options for the somewhat comparable case of analyzing hurricane events. One applicable approach is to redefine the number of events in the plotting-position formula as being equal to the total number of years of record analyzed. This tacitly as-

sumes that the record is continuous and that all events in the subpopulation have been identified. Morris also suggests that the frequency curve be developed by drawing a best-fit line by eye, rather than using regression equations, so that outliers do not unduly affect the derived line. Because of the small sample size typical of this type of analysis, there can be significant uncertainty in the accuracy of the resultant frequency curve.

(2) Very often, there is no long-term, reliable gaging station at the project site, and it becomes necessary to combine information from several sources of varying accuracy and reliability. There may also be years in which no data were recorded, but it is not clear whether there was no event or whether it simply was not recorded. This inhomogeneity of data can reduce the reliability of the resulting frequency curve. If the record is clearly incomplete, consideration should be given to employing the indirect method of analysis, with checks against the available historical data, as discussed later.

(3) When analyzing a data set with multiple data sources, it is necessary to determine which one is the most reliable, when more than one data source records an event, and also to determine the maximum stage that may have occurred in years when there were no reports on ice-affected stages. While there is no standard technique for this integration of data sources, a reasonable methodology has been given by Gerard and Karpuk (1979), as outlined briefly below.

(a) *Perception stage*. One must determine the minimum stage (or *perception stage*) that would be recorded by various data sources. This perception stage is defined as the minimum stage required for a given source to perceive and record an event. For example, for a gaging station, the perception stage would be the minimum stage it was capable of recording, while for a local resident, it would be that stage below which the event would have gone unnoticed or unremembered. Newspaper accounts would require an event of interest to its readers, and photographs would require an event significant enough for a person to want a permanent record (unless the event was captured incidental to a different subject). The significance of the perception stage is that, if a source was in a position to observe events during a given year, but didn't report any, then one can presume that the maximum stage during that year was less than the perception stage of the source. This simple constraint provides an objective means of merging data from several sources and of increasing the record length beyond the recorded number of events.

(b) *Environmental indicators of stage*. Environmental indicators, such as structural markings and high-water marks, can be used, providing one knows when they happened. The same is typically true for other environmental evidence, except that it is sometimes possible to date old tree scar data by analyzing tree rings. This has been used with success in prior studies to document high-water levels that were several decades old. In either case, analysis can be complex, since a stable object would have to have been located at a proper location and elevation to allow recording, and the markings would have had to be high enough and long lasting enough to persist through subsequent floods.

(c) *Record length*. In this method, the record length will vary with stage. Record length for an individual peak is equal to the number of years in which any source with a perception stage lower than that peak was present on the river. For example, assume that the hypothetical data in Table 5-1 came from three different sources, such as 1) the memory of a local resident, 2) an early water-level gage, and 3) a more recent water-level gage. Perception stages of 2.7, 0.9, and 0 meters (9, 3, and 0 feet), relative to a zero-flow stage, have been assigned to these sources. Further, assume that the local resident was present throughout the period of record, but that the first water-level gage operated only in years 7–14 and the final gage operated in years 15–20, except when it malfunctioned during year 19. Under this scenario, if the third source recorded a stage of 0.88 meters (2.89 feet), the record length associated with that event would correspond to only the 5 years for which that source reported data. If the first data source had reported a stage of 3.05 meters (10 feet) during the first 6 years, the record length for that event would equal the total number of years that any of the three sources were active, since any of the three sources would have recorded the event had they been present.

(d) *Stage ranking.* This method also requires a modified technique for determining the rank of peak stages. When the data are tabulated for such a scenario, the rank for an individual peak is determined by ranking all peaks having a perception stage less than or equal to the value of the peak. Thus, peaks above 2.7 meters (9 feet) would be ranked in terms of the entire data set, but peaks between 0.9 and 2.7 meters (3 and 9 feet) would only be ranked with those events from the second and third sources, since an event of that magnitude may have occurred during the years when only the first source was active and gone unnoticed. As noted in Table 5-2, this can result in two or more peaks being assigned equal rank, but their record length will differ.

(4) Plotting positions can now be calculated using standard formulations and the redefined values of record lengths and rank, and the stage-frequency distribution determined as before. Although this method allows a logical means of combining inhomogeneous data sets, the discontinuities in record lengths and rank can persist as discontinuities in plotting positions. Although there are a number of available plotting-position formulas (the Weibull simulation was used in Table 5-2), they all basically divide rank by record length without any other reference to the associated stage. Thus, it is possible for an event of record length 20 and rank 7 to have the same calculated plotting position as an event of record length 14 and rank 5. For example, if the missing record from year 19 had an actual stage of less than 2.48 meters (8.15 feet), then the record length for the event in year 16 would have been 14 and the plotting position would have been 0.333, equal to that for the event in year 14. By similar reasoning, it is possible to calculate a given stage as being more probable than a lesser stage, which is clearly not realistic. If such an overlap of data groups occurs, it is generally slight, and is best treated as data scatter with the final frequency-distribution curve smoothed by eye.

Table 5-1
Example Historic Data Set

Year	Data Source*	Perception Stage m	Perception Stage ft	Stage m	Stage ft	Record Length
1	1	2.7	9	3.20	10.5	20
2	1	2.7	9	——	—	—
3	1	2.7	9	——	—	—
4	1	2.7	9	——	—	—
5	1	2.7	9	3.66	12.0	20
6	1	2.7	9	3.05	10.0	20
7	1,2	0.9	3	——	—	—
8	1,2	0.9	3	4.59	15.05	20
9	1,2	0.9	3	0.96	3.15	13
10	1,2	0.9	3	1.18	3.88	13
11	1,2	0.9	3	1.00	3.28	13
12	1,2	0.9	3	1.19	3.89	13
13	1,2	0.9	3	——	—	—
14	1,2	0.9	3	2.88	9.46	20
15	1,3	0.0	0	6.58	21.59	20
16	1,3	0.0	0	2.48	8.15	13
17	1,3	0.0	0	0.88	2.89	5
18	1,3	0.0	0	5.22	17.12	20
19	1	2.7	9	——	—	—
20	1,3	0.0	0	1.97	6.45	13

* Key:
1. Memory of a local resident
2. Early water-level gage
3. Recent water-level gage

b. Indirect method. The indirect method of stage-frequency analysis uses stage data synthesized from estimates of discharge frequency and knowledge of ice processes. While data synthesis is more difficult than in the open-water case, it is also more necessary because of the general lack of appropriately sited gaging stations or other sources of historical data. Further, it is the only feasible approach if the ice regime has changed or will be changed, making historical data obsolete. Major obstacles to be overcome include estimating the appropriate ice conditions and assessing the frequency of ice jamming at a particular site.

Table 5-2
Example Data Tabulation

Year	*Stage, m (ft)*		*Perception Stage, m (ft)*		*Record Length*	*Rank*	*Plotting Position*
15	6.58	(21.59)	0.0	(0)	20	1	0.048
18	5.22	(17.12)	0.0	(0)	20	2	0.095
8	4.59	(15.05)	0.9	(3)	20	3	0.143
5	3.66	(12.0)	2.7	(9)	20	4	0.190
1	3.20	(10.5)	2.7	(9)	20	5	0.238
6	3.05	(10.0)	2.7	(9)	20	6	0.286
14	2.88	(9.46)	0.9	(3)	20	7	0.333
16	2.48	(8.15)	0.0	(0)	13	5	0.357
20	1.97	(6.45)	0.0	(0)	13	6	0.429
12	1.19	(3.89)	0.9	(3)	13	7	0.500
10	1.18	(3.88)	0.9	(3)	13	8	0.571
11	1.00	(3.28)	0.9	(3)	13	9	0.643
9	0.96	(3.15)	0.9	(3)	13	10	0.714
17	0.88	(2.89)	0.0	(0)	5	5	0.833

(1)As in the open-water case, discharge and meteorological data may be used to generate probable ice-related events for each year of record. The period stage-frequency distribution is then developed using the appropriate ice-cover-period or ice-jam-period discharge frequency, available ice data, an analysis of probable ice-related water levels (i.e., HEC-RAS, see Chapter 4), and some estimate of jam frequency.

(2) The first step is a year-by-year analysis of flow records to determine the maximum annual discharge for each desired subpopulation. Ideally, these values would reflect the instantaneous peak flows, since they are the ones that determine the severity of ice effects. On the other hand, a careful review of the records is required to ensure that the flows are from the ice-jam period, and not an open-water peak following the final breakup ice run. If necessary, these data may be transposed from gage data elsewhere on the river, transposed from other rivers in the vicinity, or estimated using a precipitation-runoff model. Next, representative ice conditions must be estimated for the range of expected breakup events. Such information might include estimates of ice thickness, ice-cover or ice-jam roughness, position of the ice jam's toe and head, and the upstream length of river contributing ice to a jam.

(3) Lacking field data, it is very difficult to predict where, and with what frequency, jams will form along a river, and analysis is often limited to estimating upper and lower limits of probable stages. If a jam is known (or assumed) to form at a given location, it is possible to estimate the maximum resulting flood levels. It can be shown that, for a given scenario of water discharge and ice conditions, the maximum water levels will occur within the equilibrium portion of the jam described earlier. Since ice and flow conditions are relatively uniform within the

equilibrium reach, it is a fairly simple matter to estimate the water levels in this portion of the jam. Depending on where a jam forms, and whether there is a sufficient upstream ice discharge to form a jam long enough to develop an equilibrium reach, actual water levels may be less and the estimate will be conservative.

(4) Thus, if no site information is available, the range of possible ice conditions might be assumed to include the limiting conditions of a solid cover of sheet ice and a fully developed equilibrium ice jam. The solid-ice-cover case would represent the minimum ice-affected stage, while the equilibrium-ice-jam case would represent the maximum stage possible for a given discharge. If, for example, we were to assume that the problem at hand is an analysis of flooding attributable to breakup jams in the spring, and that little or no information exists for the ice regime, a suggested procedure is as follows.

(a) *List peak flows.* Develop a table of peak flows for the period of breakup, as discussed above. These flows should be estimates of the instantaneous peak flows, since they are the ones that govern the maximum severity of the event.

(b) *Define range of flows.* From this tabulation of flows, select a range of flows from discharges too low to cause breakup of the ice cover to discharges where all ice would move downstream without jamming. These estimates might be based on personal observations, observations by local residents, notes on nearby gaging records, sharp breaks in the trend of continuous stage measurements, or other sources of information. These estimates might also vary through the winter because of variations in ice strength. If such estimates are not possible, select a range of flows representative of all historical breakup period flows.

(c) *Calculate stages*. For a number of discharges covering the range of flows defined in the preceding paragraph, calculate the stages associated with both the solid-ice-cover and equilibrium-ice-jam cases using either a numerical model such as HEC-RAS or manually using a procedure such as the one outlined in Beltaos (1983).

(d) *Develop rating curve*. Using the above information, develop a stage-discharge rating curve for both the lower bound of a solid ice cover and the upper bound of an equilibrium ice jam.

(e) *Rank stages.* From the tabulation of historical discharges and the stage-discharge rating curve, develop a ranked tabulation of estimated historical stage data. As in the direct method, a stage-probability distribution may now be developed for the upper and lower bound cases by assigning plotting positions and plotting on log-normal paper.

(5) The task of developing a compromise distribution from these upper and lower bound distributions remains, and one should consider limiting conditions on the stage-discharge relations. The first limit is the discharge (or stage) at which the ice cover is expected to break up, as described above in paragraph 5-5*b*(4)(b). If this lower limit can be estimated, then it can be assumed that the solid-ice-cover curve is appropriate for all discharges below that level.

(6) If a large floodplain exists at the site, it may provide an upper limit on ice-induced stages. Since ice-related discharges are typically low relative to open-water events, once the stage is high enough to allow water to enter the floodplain, the slope of the stage-discharge curve should flatten considerably. Further, with continued increases in discharge, a point may be reached at which no stable ice jam is possible—all ice will simply be transported downstream. The development of an ice jam can also be limited by the volume of ice available for accumulation. If there is some physical limit to the upstream river length contributing ice (e.g., the presence of an upstream dam), there may be an insufficient ice supply to develop an equilibrium jam at the project site. Thus, extrapolation of ice-induced stages to more extreme events is generally not reliable, particularly if such limiting factors are not considered.

(7) Beyond imposing such limits, developing a compromise distribution between the ice-cover and ice-jam distributions is largely a matter of engineering judgment. If the results are to be used for project design, it might be desirable to conservatively assume that ice jams always form and employ that distribution. However, for the determination of average annual damages, even a few reliable historical data could be of immense help in the interpretation of the two analytically derived distributions. By comparing a historical observation with the analytical estimates for a comparable event (and using judgment), a compromise best-estimate of the stage for an event of that magnitude can be developed.

(8) If no such data are available, some idea of the frequency of significant ice jamming in the vicinity of the site can be helpful (e.g., do jams occur every other year, or in about 3 out of 10 years?). Although not related to specific years, this general information can be used in the development of a compromise curve (Figure 5-2) by employing the methodology of Gerard and Calkins (1984) as follows:

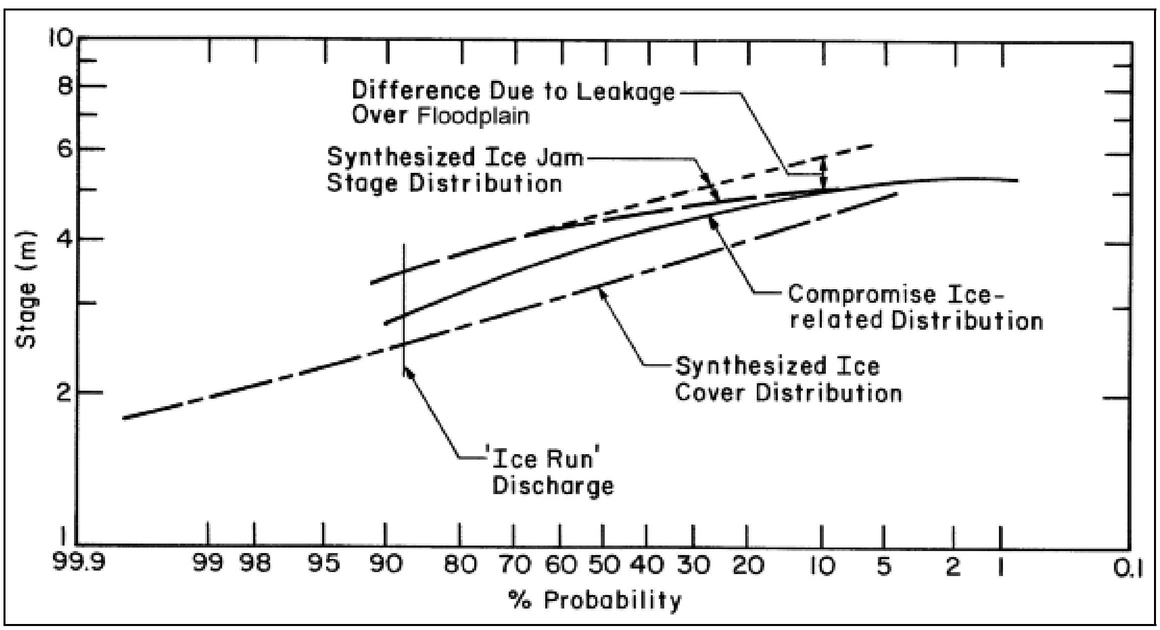

Figure 5-2. Development of a compromise distribution

(a) *Probability of stage exceedance because of jamming.* If the probability that a significant ice jam may form in a given year is $P(J) = m/N$ (m being the estimated number of jam events in N years), then the probability $P(\$_J)$ of a given stage being equaled or exceeded in a given year is given by

$$P(\$_J) = P(J) \cdot P(\$ \mid J) \quad (5\text{-}6)$$

where $P(\$ \mid J)$ is the probability of the stage being exceeded if an ice jam forms (i.e., a conditional probability). $P(\$ \mid J)$ corresponds to the probability coordinate of the upper bound for a given stage.

(b) *Probability of stage exceedance because of a solid ice cover.* The probability $P(\$_C)$ of the stage being exceeded when a solid ice cover exists is likewise given by

$$P(\$_C) = P(C) \cdot P(\$ \mid C) \quad (5\text{-}7)$$

where $P(C) = 1 - P(J)$ is the probability of a significant ice jam not occurring (and therefore the peak stage being associated with a solid ice cover), and $P(\$ \mid C)$ is the conditional probability of the stage being exceeded if a significant ice jam does not form (the lower bound).

(c) *Probability of stage exceedance because of ice in general.* As the ice cover and ice jam situations are mutually exclusive, the probability $P(\$)$ of a stage being equaled or exceeded is given by

$$P(\$) = P(\$_J) + P(\$_C). \quad (5\text{-}8)$$

Thus, if a jam forms in about 3 out of every 10 years, $P(J) = 0.3$ and

$$P(C) = 1 - P(J) = 1 - 0.3 = 0.7.$$

For a given stage, $P(\$ \mid J)$ and $P(\$ \mid C)$ are determined from the upper and lower bound frequency curves, respectively. Equation 5-8 can then be used to calculate the compromise probability $P(\$)$ of a given stage being exceeded.

(9) Repeating this procedure for the range of breakup flows allows the development of a compromise frequency curve between the upper and lower bounds. However, at the lower end it should merge with the solid-ice-cover case at a point where the discharge would be too low to cause ice-cover breakup, and the upper end must be reconciled with the limits imposed by floodplain flow or a finite ice supply as discussed earlier. It must be emphasized that extrapolation of ice-induced stages to extreme events is generally not reliable, particularly if such limiting factors have not been considered.

5-6. Summary

This chapter has reviewed methodologies for the analysis of ice-related flood frequency. Since ice-induced flooding is dominated by ice processes, rather than water quantity, we have emphasized the need for a stage-related, rather than discharge-related, analysis. Further, since detailed data for ice-affected events are typically unavailable, and the site-specific nature of ice-related flooding generally precludes transposing data from other sites, methodologies are outlined for performing the analysis based on limited historical data and data synthesized from discharge records and estimates of ice conditions.

5-7. References

a. Required publications.

None.

b. Related publications.

Beltaos 1983
Beltaos, S. 1983. "River Ice Jams: Theory, Case Studies, and Applications," *Journal of Hydraulic Engineering,* American Society of Civil Engineers, Vol. 109, No. 10, pp. 1338–1359.

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Gerard, R.L., and E.W. Karpuk. 1979. "Probability Analysis of Historical Flood Data" *Journal of the Hydraulics Division,* American Society of Civil Engineers, Vol. 105, No. HY9, pp. 1153–1165.

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Morris, E.C. 1982. *Mixed-Population Frequency Analysis*, Training Document No. 17, U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis, California.

U.S. Geological Survey 1982
U.S. Geological Survey 1982. *Guidelines for Determining Flood Flow Frequencies*, Bulletin 17B, Interagency Advisory Committee on Water Data, Hydrology Subcommittee, U.S. Geological Survey, Office of Water Data Coordination.

CHAPTER 6
Ice Force on Structures

6-1. Introduction

a. Any structure placed in an environment where the presence of ice is a hazard to its integrity and stability needs to be designed to withstand the forces generated by ice moving against it. A designer should also consider how the cold may affect the intended operations of a structure, because freezing of ice may hinder some of the normal warm weather operations. These guidelines are intended for structures placed in inland waters, e.g., lakes, rivers, and coastal waters. To estimate ice forces on an offshore structure see API (1995).

b. An ice sheet moves under the influence of shear stresses imparted by wind and water and by thermal expansion (as long as the ice sheet is intact). It transmits the accumulated forces to a structure situated in its path. The shear drag forces attributable to wind and water can be transmitted over large distances through an intact ice cover. In many situations, these environmental forces can be large, and the ice sheet fails during its interaction with a structure. The ice failure process limits the large environmental force being transmitted to the structure. Unless the environmental forces can be estimated with confidence to be small, the methodology to estimate ice forces from floating ice is generally to determine the forces required to fail an ice sheet in the vicinity of a structure. An ice sheet fails by crushing, splitting, bending, buckling, or a combination of these modes. For a given failure mode and structure shape, theoretical formulations or experimental results, along with ice properties, are used to estimate the forces required to fail an ice sheet. The forces are estimated for one, two, or all possible failure modes, and the failure mode with the lowest estimated force is assumed to occur at the ice–structure interface. At times, it may be necessary to conduct model tests to simulate an ice–structure interaction to determine the interaction forces. Attention should also be given to the clearance of broken ice pieces, because the advancing ice sheet will interact with the broken pieces if they accumulate in front of the structure. It is also possible that the accumulation of broken ice pieces may freeze together to form a grounded collar, which may provide some protection from further ice movement.

c. In situations where an ice cover is made up of drifting ice floes, the impact of these floes causes a horizontal force on a structure. (Although impact from a drifting iceberg falls into this category, we will limit our discussion to drifting ice floes.) The forces generated when ice floes strike a structure depend on the mass and the initial velocity of the floes. If the kinetic energy of the moving ice floes is greater than the work done in failing the ice along the entire width of the structure, the design force is then limited by the ice failure processes mentioned above. If the kinetic energy and the momentum of drifting ice floes are small, resulting in indentation of the structure into the ice floes over a part of its width, ice forces are estimated from balancing the momentum and the energy before and after an impact.

d. The methodology given in this Manual for estimating ice forces is based on the results of theoretical and experimental research in ice mechanics and measurements of ice forces in the field. Most recently, our understanding of processes active during crushing of ice at various indentation speeds has been increased. Data on measured ice forces on large structures have recently been published. Except for the recommended values of effective pressure, the Corps guidelines for ice forces on structures are almost the same as those of the American Association of State Highway and Transportation Officials (AASHTO 1994), which in turn were adopted from the Canadian Standards Association (CSA 1988, 2000). Montgomery et al. (1984) provide the background information for the recommendations in CSA (1988). The CSA (2000) and the AASHTO (1994) codes consider dynamic and static loads on bridge piers located in rivers, lakes, and coastal waters. The dynamic loads develop when moving ice fails against a pier during spring breakup, or when currents and wind move ice sheets past piers at other times of the year. The static loads are generated by thermal expansion or contraction of the ice and by fluctuations in the water levels.

6-2. Mechanical Properties of Ice

a. Introduction.

(1) Because the forces necessary to fail an ice sheet depend on the mechanical properties of ice, the mechanical properties of the freshwater and sea ice are briefly reviewed below before methodologies to estimate the ice forces on a structure are given. Ice is a unique material. In the temperature range under which it is normally encountered, it is very close to its melting point. Ice can creep with very little applied stress, or it can fracture catastrophically under a high strain rate.

(2) There are two primary ways to categorize ice. One is based on the melt from which the ice is grown (freshwater or sea water), and the other is based on the size of the ice blocks (i.e., large ice floes or accumulations of broken ice in a random ice rubble). The conditions under which ice forms will determine its grain structure, with common forms being frazil ice, columnar ice, discontinuous columnar ice, and granular ice. Both the porosity within the ice and the grain structure significantly influence the mechanical properties of the ice. Various books (e.g., Michel 1978, Ashton 1986, Cammaert and Muggeridge 1988, Sanderson 1988) cover the subjects of formation and types of ice, as well as ice properties.

(3) The porosity attributable to brine and air pockets affects the ice properties. The brine volume ν_b ($^o/_{oo}$) is obtained from the following relation (Frankenstein and Garner 1967):

$$\nu_b = S_i\,(0.532 + 49.185/|T|) \qquad (6\text{-}1)$$

where S_i ($^o/_{oo}$) = salinity, T (°C) = temperature of the ice, and the symbol $^o/_{oo}$ refers to parts per thousand.

(4) The porosity ascribable to air can be obtained from the following relation after the bulk density ρ of ice containing salt and air are measured (Cox and Weeks 1983)

$$V_a/\,V = 1\text{-}\rho/\rho_1 + \rho S_i F_2(T)/F_1(T) \qquad (6\text{-}2)$$

where

V_a = volume of air
V = bulk volume

ρ_i = density of pure ice
S_i = salinity of ice
$F_1(T)$ and $F_2(T)$ = functions of temperature derived from a phase equilibrium table (Cox and Weeks 1983) and given in Figure 6-1.

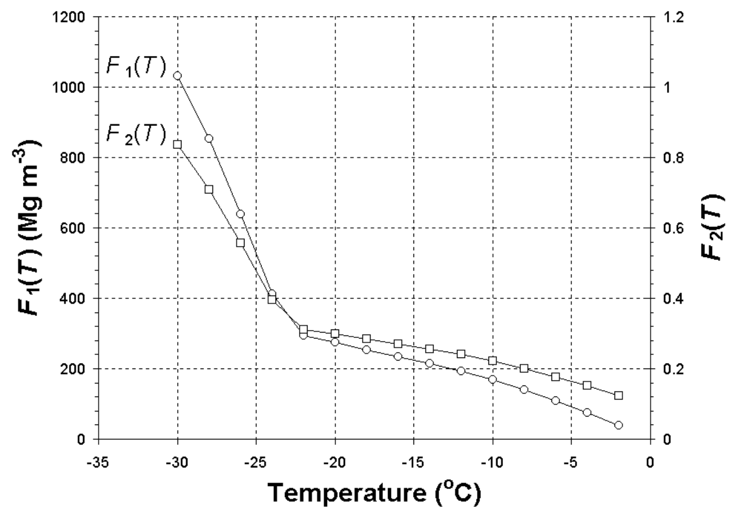

Figure 6-1. Plots of $F_1(T)$ and $F_2(T)$ with respect to temperature. To convert degrees C to degrees F use the following: °F = °C × 1.8 +32.

b. Compressive Strength. Values of the uni-axial compressive strength for ice range from 0.5 to 20 MPa (72.5 to 2900 psi). The strength is a function of strain rate, temperature, grain size, grain structure, and porosity. Analyses of strength measurements have shown that the strength increases with strain rate, up to a rate of 10^{-3} s^{-1} , whereupon the strength generally decreases at higher strain rates because of brittle fracture.

(1) In the lower strain rate range below 10^{-3} s^{-1}, the compressive strength of freshwater ice is given by (Sinha et al. 1987)

$$\sigma_c = 212\dot{\varepsilon}^{0.34} \quad (3.07 \times 10^4\ \dot{\varepsilon}^{0.34}) \tag{6-3}$$

where σ_c is in MPa (psi) and $\dot{\varepsilon}$ is in s^{-1}.

(2) The above expression is for the compressive strength of ice at –10°C (263 K or 14ºF). The compressive strength at another temperature T(K) can be obtained by multiplying the strength at –10°C (14ºF) by a correction factor $[\exp\{(Q/R)(263–T)/(263T)\}]^{1/3}$, where Q = 65 kJ mol^{-1} (61.6 Btu mol^{-1}) (the activation energy for columnar ice) and R = 8.314 J mol^{-1} K^{-1} (1.986 Btu lb^{-1} mol^{-1} R^{-1}) (the universal gas constant).

(3) For sea ice, the following equations for compressive strength were derived from an analysis of over 400 small sample tests (Timco and Frederking 1990). These equations are:

$$\sigma_c = 37\dot{\varepsilon}^{0.22}\left[1-(\upsilon_T/270)^{0.5}\right] \text{ for horizontally loaded columnar sea ice} \quad (6\text{-}4)$$

$$\sigma_c = 160\dot{\varepsilon}^{0.22}\left[1-(\upsilon_T/200)^{0.5}\right] \text{ for vertically loaded columnar sea ice} \quad (6\text{-}5)$$

$$\sigma_c = 49\dot{\varepsilon}^{0.22}\left[1-(\upsilon_T/280)^{0.5}\right] \text{ for granular sea ice} \quad (6\text{-}6)$$

where $\dot{\varepsilon}$ is the strain rate in s^{-1}, and υ_T is the total porosity in the ice (brine and air) in parts per thousand. The range of strain rate for these equations is 10^{-7} to 10^{-4} s^{-1}. Above this strain rate, the ice can experience brittle failure with compressive strengths exhibiting a wide range of variability.

c. Flexural Strength. The flexural strength is generally lower than the compressive strength. Measurements on freshwater ice range from 0.5 to 3 MPa (72.5 to 435 psi), with an average of 1.73 MPa (for temperatures less than –5°C (23ºF) (Timco and O'Brien 1994). There is very little temperature or strain rate dependence, but there is a wide scatter in the measured flexural strength with higher values from smaller samples. At temperatures close to 0°C (32°F), the strength of freshwater ice can be essentially zero if solar radiation has caused pronounced "candling." For sea ice, Timco and O'Brien (1994) compiled the results of over 900 flexural strength measurements to obtain the following dependence of the flexural strength on the brine volume.

$$\sigma_f = 1.76e^{-5.88\sqrt{\upsilon_b}} \quad (255\,e^{-5.88\sqrt{\upsilon_b}}) \quad (6\text{-}7)$$

where σ_f is in MPa (psi) and ν_b is the brine volume fraction. The strength value for zero brine volume (1.76 MPa or 255.3 psi) agrees with the average value of 1.73 MPa (250.9 psi) determined from tests on freshwater ice.

d. Fracture Toughness. The fracture toughness depends on the loading rate and the ice type, with less variation ascribable to temperature and grain size. Typical values for freshwater ice range from 109 ± 8 kPa $m^{0.5}$ (0.01581 ± 0.00116 ksi $in.^{0.5}$), for columnar-grained S2 ice, to 151 ± 12 kPa $m^{0.5}$ (0.0219 ± 0.00174 ksi $in^{0.5}$)for granular ice (Weber and Nixon 1992). In-situ measurements of the fracture properties of lake ice and sea ice revealed that fracture toughness depends on the size of the specimen, and that its range is 50–250 kPa $m^{0.5}$ (0.00725 to 0.03626 ksi $in.^{0.5}$) (Dempsey et al. 1999a,b)

e. Elastic Modulus. Ice deformation involves elastic and creep processes, and the large-scale modulus is usually discussed in terms of an "effective modulus" that incorporates these processes. This modulus is a strong function of loading rate, temperature, and grain size and type. The values of elastic modulus range from approximately 2 GPa (2.9×10^5 psi) at low frequency loading to a high frequency value of 9 GPa (1.3×10^6 psi) (Sinha et al 1987, Cole 1995a,b).

f. Broken Ice Properties. Ice rubble is usually assumed to behave as a linear Mohr-Coulomb material, for which the shear stress τ and the normal stress σ_n on a failure plane are related by

$$\tau = c + \sigma_n \tan\phi \quad (6\text{-}8)$$

where c is the apparent cohesion and ϕ is the effective angle of internal friction. Recent studies (Prodanovic 1979, Ettema and Urroz-Aguirre 1991, Løset and Sayed 1993, Cornett and Timco 1996) have shown that the yield envelope is non-linear but can be approximated with a linear envelope for a limited range of conditions; that cohesion is negligible for unconsolidated rubble; that ϕ depends on the stress history and decreases with increasing pressure; that ϕ is less than the maximum angle of repose; and that ϕ depends on the strain path and pressure. Measured values of ϕ range from 20° to 45°.

6-3. Environmental Forces

a. Wind and Water Drag Forces. The drag force, caused by wind and water shear stresses on the top and bottom surfaces of an ice cover, can be estimated from the following expression:

$$F_d = C_d \rho A V^2 \tag{6-9}$$

where

C_d = drag coefficient
ρ = density of air or water
A = fetch area
V = velocity of air or water measured at a certain distance above or below an ice cover.

Typical values for C_d are 0.002 for a smooth ice cover, and 0.005 for a rough ice cover (Banke and Smith 1973). Typical values for the density of air and water are 1.3 and 1000 kg m^{-3} (0.08116 and 62.4 lb ft^{-3}), respectively. When sufficient information is available on the wind and water velocities and the fetch area, it may be possible to estimate the wind and water drag forces. However, it is difficult, in most cases, to estimate the fetch area that contributes directly to wind and water drag forces on a structure. In most situations, the estimates of wind and water drag force are greater than the force required to fail an ice sheet, and the ice failure process limits the force to that necessary to fail the ice against the structure. If wind and water drag forces can be estimated to be less than the ice failure force, the design force on the structure is taken to be the estimate of wind and water drag forces.

b. Thermal Ice Forces. Like other materials, ice expands with increasing temperature, and vice versa. However, unlike other materials, water expands when it changes phase from liquid to solid. These two properties, along with the creep of ice, explain the forces that develop when ice undergoes a temperature change. The temperature of ice changes because of conduction, radiation, and convection heat transfer at its surface. The depth to which temperature changes take place depends on the thickness of the ice cover, the presence or absence of snow on its top surface, and the environmental conditions (Michel 1970, 1978; Sanderson 1988).

(1) An unrestricted ice cover will expand as a whole in response to a change in temperature. While the top layer of the ice sheet expands as a result of the change in temperature, the bottom layer, because it undergoes no temperature change, restrains the top layer from expanding. This process causes the rate of expansion of the ice sheet to depend on the ice thickness. If

one edge of the ice cover is fixed to a shore, the rest of the ice sheet expands away from the shore. A structure placed some distance away from the shore will experience an ice force as a result of ice moving past it. For distances of shores on the order of 50 kilometers (31 miles), observers have measured the ice edge to move at a rate of about 0.9 meter (3 feet) per day (Strilchuk 1977).

(2) When an ice sheet is restricted from expansion from four or two sides, the confinement causes, respectively, biaxial or uniaxial stress (Sanderson 1984, 1988). The method of calculating thermal ice force in a confined ice sheet is as follows.

(*a*) Calculate temperature change as a function of depth, taking into account heat transfer by conduction, radiation, and convection.

(*b*) Calculate the rate of thermal expansion $\dot{\varepsilon}$ as if the ice would have been unconfined.

(*c*) Apply $-\dot{\varepsilon}$ at those depths to satisfy the assumption of complete restraint.

(*d*) Calculate the stress needed to deform the ice at those strain rates using one of Equations 6-3, 6-4, 6-5 or 6-6.

(*e*) Integrate the stress through the ice thickness to obtain force per unit width. In the case of a confined ice sheet having thicknesses greater than 0.5 meter (1.6 feet), the force per unit width does not strongly depend on ice thickness, because the ice layer below the 0.5-meter (1.6-foot) depth does not undergo a change in temperature and restricts expansion of ice in the top layer. Calculations of typical thermal ice force are in the range of 200–400 kN m^{-1} (1.5×10^5 to 2.95×10^5 lb_f ft^{-1}), whereas some of the measured values are in the range of 100–350 kN m^{-1} (7.4×10^4 to 2.6×10^5 lb_f ft^{-1}) (Sanderson 1984).

(3) The presence of cracks in an ice cover has a profound effect on thermally generated pressure within it. Metge (1976) observed three types of cracks: dry micro-cracks, wet micro-cracks, and wet large cracks. Dry micro-cracks are found at the top of an ice sheet and do not penetrate to the water below. Dry cracks close when an ice sheet thermally expands, and this closure of cracks does not result in a significant push against a structure. Wet micro-cracks are filled with water that freezes within them during cold periods. With repeated cooling, cracking, and freezing, a floating ice sheet can expand and push against a structure. Water within large wet cracks freezes only at the top surface during cold periods, and this creates a thin ice bridge across the gap of a crack. When the ice sheet expands during warm periods, these bridges are crushed, forming small pressure ridges along the crack.

(4) In summary, factors influencing thermally generated ice forces are the magnitude and the rate of temperature increase, heat transfer at the top surface and in the ice sheet, boundaries resisting expansion of an ice cover, creep relaxation of ice pressure, and dry and wet cracks. Several theories (Rose 1947; Belkov 1973; Drouin and Michel 1974; Xu Bomeng 1981, 1986; Fransson 1988) have been proposed to calculate the thermally induced ice force, and thermally induced ice pressures have been reviewed by several authors (Michel 1970, Kjeldgaard and Carstens 1980, Sanderson 1984). More recently, the predicted loads of these five theories were compared to the

results of a comprehensive field data set (Comfort and Abdelnour 1994). The comparison of each model with measured data showed a wide disparity, and no model predicted the measured loads (Timco et al. 1996). The disparity between theoretical estimates and measured values of thrust on dam walls may be attributed to changes in water levels in reservoirs and large wet cracks in the ice cover.

(5) In recent years, two measurement programs were launched.

(*a*) Comfort et al. (2000a,b) undertook a 9-year program, beginning in 1991–92, to measure the loads in the ice sheet adjacent to eight dam sites in Manitoba, Ontario, Quebec, and Labrador.

(*b*) Carter et al. (1998) undertook a 3-year program from 1995 to 1998 to measure the static ice forces in four reservoirs in central and northern Quebec. In both of these programs, changes in measured stress in an ice sheet correlated with changes in air temperature as well as water level.

(6) Carter et al. (1998) proposed that thermal ice loads are limited by the instability of ice blocks between two or three parallel cracks along a dam wall. Their measurements indicate that the ice thrust changes with increasing water level; the maximum values was about 150 kN m^{-1} (1.1×10^5 lb_f ft^{-1}). Comfort et al. (2000a, b) identified the importance of water level fluctuations to the ice loads on dam walls. They found the ice loads to be higher and more variable than those generated by thermal process alone when there were significant, but not excessive, water level changes. The range of ice thickness during their measurement program was 0.3–0.7 meters (1–2 feet). The maximum values of the measured line load resulting from thermal events with negligible change in water level at four dam sites in central and eastern Canada were in the range of 61 to 85 kN m^{-1} (4.5×10^4 to 6.3×10^4 lb_f ft^{-1}), with average value of 70 kN m^{-1} (5.2×10^4 lb_f ft^{-1}) (Comfort and Armstrong 2001). Similar values resulting from thermal events, combined with significant change in water level at four dams in central and eastern Canada, were in the range of 52 to 374 kN m^{-1} (3.8×10^4 to 2.8×10^5 lb_f ft^{-1}), with average value of 186 kN m^{-1} (1.4×10^5 lb_f ft^{-1}) (Comfort and Armstrong 2001). At Seven Sisters Dam in Manitoba, Comfort and Armstrong observed a significant reduction by a factor of 3–5 in ice thrust when the water level was lowered in early January by 45 centimeters (18 inches) and maintained there for the rest of the winter. More recently, they observed a similar reduction in ice thrust at the same site when the water level was lowered in late December or early January by 35 centimeters (14 inches) and then brought up to normal levels a few days later (Comfort and Armstrong 2001). These operations introduce large wet cracks and hinges in the ice sheets to limit the ice thrust to dam walls.

6-4. Forces Limited by Ice Failure

a. Introduction. The force resulting when a moving ice sheet and a structure interact is limited to the magnitude of force necessary to fail the ice sheet in crushing, bending, buckling, splitting, or a combination of these modes. In the following, procedures to estimate forces to fail ice sheets in the above mentioned modes are given.

(1) It is important to consider the magnitude of the area over which the ice forces act. The total force on the entire structure is important for designing foundations to resist sliding and overturning. Contact forces over small areas, or local contact pressures, are important for designing internal structural members and the external skin of a structure.

(2) The total ice force *F* on a structure of width *D* attributable to failure of an ice sheet of thickness *h*, as shown in Figure 6-2, is expressed in terms of the effective pressure p_e:

$$F = p_e D h \qquad (6\text{-}10)$$

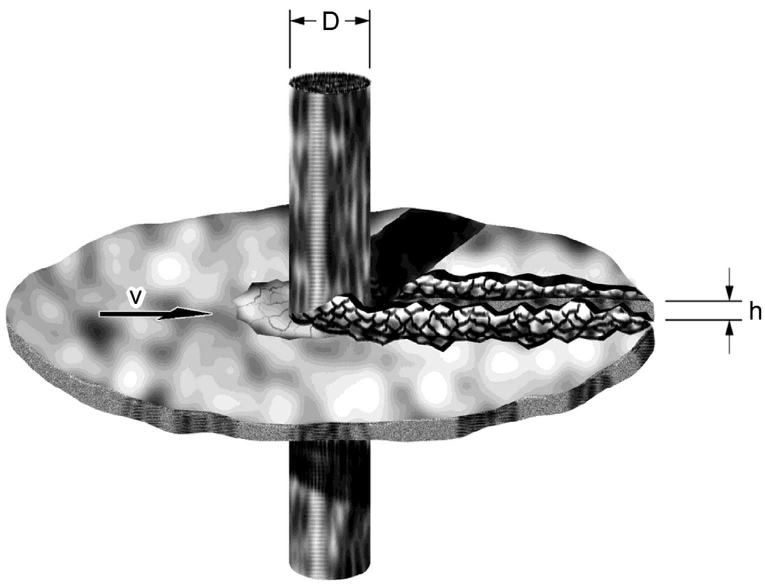

Figure 6-2. Total ice force *F* on a structure of width *D* attributable to failure of an ice sheet of thickness *h.*

(3) It is important to distinguish between the contact pressure acting over the ice–structure contact area and the effective pressure. Because the actual contact area between a structure and an ice sheet is either equal to or less than the nominal contact area (product of ice thickness and structure width), the contact pressure is either equal to or higher than the effective pressure. The relative speed of an ice sheet with respect to a structure is an important factor in determining the mode of ice failure and the resulting contact areas and effective pressures.

b. Crushing Failure. Ice crushing is one of the common modes of ice failure. Much work has been done to understand the processes taking place during ice crushing and to determine the forces generated at the interface. Because ice exists close to its melting temperature, its temperature strongly affects its properties. Ice at lower temperatures is stronger and also has more brittle characteristics. Ice creeps at low rates of loading, and it fails in a brittle manner at high loading rates. The complex behavior of ice depends on the temperature and the indentation speed. In engineering applications, one has to contend with both types of ice behavior.

(1) *General*. The effective pressure depends on the mode of ice crushing, which in turn depends on the rate of indentation, or the relative speed of an ice feature with respect to a structure.

(*a*) At low indentation rates, the ice deforms in creep, resulting in full contact and uniform pressure at the interface. During an interaction involving creep deformation of ice against a narrow structure, the force between an ice sheet and a structure increases gradually, attains a peak value, and then gradually reduces to a steady-state value at 50–60% of the peak force without any structural vibration (Sodhi 1991).

(*b*) At high rates of ice indentation against both narrow and wide structures, ice crushes continuously in a brittle manner, resulting in non-simultaneous, partial contact and non-uniform pressure over the nominal contact area. In this mode of crushing, the variations of force over small areas of a wide structure are large, but the summation of these forces across the whole width of a structure averages out the variations in local forces, resulting in smaller variations in the total ice force across the whole structure (Kry 1978, Sodhi 1998, Sodhi 2001). During continuous brittle crushing, the structure does not respond to rapid variations of the interaction forces, and its vibrations are not so severe because it deflects to a steady-state value in response to the average force.

(*c*) At intermediate speeds, the interaction between structural deformation and an advancing ice sheet produces alternating ductile and brittle crushing, resulting in ice force records taking a saw-tooth form. During each cycle of intermittent crushing, the advancing ice sheet deflects the structure while undergoing ductile deformation with increasing interaction force. When the ice sheet fails at a certain force level, the stored potential energy in the structure is released to move the structure back to its original position, resulting in high relative speeds and brittle crushing. When the transient oscillations decay, the cycle repeats, causing the structure to indent into the ice at varying speeds and to undergo either transient or steady-state vibrations (Jefferies and Wright 1988; Sodhi 1991, 1995, 2001).

(*d*) Figure 6-3 shows a map of ice crushing failure during interactions with rigid and compliant structures. During an ice interaction with a rigid structure, the ice fails in the ductile and brittle modes, and there is a sharp transition at an indentation speed that has been found to be close to 3 mm s^{-1} (0.01 ft s^{-1}) (Sodhi et al. 1998, Masterson et al. 1999). During an ice interaction with a compliant structure, the failure modes are ductile and brittle at low and high rates of indentation, respectively. At intermediate indentation speeds, the ice fails in the alternating ductile–brittle mode as a result of variable indentation rates into the edge of an ice sheet. Because of this, there are two transition speeds, ductile to intermittent and intermittent to continuous brittle crushing, during interactions with compliant structures. A video display of the interfacial pressure during three modes of ice crushing (ductile deformation, alternating ductile-brittle and continuous brittle crushing) can be seen at the following URL: www.crrel.usace.army.mil/permanent/ice_crushing.

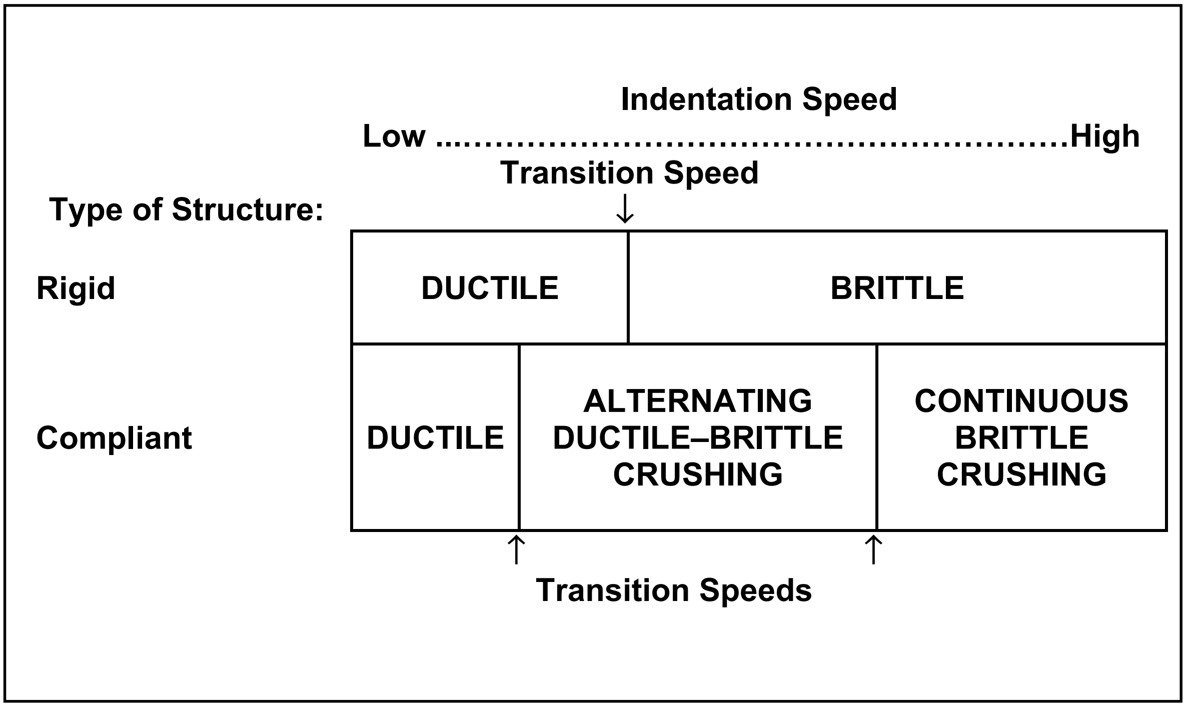

Figure 6-3. Failure map of ice crushing with respect to indentation speed and structural compliance.

(2) *Ductile Deformation of Ice.* Results of small-scale indentation tests on freshwater columnar ice (Michel and Toussaint 1977) indicate that the effective pressure for ductile (creep) deformation of ice at strain rates between 10^{-8} s^{-1} and 5×10^{-4} s^{-1} is

$$p_e = Cmk\sigma_0(\dot{\varepsilon}/\dot{\varepsilon}_0)^{0.32}, \qquad (6\text{-}11)$$

where

C = indentation factor (=2.97)

m = shape factor (=1 for flat indentors)

k = contact factor (=1 for the first peak force, and =0.6 the for steady-state pressure after the first peak force)

σ_0 = uniaxial compressive strength of columnar ice at a temperature of –10°C (14ºF) and at a strain rate of $\dot{\varepsilon}_0$=5×10^{-4} s^{-1} (=7 MPa or 1015 psi)

$\dot{\varepsilon} = v/(4D)$ = empirically defined strain rate

v = indentation rate

D = indenter width.

This relation is similar to the strain rate dependence of uniaxial compressive strength for freshwater columnar ice.

(*a*) Figure 6-4 shows this comparison with good agreement between the plots of uniaxial compressive strength versus strain rate and the plots of effective indentation pressure divided by 2.97 versus the empirical strain rate (*v*/4*D*). This expression may also be used for creep indentation of sea ice at any temperature by using the compressive strength of sea ice (Equations 6-2 to 6-4). While Figure 6-4 shows good correlation between effective indentation pressure and the uniaxial compressive strength of columnar ice at the appropriate strain rates, there is no confirmation whether the indentation factor and the empirical definition of strain rate (*v*/4*D*) will remain applicable for very large aspect ratios (*D*/*h*). Such confirmation is perhaps an impossibility because of creep buckling of floating ice sheets against wide structures at a lower effective pressure than that required for in-plane creep indentation.

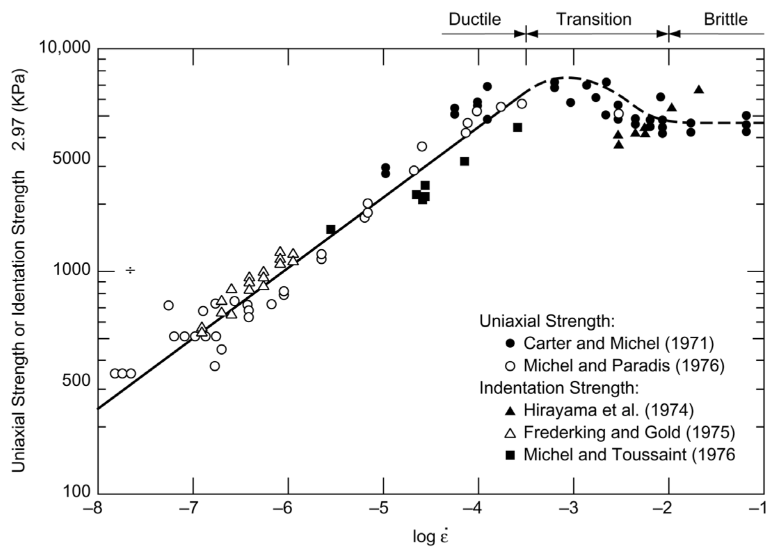

Figure 6-4. Plots of uniaxial compressive strength versus strain rate and the plots of effective indentation pressure divided by 2.97 versus the empirical strain rate (*v*/4*D*). (1 kPa × 0.145 = 1 psi.)

(*b*) Other methodologies to estimate the ice force ascribable to creep deformation of ice are the plastic limit analysis (Croasdale et al. 1977), and the reference stress method (Ponter et al. 1983, Sanderson 1988, also given in API 1995).

(3) *Brittle Crushing*. For edge indentation into floating ice sheets, the main characteristics of brittle crushing are the line-like contact in the middle third of the ice sheet thickness, the non-simultaneous contact in different parts of the contact line, and the non-uniform pressure in the contact area (Joensuu and Riska 1989, Sodhi et al. 1998, Sodhi 2001). This is caused by fracturing of ice at a high rate of loading, resulting in flaking failure of ice. Line-like contacts in the form of an "X" have also been observed during medium-scale indentation tests, in which spherical indentors were pushed into walls of ice at speeds greater than 3 mm s^{-1} (0.01 ft s^{-1}) (Frederking et al. 1990; Gagnon 1998). The results of full-scale measurements of ice forces, and medium- and small-scale tests indicate that the effective pressure for brittle crushing and for high aspect ratio (*D*/*h*) is in the range of 1 and 3 MPa (145 to 435 psi), which is less by a factor of three to four in comparison to the maximum pressure that develops at the high end of speed range for ductile deformation of ice over small areas or small aspect ratios (*D*/*h*). The reason for the reduction in effective pressure can be attributed to the actual contact area during brittle

crushing being much smaller than full contact during ductile deformation of ice. The following is an expression to estimate ice force *F* on a structure of width *D* for continuous brittle crushing of ice of thickness *h* at high indentation rates:

$$F = A_r p D h$$

where *p* is the effective pressure (1.5 to 2 MPa, or 217.5 to 290 psi) for brittle crushing of ice, and $A_r=(5h/D+1)^{0.5}$ is an empirical factor to account for the aspect ratio effect of high effective pressure over small aspect ratios.

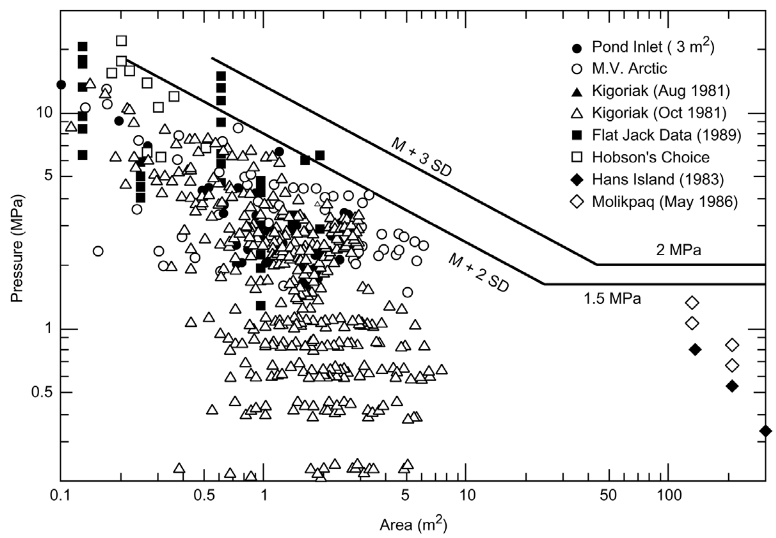

Figure 6-5. plots of effective pressures measured during small- and medium-scale tests, ship ramming, and large-scale field monitoring of ice forces versus nominal contact area. (1 MPa × 145 = 1 psi.)

(4) *Empirical Approach.* Figure 6-5 shows plots of effective pressures measured during small- and medium-scale tests, ship ramming, and large-scale field monitoring of ice forces versus nominal contact area (Masterson and Frederking 1993). Others have also compiled the so-called pressure-area plots(Iyer 1988, Metge et al. 1988, Sanderson 1988). In plotting these data, no regard is given to the speed of indentation into the ice. There is a large scatter in the data on effective pressures for contact areas less than 5 m^2, and this can be attributed to variations in indentation speed. The results of small-scale tests show that there is a decrease in effective pressure with increasing indentation speed, even when the contact area is kept constant (Sodhi 1991, 2001). Lack of scatter in the data for effective pressure for areas greater than 100 meters^2 (1076 feet^2) can be attributed to brittle crushing having been active at high indentation speeds and the creep buckling of floating ice sheet against wide structures preventing the development of high indentation pressure at low ice speeds (Blanchet 1998). The effective pressure, measured during crushing of first-year ice against the 100-meter-wide (328-foot-wide) Molikpaq structure at ice speeds greater than 100 mm s^{-1} (0.328 ft s^{-1}), was in the range of 1 to 2.5 MPa (145 to 363 psi) (Wright et al. 1986, Wright and Timco 1994). Effective pressure in the range of 1–3 MPa (145 to 435 psi) have also been measured on indentors during small-scale tests in the same velocity range (Sodhi 1992, 2001). These two observations indicate that, when continuous brittle crushing

is active, the effective pressure is independent of the nominal contact area. Because high contact pressure can act over a small area resulting from ductile deformation of ice, the trend in the upper bound of effective pressure versus contact area (Figure 6-5) shows a decrease in effective pressure with increasing contact area. Though this trend is known as a scale effect in the literature, the real reason for the decrease in effective pressure with increasing contact area is the possibility of high pressure developing over a small area because of ductile deformation and crushing of the ice in the brittle mode over a large contact area or high aspect ratio (D/h).

(*a*) Two lines in Figure 6-5, labeled as M+2SD and M+3SD, signify trend lines of mean (M) plus two and three standard deviations (SD) of the data, respectively. These are given by:

$$\text{M+2SD: } p(\text{MPa}) = 8.1\,A^{-0.5} \text{ for } 0.1\text{ m}^2 < A < 29\text{ m}^2\text{, and } p = 1.5\text{ MPa for } A > 29\text{ m}^2\text{,} \quad (6\text{-}12)$$
$$(\text{M+2SD: } p(\text{psi}) = 1175\,A^{-0.5} \text{ for } 1\text{ ft}^2 < A < 312\text{ ft}^2\text{, and } p = 217.5\text{ psi for } A > 312\text{ ft}^2)$$

$$\text{M+3SD: } p(\text{MPa}) = 13\,A^{-0.5} \text{ for } 0.1\text{ m}^2 < A < 42\text{ m}^2\text{, and } p = 2\text{ MPa for } A > 42\text{ m}^2. \quad (6\text{-}13)$$
$$(\text{M+3SD: } p(\text{psi}) = 1885\,A^{-0.5} \text{ for } 1\text{ ft}^2 < A < 452\text{ ft}^2\text{, and } p = 290\text{ psi for } A > 452\text{ ft}^2)$$

(*b*) Both of these equations have been recommended in API (1995). The recommended pressures in the Canadian codes for offshore structures (CSA 1992) are similar. A designer needs to choose the design pressure either higher or lower than the values obtained from Equations 6-12 or 6-13, depending on location of the structure. For example, the Molikpaq structure and its structural components have been designed using pressures given by Equation 6-12 with no visible local damage to the structure, whereas the ice pressure measured on subarctic regions such as Cook Inlet have been less than the pressures given by Equation 6-12.

c. Bending Failure.

(1) *Sloping Structure.* When a floating ice sheet moves against an upward or downward sloping structure, the sheet is pushed either up or down, and breaks by bending into blocks. As the ice sheet continues to be pushed up or down, the broken slabs are further broken into slabs that are typically 4 to 8 times the ice thickness. The force on the structure is limited by the amount required to fail the ice sheet in bending and to overcome the weight and frictional forces of the broken ice blocks. If the structure is narrow, the broken pieces of ice may be able to go around the structure. For wide structures, the broken pieces of ice either ride up to clear over the top of the structure or forms an ice rubble mound. Procedures to estimate ice forces on sloping and conical structures are given in textbooks (Ashton 1986, Cammaert and Muggerdige 1988, Sanderson 1988).

(*a*) API (1995) gives equations for determining the ice forces on a sloping structure, where the broken ice pieces are assumed to ride up the sloping surface and fall off into the water on the other side. Figure 6-6 shows forces during an interaction of a floating ice sheet of thickness h being pushed against a wide sloping surface at an angle α with the horizontal. If the ice blocks are lifted up a height z along the sloping surface, the weight of the broken ice sheet on the sloping surface has a magnitude per unit width of $W=\rho_i ghz/\sin\alpha$, where $\rho_i g$ is the specific weight of ice, and h is the ice thickness. The normal force per unit width on the surface is $N=W\cos\alpha$, and the tangential force along the surface is μN, where μ is the coefficient of friction between the surface and the ice. As shown in Figure 6-6, the force T acting between the broken ice on the sloping surface and the top of the floating ice sheet has a magnitude per unit width of $T=W(\sin\alpha + \mu\cos\alpha)$.

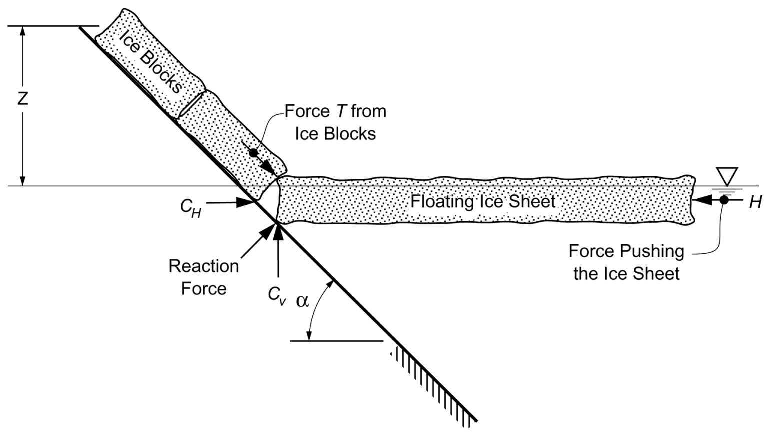

Figure 6-6. forces during an interaction of a floating ice sheet of thickness *h* being pushed against a wide sloping surface at an angle α with the horizontal.

(*b*) The reaction force (Figure 6-6) acting on the contact between the sloping structure and the advancing ice sheet has components C_H and C_V in the horizontal and vertical directions, respectively. The total horizontal force per unit width is given by $C_H + T\cos\alpha$. As the structure pushes the advancing ice sheet up, the vertical force acting at the end of the ice sheet has a magnitude per unit width equal to $C_V - T\sin\alpha$.

(*c*) Under the assumption that there is no moment acting on the floating ice sheet, the vertical force component C_V per unit width required to break the floating ice sheet and push it up is given by:

$$C_V = \frac{\sigma h^2 + 6\ell e^{-\frac{\pi}{4}} T \sin\alpha + Th\cos\alpha}{6\ell e^{-\frac{\pi}{4}} - h\tan(\alpha + \arctan\mu)}, \qquad (6\text{-}14)$$

where

σ = flexural strength of ice sheet
h = ice thickness
α = angle between the sloping surface and the horizontal
ℓ = $[Eh^3/\{12(1-\nu^2)\rho_w g\}]^{1/4}$ (the characteristic length of floating ice sheet)
E = effective elastic modulus of ice
ν = Poisson's ratio of ice
$\rho_w g$ = specific weight of ice.

For typical bending rates, the effective elastic modulus of freshwater ice is in the range of 1–3 GPa (1.45×10^5 to 4.35×10^5 psi), and Poisson's ratio is about 1/3. The range of the coefficient of friction between ice and a structure is between 0.1 for freshly coated surfaces and 0.5 for rusty, rough surfaces. There are, at present, no guidelines available for the coefficient of friction on rough surfaces or on riprap protected surfaces.

(*d*) The horizontal force C_H per unit width from the structure on the ice sheet is

$$C_H = C_V \tan(\alpha + \arctan \mu) \tag{6-15}$$

The total force *H* per unit width generated during the interaction to break the ice sheet at a distance away from the contact zone and to push the broken ice block along the sloping surface is given by:

$$H = C_H + T\cos\alpha.$$

Besides other parameters, the total horizontal force on a sloping structure of width *D* is composed of an icebreaking force proportional to $\sigma h^2 D/\ell$ and an ice ride up force proportional to $\rho_i ghzD$. For narrow structures, the ice breaking component is greater than ice ride up component, whereas the opposite is true for wide structures. Using the above two-dimensional formulation to estimate ice force on a sloping structure gives an order of magnitude of forces, which can be compared to estimates of ice force from other failure modes.

(*e*) The above formulation does not take into account non-simultaneous and incomplete contact between the edge of an ice sheet and a wide structure, as is observed in small-scale tests (Izumiyama et al. 1992, Kovacs and Sodhi 1988). If broken ice pieces accumulate above and below the water surface near the ice–structure contact, the estimate of ice forces should take into account the effect of forces acting on the top and bottom surfaces of the advancing ice sheet (Määttänen and Hoikannen 1990, Croasdale and Cammaert 1993).

(2) *Conical Structure***.** There are several methodologies to estimate the ice forces on a conical structure: the elasticity method (e.g., Nevel 1992), the plasticity method (e.g., Ralston 1977, 1980; Izumiyama et al. 1992; Lau 2001), and the results of model tests. Some of these methodologies are briefly presented in API (1995). Several reviews of the literature on the ice forces on conical structures have been presented (Croasdale 1980, Wessels and Kato 1988), and theoretical and experimental results have also been compared (Chao 1992, Wang et al. 1993). Equation 6-15 has also been used to estimate the ice forces on a conical structure by the assuming the width of the conical structure to be $\pi(R+x)$, *R* being the waterline radius of the conical structure, and $x = \sqrt{2}(\pi/4)\ell$, where ℓ is the characteristic length of floating ice sheets (Croasdale 1980).

(3) *Indentation at High Speeds*. The interaction of a slowing moving ice sheet with a narrow sloping structure usually results in bending failure, resulting in large ice blocks in comparison to their ice thickness. However, when the speed of the moving ice sheet is large, the failure mode changes to shearing or crushing, resulting in small broken ice pieces. Both modes of ice failure against sloping structures have been observed in the field (Neill 1976, Lipsett and Gerard 1980) as well as during small-scale tests in the laboratory (Haynes et al. 1983, Sodhi 1987). This observation implies that ice may fail in crushing, instead of the expected bending, while moving towards a sloping structure at high speeds.

c. Buckling Failure. The ice force on a vertical structure may be limited by the buckling of a floating ice sheet. It depends on the properties of the ice sheet, the width of structure, and the boundary conditions at the ice–structure interface. The boundary conditions along the ice–structure contact line may be defined as rigid, if the ice sheet is frozen to the structure, preventing vertical displacement and rotation. They may be defined as hinged if the ice sheet is allowed to rotate, but is prevented from vertical displacement. And they may be described as free if the ice sheet can displace vertically without encountering any resistance and rotate freely. Discussions of the elastic buckling of beams and plates are given in textbooks and review papers (Hetenyi 1946, Michel 1978, Sodhi and Nevel 1980, Ashton 1986, Cammaert and Muggeridge 1988)

(1) *Elastic Buckling.* For a beam of floating ice sheet, the elastic buckling force (Hetenyi 1946) is given by

$$F_b = \alpha \rho_w g B L_b^2 \tag{6-16}$$

where

α = factor that depends on the ratio of beam length to the characteristic length and the boundary conditions at the ends of the beam.

$\rho_w g$ = specific weight of water,

B = beam width,

L_b = characteristic length of the floating ice beam and is equal to $[Eh^3/(12\rho_w g)]^{1/4}$

h = ice thickness

E = modulus of elasticity of ice.

For beam lengths much longer than the characteristic length of a floating ice beam, the factor α is either equal to 1 if one or both ends of the beam are free, or equal to 2 if one or both ends of the beam are either rigid or hinged (Sodhi and Nevel 1980).

(*a*) The elastic buckling forces of wedge-shaped, semi-infinite ice sheets is given by

$$F_p = [C + D/(R/L)]\rho_w g B L^2 \tag{6-17}$$

where

C and D = coefficients given in Table 6-1 for three boundary conditions and five wedge angles in the range of 2 to 180°

R = radius of the structure at the contact line

$\rho_w g$ = specific weight of water

B = structure width

L = characteristic length of the floating ice sheet and is equal to $[Eh^3/\{12(1-\nu^2)\rho_w g\}]^{1/4}$,

h = ice thickness

E = modulus of elasticity of ice.

A recommended value of the characteristic length of freshwater ice $L = 16h^{3/4}$, and that of sea ice $L = 13h^{3/4}$, where L and h are in meters (Gold 1971).

Table 6-1
Coefficients for the estimation of buckling force

	Boundary conditions at the ice–structure contact line					
	Free		Hinged		Rigid	
Angle	C	D	C	D	C	D
2°	0.96	0.80	2.11	2.76	2.57	4.47
30°	1.00	0.82	2.20	3.11	2.55	4.70
90°	0.95	1.01	2.04	3.78	2.35	5.34
150°	0.84	1.36	1.81	4.30	2.08	5.83
180°	0.81	1.66	0.75	4.67	2.04	6.05

(*b*) Experimental studies on the buckling of floating ice sheet indicate that the non-dimensional buckling forces fall between those for free and hinged boundary conditions at the contact line (Sodhi et al. 1983). For tests in which the boundary condition was simulated as hinged, the experimental and theoretical results are close to each other (Sodhi and Adley 1984).

(2) *Creep Buckling***.** For creep buckling, a floating ice sheet is considered to become unstable when the vertical deflections of the ice sheet suddenly increase after a long period of slow in-plane deformation. In a series of finite element analyses of an ice sheet being pushed slowly against a 152-meter-diameter (500-foot-diameter)structure, the results show that the ice sheet deforms slowly in the vertical direction until a critical time when large deformations suddenly occur in the vicinity of the structure (Luk 1990). The critical time t_{cr} at which large deformations take place can be estimated as

$$t_{cr} = 0.36\, D/v, \qquad (6\text{-}18)$$

where D is the width of the structure, and v is the ice velocity. For an elastic modulus of 4.83 GPa (7.0×10^5 psi), a Poisson's ratio of 0.3, and a creep exponent of 3, the results of finite element analysis show that the following relationship between the effective pressure p and the critical time t_{cr} is

$$(p/\text{MPa}) = (7.07 \text{ days}/t_{cr})^{0.336}. \qquad (6\text{-}19)$$

d. Floe Splitting. When a floating ice floe impacts and crushes against a structure, the floe may split up after some amount of crushing. The ice–structure interaction results in deceleration of the ice floe, which creates a distributed inertia body force per unit volume over the entire floe. Depending on the geometry of the structure, the ice crushing in the contact zone produces a longitudinal force as well as a pair of self-equilibrating transverse forces, which are a fraction β of the longitudinal force. Under the assumption that the linear elastic fracture mechanics is applicable, the critical force F_{sp} to split a square floe of length λ and of thickness h is given by

$$F_{sp} = 3.3\, h\, K_{1c}\, \lambda^{1/2}, \tag{6-20}$$

where K_{1c} is the fracture toughness of ice (Bhat 1988). Similar ice splitting forces can also be estimated for different floe width-to-length ratios and different values of β (Dempsey et al. 1993). The fracture toughness of freshwater and saline ice through small-scale and large-scale measurements is in the range of 50 to 250 kPa m$^{1/2}$ (0.007 to 0.036 ksi in$^{0.5}$) (Dempsey et al. 1999a,b). Small-scale tests were conducted with freshwater ice floes of different thicknesses and widths, and those experimental results were found to be close to the theoretical forces obtained from finite element analysis using linear elastic fracture mechanics (Sodhi and Chin 1995).

e. Structures Going Through Broken Ice Cover. When a structure goes through a broken up ice cover having a depth t_k and a height t_s from the water surface, the force F per unit width (Mellor 1980) is given by

$$F = \frac{1}{2}\frac{1+\sin\phi}{1-\sin\phi}(1-n)\left[\rho_i g t_s^2 + (\rho_w - \rho_i) g t_k^2\right] + 2c\sqrt{\frac{1+\sin\phi}{1-\sin\phi}}(t_s + t_k), \tag{6-21}$$

where

ϕ = angle of internal friction
c = cohesive strength of rubble ice
n = porosity of rubble ice
$\rho_i g$ = specific weight of ice
$\rho_w g$ = specific weight of water.

6-5. Forces Limited by the Momentum of an Ice Feature

a. When an isolated ice feature impacts a structure, it may come to rest, deflect, or rebound from the structure. The interaction forces during an impact may be computed from the equations of momentum and energy of the two colliding bodies (Goldsmith 1960). Because the rate of indentation during an ice impact is usually high, brittle crushing of ice is expected to take place in the contact area, which depends on the local geometry of the ice feature and the structure.

b. For a head-on collision in which a moving ice feature comes to a stop against a structure, the initial kinetic energy is dissipated to crush a certain volume V of ice at an effective pressure of p_e to give

$$Mv^2/2 = p_e V, \tag{6-22}$$

where M is the mass of the ice feature including the added mass of water, and v is its velocity. The depth d and the area A of ice crushing can be calculated from the estimated volume V of the crushed ice and the local geometry of the ice feature and the structure. The interaction force can now be estimated as $F = p_e A$.

c. An eccentric impact (Figure 6-7) will rotate the ice floe, and the ice feature will retain a portion of the initial kinetic energy after the impact. By equating the initial kinetic energy to the sum of remaining kinetic energy and dissipation of energy during ice crushing, the following relationship can be shown under the assumption of brittle crushing (Nevel 1986):

$$\frac{Mv^2}{2} = \frac{Mv^2}{2}\left[\frac{(Y/R)^2}{1+(R_g/R)}\right] + (1+\mu \tan \beta)\, p_e V \tag{6-23}$$

where

M = mass of ice feature, including the added mass of water
v = ice feature velocity
Y = eccentricity of the center of gravity from the point of impact
R = distance of the center of gravity from the point of impact
R_g = radius of gyration of the ice feature about the vertical axis through its center of gravity
μ = ratio of tangential force to normal force in the contact area
β = angle of local contact geometry (β = 0 for head-on impact
p_e = effective pressure to crush ice
V = volume of ice crushed.

For a particular impact situation, the volume of ice crushed during an impact is estimated, and then the depth d and the area A of ice crushed are estimated from the local contact geometry. Lastly, the interaction force is estimated as $F = p_e A$.

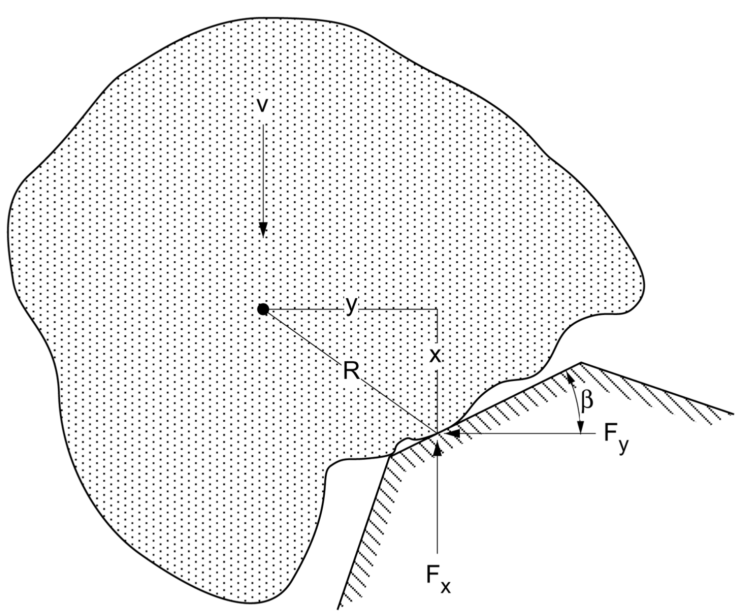

Figure 6-7. An eccentric impact that will rotate the ice floe, allowing the ice feature to retain a portion of the initial kinetic energy after the impact.

6-6. Canadian and American Codes

a. To estimate dynamic ice force F on bridge piers resulting from moving ice, CSA (2000) and AASHTO (1994) codes specify the following:

$$F = \text{lesser of the } F_c \text{ or } F_b \text{ for } D/h<6$$

and

$$F = F_c \text{ for } D/h>6$$

where

F_c = $C_a pDh$ (horizontal force in when ice floes fail by crushing over full width of the pier)

F_b = $C_n ph^2$ (horizontal force in when ice floes fail in bending against a sloping pier)

D = the pier width

h = the ice thickness

C_a = $(5h/D+1)^{0.5}$ (to account for the aspect ratio effect found in small-scale identation tests)

C_n = $0.5 \tan(\alpha+15°)$

α = slope of the pier from the downstream horizontal (<75°)

p = effective ice crushing pressure for which following values have been recommended.

0.7 MPa (101.5 psi)	Ice breaks up at melting temperature and is somewhat disintegrated.
1.1 MPa (159.5 psi)	Ice breaks up or moves at melting temperature, but the ice moves in large floes and is internally sound.
1.5 MPa (217.5 psi)	Ice breaks up or moves at temperatures considerably below its melting point. Even higher pressures are recommended for ice temperatures 2 or 3°C (35.6 or 37.4ºF) below melting temperatures.

b. Further, these codes recommend reducing the dynamic ice force F by 50% of the values derived above for piers in small streams where it is unlikely to encounter large-size floes.

c. For oblique impacts, readers should see the CSA (2000) and AASHTO (1994) codes.

d. It should be mentioned here that the above-recommended values of effective crushing pressure have been obtained from measurements of ice forces on two bridge piers in Alberta, Canada (Lipsett and Gerard 1980). These recommended values for effective pressure for wide structures are the same as those given by Equation 6-12. For narrow structures, the factor C_a accounting for the aspect ratio effect raises the effective pressure to higher values, similar to given by Equation 6-12 for nominal contact area less than 29 meters^2 (312 feet^2).

6-7. Vertical Ice Forces

a. Marine structures that become frozen into an ice sheet are subjected to vertical ice forces as the ice sheet responds to changes in water level. Typically, the uplifting load resulting from changes in water level governs the design of light-duty, pile-founded docks common in marinas. Thus, reducing the vertical ice loads by active (bubblers or water jet) or passive (pile jacket or low-adhesive coatings) means will directly lead to lower costs for such structures. Theoretical estimates of vertical ice loads in the literature (e.g., Ashton 1986) depend on the assumed mode of ice failure, which is often difficult to ascertain for a particular situation. For instance, Muschell and Lawrence (1980) conducted pull-out tests after freezing a conventional capped pipe pile (filled with air) and another similar pile filled with vermiculite insulation, and found a 30% reduction in vertical ice force. In a conventional capped pipe pile, a thermal convection cell develops, resulting in freezing of thicker ice adjacent to the pile. The insulation-filled pipe interrupted this heat transfer, reducing the localized ice thickening and thus yielding a 30% reduction in pull-out force. An epoxy coating was applied to both air-filled and vermiculite-filled piles, which resulted in a net load reduction of 35 and 70%, respectively. Frederking and Karri (1983) used polyethylene and PVC piles with an average reduction in failure stress of 70% compared with similar size wooden piles used in a previous study (Frederking 1979). It was observed that the failure occurred at the ice/ice interface in the case of conventional piles, whereas the relative movement in the case of epoxy coated or plastic piles was at the pile/ice interface.

b. While reviewing the results of pull out tests in the literature, Zabilansky (1998) noted that the researchers used the following three test techniques to conduct a test.

(1) *Socket.* A hole was drilled through part of an ice sheet, a pile was placed in the counter-bored hole, and the void between the ice and the pile was filled with water. This test technique measured the anchoring capacity of the pile, which is not representative of the marina application.

(2) *Confined.* Most of these tests were conducted using a testing machine to extract a pile out a block of ice. Muschell and Lawrence (1980) conducted a series of tests on a lake. They froze a pile into an ice sheet by placing it in a hole cut in the ice sheet and allowing the annulus water between the pile and the ice sheet to freeze. The test was conducted about a week later by jacking the pile out while reacting the parent ice sheet. In these tests, the reaction ring or plate was slightly larger than the pile, resulting in shear failure of ice adjacent to the pile.

(3) *Unconfined.* A pile was either placed into a tank of water during freezing of an ice sheet or frozen into an ice sheet on a lake. The tests were conducted by pulling out the pile while reacting against either the edge of a tank or a support frame placed on top of the ice sheet. This mode of loading subjected the ice sheet to both bending and shear stresses, and was more representative of the observed failure mode in the field.

c. Zabilansky (1998) compiled the data from the pull-out tests with wooden piles conducted at CRREL (Zabilansky 1986) and unconfined tests reported in the literature. He plotted the shear stress (force/circumferential contact area) with respected to the ratio of pile diameter to ice thickness, as shown in Figure 6-8. A line of best fit through the data is given by:

$$\sigma = 300/(d/h)^{0.} \qquad (6\text{-}24)$$

The equation for the pull out force is given as:

$$P = \sigma \pi d h = 300\pi h^{1.6} d^{0.4} \qquad (6\text{-}25)$$

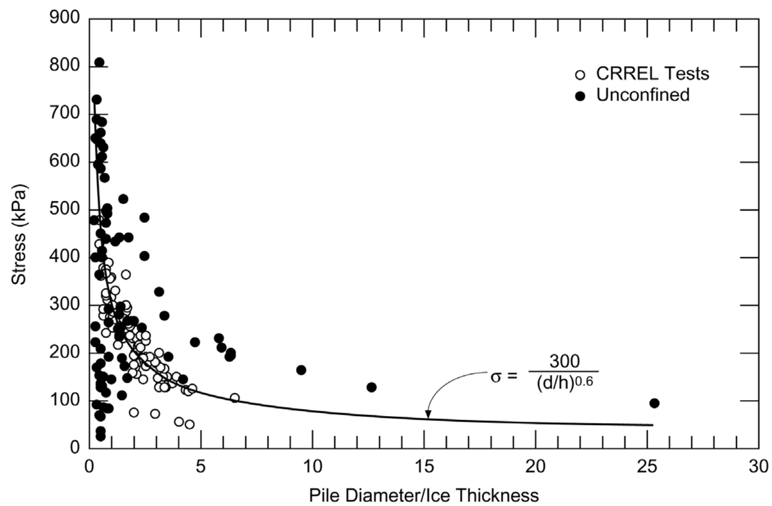

Figure 6-8. Failure shear stress vs. ratio of pile diameter to ice thickness. (1 kPa × 0.145 = 1 psi.)

6-8. Summary

This Chapter estimates ice forces on the basis of ice mechanics for its failure in various modes, as well as on empirical values of effective pressure measured on full-scale structures. For ice crushing, which induces the highest effective pressure on a structure, the effective pressure depends on the indentation speed and the aspect ratio (*D*/*h*). Most of the codes take these factors into account for estimating ice forces on structures. When an ice sheet fails in modes other than crushing, the effective pressure is generally less.

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CHAPTER 7
Sediment Transport

7-1. Introduction. The annual cycle of ice formation and breakup influences sediment-transport dynamics in waterways. The magnitude of the influences depends on a combination of factors. Of prime importance are factors determining the amount of ice formed and the quantities of water and sediment to be conveyed.

a. The overall amount of ice, and ice-mass thickness, are usually governed by the cumulative period of temperature degrees below the freezing temperature of water. Water-flow rate directly determines quantities of sediment transport. Under natural conditions in many waterways, rivers, and canals, the annual cycle of ice formation is accompanied by a decline in water runoff and channel flow. Rates of sediment supply and channel transport diminish commensurately. Runoff and channel flow subsequently increase during spring thaws, and it is then that ice-cover effects on sediment transport can become significant. For flow-regulated rivers and channels downstream of reservoirs, though, ice effects on sediment transport and alluvial-channel behavior are of special interest. Substantial flows may occur while such rivers and channels are ice covered in winter.

b. Ice effects can occur over varying scales of time and channel length. On the time scale of months and length scale of miles of channel, for instance, ice alters the relationships among flow rate, flow depth, and sediment transport rates. As it forms, an ice cover usually increases and redistributes a channel's resistance to flow, and reduces its overall capacity to move water and sediment. In a sense, because the channel's bed roughness does not actually increase (in fact it may reduce [Smith and Ettema 1997]), the effect on channel morphology of an ice cover's presence may be likened to the effect produced by a reduction in energy gradient associated with flow along the channel. More precisely, it may be likened to a change in thalweg geometry; the additional flow energy consumed overcoming the resistance created by the cover offsets a portion of the flow's energy the channel dissipates by thalweg lengthening or bifurcation.

c. At the local scale, an ice cover over a short reach may redistribute flow laterally across the reach, accentuating erosion in one place and deposition in another place. Such local changes of the bed may develop during the entire cycle of ice formation, presence, and release. They may develop briefly, lasting slightly longer than the ice cover and disappear shortly after the cover breaks up, or they may trigger a change that persists for some time. In any event, they should be verifiable from a site investigation.

d. Ice may dampen or amplify erosion processes locally. Obvious dampening effects of ice are reduced water runoff from a watershed, cementing of bank material by frozen water, and ice armoring of bars and shorelines by ice-cover set-down with reduction in flow rates. Yet, ice may amplify erosion and sediment-transport rates, notably during the surge of water and ice consequent to the collapse of a large ice jam. For unregulated or wild rivers, like the Yellowstone River, shown in Figure 7-1, as well as for regulated rivers, it has become important to understand channel response to the winter cycle of ice.

Figure 7-1. The Yellowstone River, Montana, under an ice cover, whose formation, presence, and eventual breakup significantly influence sediment-transport dynamics, channel-thalweg location, and riverbank erosion.

e. This chapter of the Manual considers the following topics related to sediment transport:

- Ice-cover influences on flow distribution.
- Sediment transport by ice (i.e., sediment included in drifting ice).
- Sediment transport under ice.
- Ice influences on channel morphology.

Sediment transport under ice is the central topic addressed herein.

f. The present description of sediment processes in ice-covered rivers and channels does not address the influences of permafrost on sediment transport. Permafrost is an important factor affecting riverbank and channel stability of high-latitude rivers. Lawson (1983) and Scott (1978), for example, provide some insights into channel behavior in permafrost. Andersland and Anderson (1990). and Johnston (1981) usefully describe the geotechnical properties of permafrost.

7-2. Ice-Cover Influence On Flow Distribution. Though the influence of an ice cover on flow distribution is described in earlier chapters of this Manual, it is useful to briefly elaborate on influences concerning sediment transport.

a. An ice cover imposes an additional resistant boundary that decreases a channel's flow capacity and vertically redistributes streamwise velocity of flow in a channel. If the cover is free-floating, it may reduce the erosive force of flow in the channel and thereby reduce rates of sediment transport. However, cover presence also may laterally redistribute flow, usually concentrating it along a thalweg. If the thalweg lies close to one side of a channel, flow concentration may locally increase bank erosion and channel shifting. On the other hand, if the thalweg is more-or-less centrally located in a channel, the cover may reduce bank erosion and channel shifting. Additionally, if the full cover is fixed to the riverbank, it may increase locally flow velocities and rates of sediment transport. The variability of flow response to ice-cover presence makes it difficult to draw simple overall conclusions about ice-cover effects on a river's bed and banks. The net effects will vary from site to site.

b. If the flow rate and channel slope were assumed constant, the main individual effects of a uniformly thick ice cover on a straight uniformly deep alluvial channel are as follow:

- Raised water level (ice-covered depth exceeds open water depth for the same flow rate, as illustrated in Figure 7-2).
- Reduced bulk velocity of flow (discharge/flow area).
- Laterally redistributed flow (Figures 7-3 and 7-4).
- Reduced drag on the channel bed.
- Reduced velocity of secondary currents, and altered pattern of secondary currents (i.e., currents associated with transverse circulation of flow in the channel, as shown in Figure 7-5).
- Reduced rates of bed-sediment transport.
- Altered size and shape of bedforms (notably dunes).

c. For steady rate of water flow in an open channel (Figure 7-3a), a free-floating and uniformly thick ice cover smears flow over the full channel width (Figure 7-3b). However, if the ice cover is fixed to the channel banks and thickened, the reverse occurs (Figure 7-3c), because flow depth reduces more in the shallower portion. Under this condition, cover presence squeezes or concentrates flow along a thalweg, where flow is deeper. If the thalweg lies close to one side of a channel (e.g., near the outer bank of a bend), such a concentration of flow may promote thalweg shifting and deepening. On the other hand, if the thalweg is located more-or-less centrally in a channel, a fixed cover may deepen or entrench the thalweg. Another important point is that the cover, by reducing flow through the shallow portion, may trigger further reductions in conveyance through the shallower portion by promoting ice accumulation (frazil slush or pans) or bed-sediment deposition, or both. Additional flow concentration is possible if the cover was not uniformly thick (Figure 7-3d), if ice grounds on the channel bed, or if shore-fast or accumulated ice develops from one or both banks.

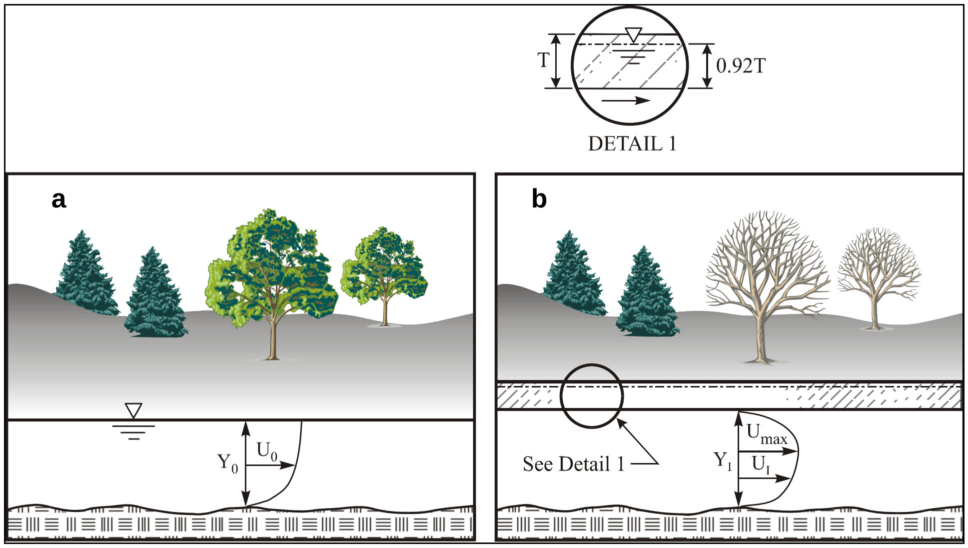


Figure 7-2. Ice-cover presence usually increases flow depth and redistributes flow.

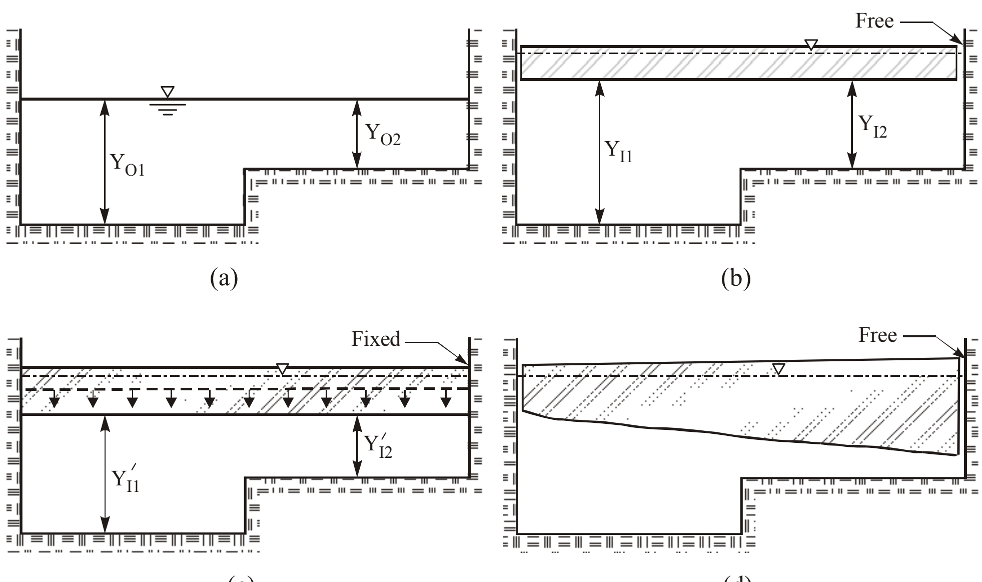
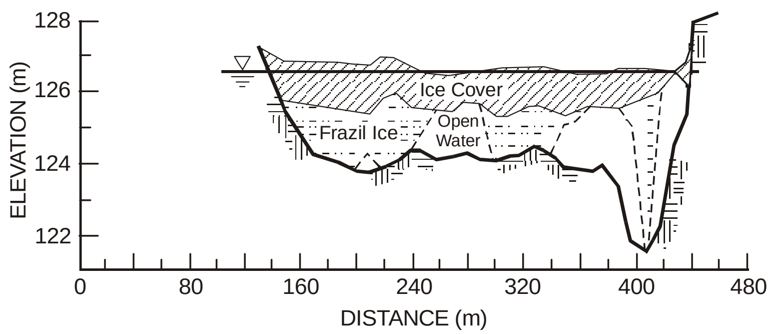
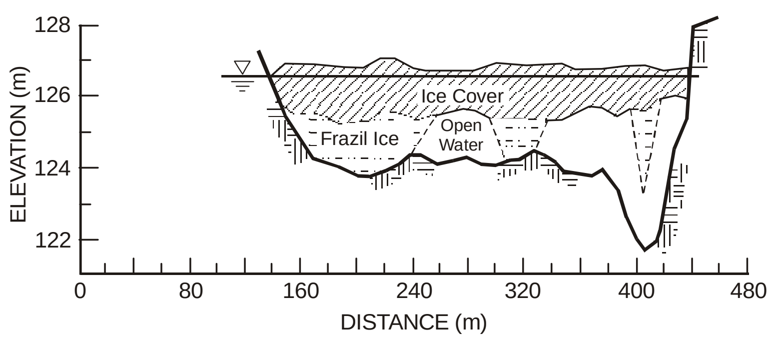


Figure 7-3. An ice cover may reduce open water proportions (a) of flow conveyance in lateral segments of a two-part compound channel if the cover is level and free floating (b); increase them if the cover is fixed and thickens (c); or, increase them if the cover is not uniformly thick (d).

d. Lateral variations in cover thickness may further concentrate flow in a channel of non-uniform depth and may override the more subtle effects to those just described for a level ice cover. Significant lateral and streamwise variations in cover thickness may occur in channels with significant variations in flow depth and velocity. Because flow velocities decrease with decreasing flow depth, velocities usually are lower in regions of shallower flows and, often, in the wake of flow obstructions, such as bars. Ice covers whose formation involved substantial amounts of frazil-ice slush may become thicker in regions of shallower flow. Lower values of flow conveyance in those regions also result in relatively faster bankfast-ice formation. Also, because flow velocities are lower, ice (frazil slush and ice pieces) is less readily conveyed through those regions, and is prone to accumulate. Figure 7-4 illustrates the accumulation of ice at a cross-section of the Tanana River, Alaska, at two times during winter (Lawson et al. 1986). That river is comparable to the lower Missouri River in flow rates, but is of steeper slope, is more braided in channel morphology, and its flow is not regulated.



a. 29 February 1984.



b. 30 March 1984.

Figure 7-4. Non-uniform ice accumulation across a section of the Tanana River, Alaska (from Lawson et al. 1986) (1 m = 3.28 ft).

e. Further concentration of flow is possible if an ice cover is not free to float upwards with increasing flow rate. Hydraulic analyses usually assume (e.g., Ashton 1986, Beltaos 1995) that ice covers are free floating; i.e., streamwise cracks separate the floating ice cover from adjoining bankfast ice. Actually, a cover may not always be free-floating. A stationary cover exposed to very frigid air may fuse to the channel banks.

The cover then becomes constrained from freely floating up or down with changes in the flow, at least initially. Therefore, increasing flow is forced partially beneath the ice cover, initially pressurizing it and increasing flow velocities, which may locally erode the bed beneath the cover. The extent to which a flow may be pressurized beneath a cover apparently has not yet been measured. Some evidence (Zabilansky et al. 2002) suggests that scour of the channel bed may possibly relieve the pressurized flow in alluvial channels. Very little information exists on this flow condition, especially with regard to how it may locally affect the channel bed and banks.

f. For constant discharge, a free-floating level ice cover reduces bulk flow velocity and alters the vertical distribution of streamwise flow. In so doing, it usually dampens secondary currents. Cover presence reduces the centrifugal acceleration exerted on flow around a river bend, though only one study has investigated this effect (Tsai and Ettema 1994). That study found that cover presence alters patterns of lateral flow distribution in a channel bend. The two sketches in Figure 7-5 show the main alteration, which is a splitting of the large secondary flow spiral into two weaker spirals; owing to centrifugal acceleration acting on moving water, a large secondary flow spiral is typical of many curved channels. The presence of a level ice cover reduces radial components of velocity and lateral bed slope in channel bends, causing the bed level to rise near the outer bank. Tsai and Ettema found a reduction in lateral bed slope of about 10%. This ice-cover effect would tend to mildly retard bank erosion in channel bends, because it may result in reduced flow velocities near the outer bank of a bend.

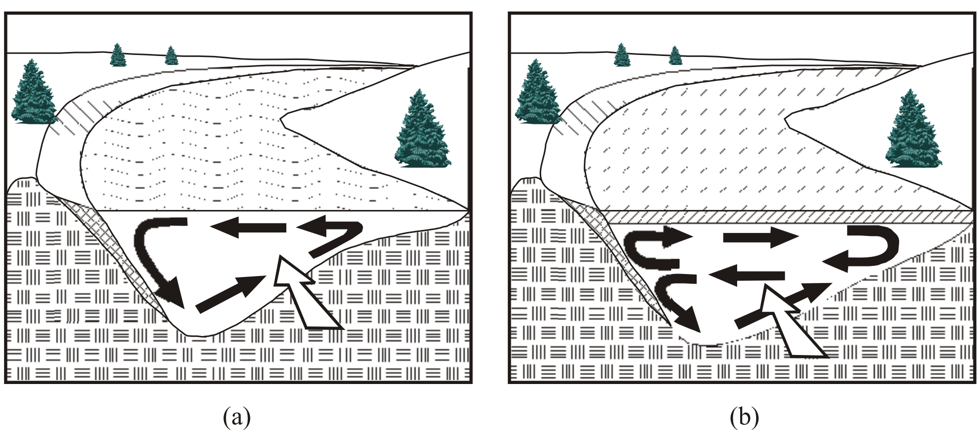


Figure 7-5. Ice-cover effects on spiral secondary current in a channel bend.

7-3. Sediment Transport by Ice. Sediment-laden ice slush and clumps of ice-bonded sediment may appear during the early stages of ice formation in certain rivers and streams subject to the winter cycle of ice formation. The ice slush and clumps usually comprise a mix of frazil ice and anchor ice that were once briefly bonded to the bed of such rivers and streams (Figure 7-6). The amounts of sediment entrained and rafted with the ice slush and clumps can produce a substantial momentary surge in the overall quantity of sediment moved by some rivers and streams, though at present there are no reliable measurements or estimates of ice-rafted sediment-transport rates. Much of the entrained sediment becomes included in an ice cover, where it remains stored until the cover breaks up. Though ice rafting of sediment is known to occur (observations are reported by, for example, Barnes 1928, Wigle 1970, Michel 1971, Benson and Osterkamp 1974, Kempema et al. 1993), the engineering and environmental implications of its occurrence are largely unknown.

a. The short treatment given in this paragraph limits itself to ice transport of sediment in rivers, canals, and streams. Shallow coastal (marine and lacustrine) waters in cold regions are also prone to bed-sediment entrainment and ice rafting by frazil and anchor ice. Barnes et al. (1982), Osterkamp and Gosink (1984), Reimnitz and Kempema (1987), and Kempema et al. (1986, 1993) describe coastal locations where ice entrains significant quantities of sediment. Storms, in frigid weather conditions, agitate coastal waters and can produce large quantities of frazil ice. The mechanisms whereby anchor ice forms in coastal waters include the same elements causing anchor ice to form in rivers and streams. The formation mechanisms for coastal anchor ice are complicated, however, by the more complex flow conditions of coastal waters and salinity considerations in marine systems. Ice can significantly affect sediment erosion and deposition in estuaries and tidal reaches of rivers. Desplanqes and Bray (1986) and Morse et al. (1999) describe the influence of ice accumulation in estuaries of the northeast portion of the Bay of Fundy. The accumulations form as ice walls from stranded ice and included sediment. The ice walls confine flow and can accentuate localized channel scour. Of particular concern in this regard is scour near hydraulic structures, such as bridge piers and abutments.

Figure 7-6. Sediment-laden frazil slush taken from Flat Creek in Jackson, Wyoming (photo by S.F. Daly, CRREL).

b. The mechanisms whereby ice entrains and transports sediment are not well understood. Also, the distances over which ice-rafted sediment typically may be transported are not really known. To date, the only detailed laboratory investigations of the entrainment mechanisms are the studies reported by Kempema et al. (1986) and (1993). A handful of experiments on anchor ice formation have been conducted, though (e.g., Tsang 1982, Kerr et al. 1998). The experiments and field observations indicate that the following two mechanisms contribute to anchor ice formation:

(1) The main mechanism is frazil adhesion to bed sediment. Large-scale turbulence in comparatively shallow, swift-flowing rivers and streams can mix suspended ice crystals and flocs of active frazil across the full depth of flow. While the flow is supercooled, the frazil may adhere to bed sediment or individual boulders and accumulate as a porous and spongy mass (Wigle 1970, Arden and Wigle 1972, Tsang 1982, Beltaos 1995). Rapids and riffles are common locations for anchor ice formation (Marcotte 1984, Terada et al. 1997). Altberg (1936) reports the occurrence of anchor ice in river flows as deep as 20 m (66 ft). The foregoing references report rapid rates of anchor ice growth, such that large volumes of anchor ice form in a short period.

(2) A much less significant mechanism for sediment transport is direct ice growth on the bed or on objects protruding from the bed. Together with frazil ice, supercooled water can be mixed across the flow depth. The downdraft of supercooled water chills objects in the flow (e.g., boulders and debris of various types) and enables ice to directly nucleate and form on those objects. The resultant ice crystals are relatively small and develop a fairly smooth and dense ice mass (e.g., Ashton 1986, Kerr et al. 1998).

c. The diurnal formation of frazil and anchor ice may result in repeated ice-rafting events along a river reach, each event potentially entraining substantial quantities of bed sediment. Under conditions of sufficiently frigid weather and substantial flow turbulence, extensive areas of a river's bed can become blanketed by anchor ice. As the larger sizes of sediment on a riverbed protrude more into the flow, they usually are more affected by the thermal condition of the flow than that of the bed on which they rest. Significant heat flux can occur from the sub-bed zone that is a degree of two above 0^{o}C (32^{o}F) and supercooled flow essentially over the full flow depth of a river or stream. Consequently, larger amounts of anchor ice typically form on beds of coarser sediment. Several factors militate against extensive anchor ice formation on riverbeds of fine, noncohesive sediment. In particular, such sediments are readily lifted and, thereby, cannot hold a significant anchor ice accumulation (Arden and Wigle 1972, Marcotte 1984).

d. The laboratory studies provide interesting insights into aspects of anchor-ice formation in the presence of bedforms. They show how frazil flocs become sediment-laden and lose their buoyancy as they tumble along the flume's sand bed, and eventually become included within an ice-sand clump of anchor ice. As the negatively buoyant flocs of frazil and sediment accumulate in the trough of a dune or a ripple (as illustrated in Figure 7-7), they become infiltrated by sand, buried, and compressed. The resulting clumps of bonded ice and sediment may then enlarge as additional frazil flocs fuse to them, or as the clumps grow amidst supercooled water.

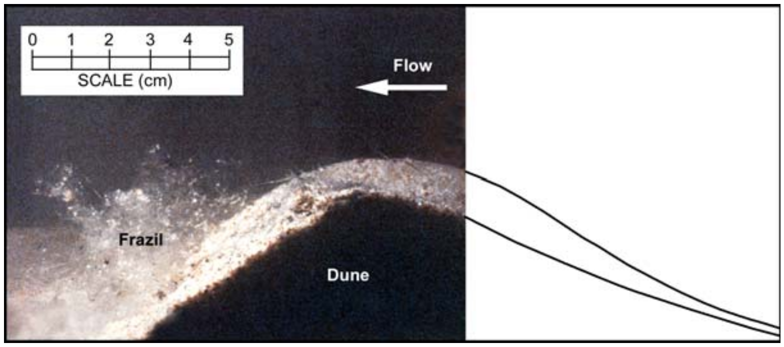


Figure 7-7. Frazil ice accumulated in the lee of a dune, which migrates and envelops the frazil, eventually forming an ice-bonded clump of sand. This photo was taken from a flume experiment described by Kempema et al. (1993). (1 cm = 2.54 in.) (Photo taken by Ed Kempema, University of Wyoming.)

e. Eventually, a clump of anchor ice accumulation may attain sufficient buoyancy to lift sediment from the bed. The resulting concentrations of suspended sediment that the ice conveys can get quite high. Kempema et al. (1986) calculate that, a neutrally buoyant clump of ice-bonded sediment may contain up to 122 g of sediment per 1 L of ice and sediment. Kempema et al. (1998) measured sediment concentrations in released anchor ice masses in southern Lake Michigan of 1.2 to 102 g/L, with an average concentration of about 26 g/L. Anchor ice may move gravel and cobbles. Martin (1981) mentions an instance where anchor ice entrained and moved boulders up to 30 kg (14 lb) in weight. Such ice rafting can move cobbles and boulders through long reaches of deep river pools with relatively sluggish flow.

f. Frazil and suspended sediment may interact directly in the water column, causing suspended sediment to be included in ice slush. The details of the interactions, and the likelihood of their occurrence, are not well understood. Barnes (1928) and Altberg (1936) mention an intriguing observation that frazil-ice formation appears to remove suspended sediment from a flow; after a frazil-ice event, water seems clearer. While frazil and anchor ice form, it is possible that they may diminish bed-sediment entrainment and transport. Initially, accumulating frazil and anchor ice would bind bed sediment, thereby retarding entrainment. Also, by virtue of the ice concentrations involved, frazil ice may dampen flow turbulence, a key factor in suspended-sediment transport. Once anchor ice lifts from a bed, however, it would entrain and convey sediment, although that sediment may become frozen and temporarily stored in a floating ice cover.

7-4. Sediment Transport Under Ice. Sediment-transport processes in ice-covered flow are not fully understood. Some influences of an ice cover on flow distribution are reasonably well understood, while some are barely recognized (e.g., on large-scale turbulence); few reliable methods exist for estimating transport rates or ice effects on channel stability. An essential feature of alluvial rivers and channels is that their morphology and flow-resistance behavior vary interactively with flow and sediment conditions. Depending on flow magnitude, ice covers modify the interaction, doing so over a range of scales in space and time.

a. Parameters. It is convenient to describe ice-cover influences in terms of key nondimensional parameters characterizing the dynamics of flow and sediment interaction. Dimensional analysis of variables associated with flow in an alluvial channel (Figure 7-8) formally identifies the important parameters.

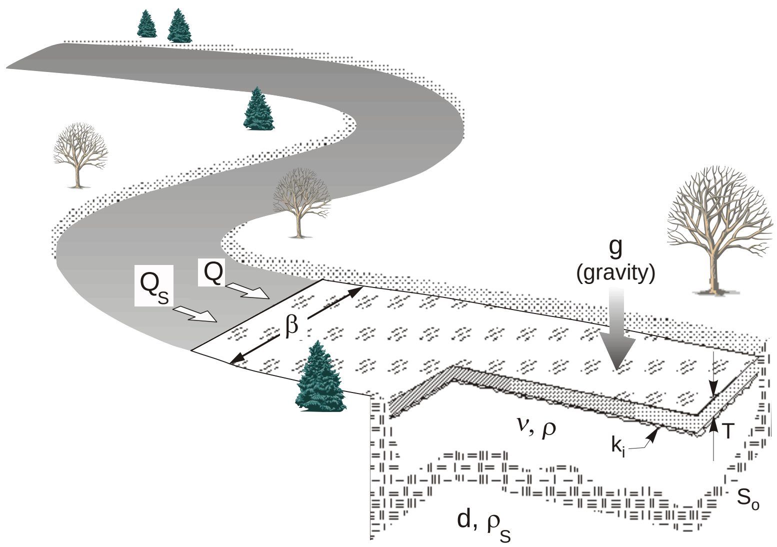


Figure 7-8. Independent variables usually associated with flow in an alluvial channel with an ice cover.

(1) Typically, a dependent quantity *A* of a channel may have the following functional dependency for flow in a reach of comparatively wide channel, comprising a bed of uniform diameter sediment under a uniformly thick ice cover:

$$A = f_A\left(Q, Q_S, \nu, \rho, \rho_s, d, g, S_0, B, T, k_i\right) \quad (7\text{-}1)$$

where

Q_S = Sediment discharge into reach
ν = kinematic viscosity of water
ρ = water density
ρ_S = sediment density
d = median size of bed particles
g = gravity acceleration
S_0 = channel slope
B = reach width
T = ice-cover thickness
k_i = hydraulic roughness of ice-cover underside.

(2) The dependent quantities (*A*) of practical concern for a channel reach are flow depth, hydraulic radius, bulk velocity of flow, flow-energy gradient, sediment-transport capacity of the flow in the reach, and possibly thalweg alignment (path of greatest depth).

(3) Though ice-cover properties T and k_i actually may be dependent variables, especially for ice covers formed from accumulated drifting ice, here they are treated as independent variables. Though k_i directly affects flow resistance, cover thickness, T, affects flow insofar that it is of use in characterizing cover rigidity and elevation of hydraulic grade line. The present focus is on the ways in which an existing ice cover modifies interactions between flow and bed. An interesting broader discussion would be to consider how flow and bed interaction influence cover formation. That discussion might include thermal variables, such as water temperature.

(4) In terms of non-dimensional parameters and, for convenience, considering unit discharges of water, q (= Q/B) and sediment q_S (= Q_S/B), Equation 7-1 may restated as:

$$\Pi_A = \varphi_A \left(\frac{q}{\nu}, \frac{q_s}{\nu}, d\left(\frac{g\Delta\rho}{\rho\nu^2}\right)^{1/3}, \frac{\rho_s}{\rho}, S_0, \frac{d}{k_i}, \frac{T}{d} \right) \tag{7-2}$$

in which sediment diameter, d, is used as the scaling or normalizing length. Here, sediment discharge is total sediment discharge. Also, $\Delta\rho = \rho_S - \rho$.

(5) The second and third parameters can be combined to more usefully express sediment transport non-dimensionally as:

$$\frac{q_s}{\nu}\left[d\left(\frac{g\Delta\rho}{\rho\nu^2}\right)^{1/3} \right]^{-3/2} = \frac{q_s}{\sqrt{g(\Delta\rho/\rho)d^3}} \tag{7-3}$$

For most situations, ρ_S/ρ is more-or-less constant (about 2.65). Whence Equation 7-3 reduces to:

$$\Pi_A = \varphi_A \left(\frac{q}{\nu}, \frac{q_S}{\sqrt{g\left(\Delta\rho/\rho\right)d^3}}, d\left(\frac{g\Delta\rho}{\rho\nu^2}\right)^{1/3}, , S_0 \frac{d}{k_i}, \frac{T}{d} \right) \tag{7-4}$$

In Equations 7-3 and 7-4, Froude number, $Fr = (q/Y)/(gY)^{0.5}$ is a dependent parameter, as flow depth, Y, is a dependent variable.

(6) For the case of a long, rigid, and uniformly thick, free-floating ice cover, in which the significance of T/d diminishes, and Equation 7-4 simplifies to:

$$\Pi_A = \varphi_A\left(\frac{q}{\nu}, \frac{q_S}{\sqrt{g(\Delta\rho/\rho)d^3}}, d\left(\frac{g\Delta\rho}{\rho\nu^2}\right)^{1/3}, \; , S_0 \; \frac{d}{k_i}\right) = \varphi_A\left(Re, \frac{q_S}{\sqrt{g(\Delta\rho/\rho)d^3}}, D_*, S_0, \frac{d}{k_i}\right)$$

(7-5)

in which

$$D_* = d\left(g\Delta\rho/\left[\rho\nu^2\right]\right)^{1/3}$$

and

$$Re = \frac{q}{\nu}.$$

(7) Many relationships in alluvial-channel hydraulics are expressed in terms of particle Reynolds number

$$Re_* = u_{*_b} d/\nu$$

and Shield's parameter

$$\theta = \rho u_{*b}^2/(g\Delta\rho d)$$

here, u_{*b} = shear velocity associated with bed component of velocity distribution.

(8) In this regard, using $D_* = (Re_*)^2/\theta$, Equation 7-5 more usefully is

$$\Pi_A = \varphi_A\left(Re, \frac{q_S}{\sqrt{g(\Delta\rho/\rho)d^3}}, D_*, S_0, \frac{d}{k_i}\right) = \varphi'_A\left(Re, \frac{(Re_*)^2}{\theta}, \frac{d}{k_i}, \frac{q_S}{\sqrt{g(\Delta\rho/\rho)d^3}}, S_0\right)$$

(7-6)

(9) Most equations for bedload transport empirically relate transport rate to a flow intensity, θ, (e.g., ASCE 1975, Chien and Wan 1999). As shown, subsequently, the parameter $\theta d/k_i$ is convenient for indicating how cover roughness moderates θ. To simplify the discussion, the inflow and outflow rates of sediment, q_S, are taken as equal, thereby relaxing Equation 7-6 to:

$$\Pi_{\mathrm{A}} = \varphi''_{\mathrm{A}}\left(Re, Re_{*}, \eta\frac{d}{k_{\mathrm{i}}}, S_0 \right) \tag{7-7}$$

which also recasts θ as $\eta = \theta/\theta_c$, thereby expressing θ relative to a critical value, θ_c, for incipient sediment movement. Many relationships for Π_A are expressed in terms of η or an excess of flow intensity, $\eta - 1$ (e.g., ASCE 1975).

(10) The ensuing discussion considers how the parameters in Equation 7-7 influence flow and sediment movement. It begins with a brief review of the pertinent cold-water properties.

b. Water-Temperature Effects. Ice is attended by cold water, usually at or slightly above 0°C (32 °F). Most empirical relationships for alluvial-channel hydraulics are based on data obtained with water in the range of 10 to 20°C (50 to 68°F). All but one of the independent parameters in Equation 7-7 directly involves water properties: ν, ρ, and $\Delta\rho$. Reduced water temperature increases kinematic viscosity, ν (it increases 100%, when water cools from 25 to 0°C [77 to 32 °F]), and slightly changes ρ (it increases about 0.3%, when water cools from 25 to 0°C, but attains a maximum at 4°C[39.2 °F]). An increase in ν directly reduces Re and Re_* values, at constant q. In so doing, it increases flow drag on the bed, decreases particle fall velocity, and thereby overall increases flow capacity to convey suspended sediment. In many respects, the effect of low water temperature can be taken into account using Re, Re_*, and θ (insofar that it scales particle size and fall velocity relative to bed shear velocity, u_{*b}). The quantitative impacts of increased fluid viscosity on macro-turbulence are, as yet, unclear.

(1) Quite a few studies have investigated water-temperature effects on sediment transport or, say, on sediment fall velocity. The studies confirm that sediment-transport rate increases with decreasing water temperature. Lane et al. (1949) and Colby and Scott (1965) show that trend in field data taken from the Missouri, Colorado, and Middle Loup Rivers. Extensive flume experiments are reported by Ho (1939), Straub (1955), Colby and Scott (1965), Taylor and Vanoni (1972), and Hong et al. (1984). Taken together, the flume data confirm that sediment transport rates increase as water temperature decreases, the increases becoming substantial when water temperature drops below about 15°C (59°F). The flume data reported by Hong et al. (1984), for instance, show that the mean concentration of bed-sediment transport increased by factors up to seven and ten for a water temperature drop from 30 to 0°C (86 to 32°F). The increase, obtained with $d = 0.11$ mm (0.004 in.), is attributable to increased concentration of sediment transport in a bed layer (layer thickness taken as $d\eta^{0.5}$) and increased uniformity of concentration distribution over the flow depth. The latter effect is largely owing to the reduced fall velocity of suspended particles. Hong et al. (1984) concluded that temperature reduction significantly increases bed-level concentration of sediment movement only if bed-layer Reynolds number, Re_B (defined by Hong et al. as $\{u_* d\eta^{0.5}\}/\nu$) exceeds about 20; $Re_B = Re(\eta)^{0.5}$.

(2) No study seems yet to have looked at the settling velocity of cohesive sediments, or cohesive-sediment behavior overall, at water temperatures close to 0^{o}C. For example, Huang (1981), examined water-temperature effects on cohesive-sediment fall velocities for the range 32^{o}C (90^{o}F) down only to 6.1^{o}C (43^{o}F).

c. Sediment Movement and Bedforms. The overall magnitude of the tractive force (drag and lift components) flow exerts on bed particles, together with the impacts of flow turbulence in all its scales, prescribe bed sediment motion. Ice-cover presence influences water drag on the bed and turbulence generation by redistributing flow and reducing the rate of flow energy expended along the bed. In so doing, cover presence poses three practical issues in using Equation 7-6.

(1) The first issue concerns estimation of τ_b or u_{*b}, shear stress or velocity associated with the channel bed. These variables are considerably more difficult to estimate than for open water loose-bed hydraulics.

(2) A second issue is that the dependent loose-bed parameters (Π_A) of practical importance for alluvial-bed flows typically are estimated using semi-empirical relationships developed for open water conditions. Simply stated, at issue is the applicability of open water empirical relationships for ice-covered flow.

(3) A third issue concerns the streamwise variation of the flow and sediment-transport capacity of an ice-covered channel. If the sediment-transport capacity of an ice-covered channel were less than the rate at which sediment load is supplied to the channel, the bed must locally aggrade. If the converse holds, the bed must degrade locally. The former condition usually would prevail for a free-floating cover, because the bulk velocity of flow decreases. The latter condition may occur when the cover is fixed or thick (large T/d), because the bulk velocity of flow under the cover increases. The various states of ice-cover condition complicate prediction of flow resistance and sediment transport in ice-covered alluvial channels.

(4) A complicating aspect of estimating flow resistance and sediment transport is that the single relevant length scale for ice-covered flow is the total flow depth, Y, which itself usually is a dependent variable. For open water flow, flow drag on the bed can be characterized using Re and D_*, because they are not explicitly dependent on flow depth and flow velocity, depending instead on q, as well as water and particle properties.

(5) Two practical concerns are whether river ice influences bedform geometry and, if so, is its influence describable using relationships developed for open water flow. These issues have implications for estimating flow resistance and mixing processes. Following from Equation 7-7, bedform length, L, and steepness, δ, can be expressed functionally as

$$L_* = L/d = \varphi_{L_*}\left(Re, Re_*, \eta \frac{d}{k_i}, S_0 \right) \qquad (7\text{-}8)$$

and

$$\delta = H / L = \varphi_{\delta}\left(Re, Re_{*}, \eta \frac{d}{k_{\mathrm{i}}}, S_0\right) \tag{7-9}$$

in which H = bedform height. Equations 7-8 and 7-9 indicate that ice-cover presence should influence bedform geometry. The practical concern is accurate estimation of η, or u_{*b}. Figures 7-9 and 7-10 show that bedform geometry in ice-covered flow essentially conforms to the same relationships as prevail for open water flow. Figure 7-10 shows additionally that an ice cover, by reducing excess flow intensity at the bed, $\eta - 1$, reduces bedform steepness for the range of values indicated.

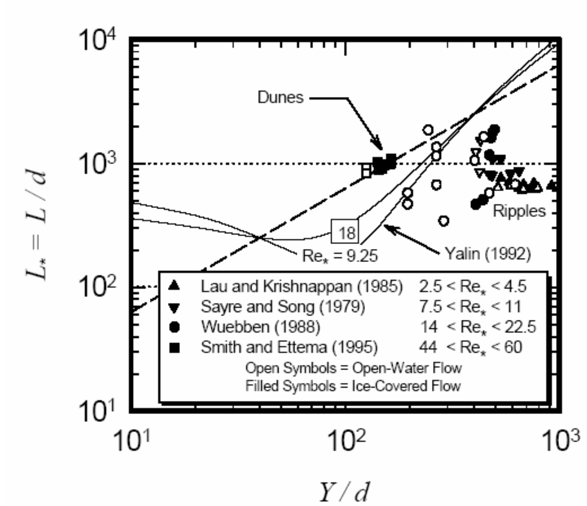


Figure 7-9. Flume data on bedform length in ice-covered flow conform to empirical open water curves developed by Yalin (1992).

(6) However, there is an important cover influence not immediately evident from Equations 7-8 and 7-9, and Figures 7-9 and 7-10. The influence is not adequately described in terms of cover influence on η or u_{*b}. Bedforms generate macro-scale turbulence or coherent turbulence structures. Cover presence, by redistributing flow, influences the development of macro-turbulence and its consequences for bed sediment suspension as well as other dispersive processes. Recent experiments by Ettema et al. (1999), suggest that a smooth, level cover may invigorate macro-turbulence generation, mildly increasing the frequency of structures generated from bedforms and enabling them to penetrate the full depth of flow.

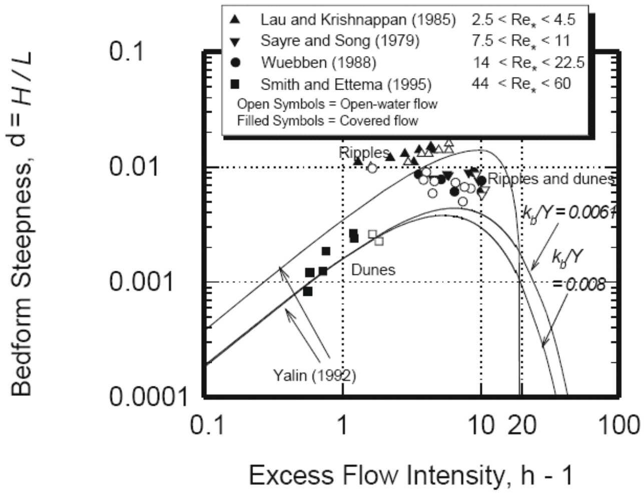


Figure 7-10. Flume data on bedform heights in ice-covered flow conform to empirical open water curves developed by Yalin (1992).

d. Flow Resistance in Alluvial Channels. The issues for flow resistance hinge on the issues mentioned above for sediment entrainment, bedforms, and macro-turbulence. They entail estimation of resistance coefficients, f_b, associated with the bed and the ice cover, f_i, then estimation of flow depth, Y, given q. From Equation 7-9

$$Y/d = Y_* = \varphi_{Y_*}\left(Re, Re_*, \eta\frac{d}{k_i}, S_0\right) \tag{7-10}$$

(1) Equation 7-10, however, is not immediately useful for predictive purposes, because open water methods estimate Y as the composite of form-drag and skin-friction resistance components. It is more helpful to use the Darcy-Weisbach relationship, written in terms of unit discharge, q, of flow in a wide channel with a free-floating ice cover

$$Y_I = \left(\frac{f_I q^2}{4gS}\right)^{1/3} \tag{7-11}$$

with flow hydraulic radius $R_I = Y/2$

$$f_I = 0.5 f_b\left(1 + \frac{f_i}{f_b}\right),$$

and

$$f_b = f_b' + f_b''.$$

(2) The functional relationship for each of these component resistance coefficients can be adjusted in terms of parameters used by existing empirical, estimation relationships.

(*a*) *For Bed-Surface Resistance.*

$$f'_{\mathrm{b}} = \varphi_{\mathrm{f}'_b}\left(Re, D_*, S_0, \frac{d}{k_{\mathrm{i}}} \right) \quad (7\text{-}12)$$

(*b*) *For Form-Drag Resistance Attributable to Bedforms, Such as Dunes.*

$$f''_{\mathrm{b}} = \varphi_{\mathrm{f}''_b}\left(Re, D_*, S_0, \frac{d}{k_{\mathrm{i}}} \right) = \varphi_{\mathrm{f}''_b}\left(Re,\ D_*,\ f'_{\mathrm{b}}, \frac{d}{k_{\mathrm{i}}} \right) \quad (7\text{-}13)$$

(*c*) *For the Ratio.*

$$f_{\mathrm{i}} / f_{\mathrm{b}} = \alpha = \varphi_{\alpha}\left(Re, D_*, S_0, \frac{d}{k_{\mathrm{i}}} \right) = \varphi'_{\alpha}\left(Re, Re_{*\mathrm{b}}, S_0, \eta \frac{d}{k_{\mathrm{i}}} \right) \quad (7\text{-}14)$$

(3) Again, an immediate practical issue implicit in Equations 7-12 through 7-14 is that flow resistance in ice-covered alluvial channels can be estimated using open water relationships, provided the influence of $\eta d/k_{\mathrm{i}}$ in conjunction with the other parameters can be determined. If its influence can be determined, open water relationships, such as that given by Einstein and Barbarossa (1952) or Engelund and Hansen (1967), can be used to predict bed resistance in ice-covered loose-bed flow. A semi-empirical expression for Equation 7-14 is given in Figure 7-11, which contains data from several flume studies.

(4) Smith and Ettema (1997) developed a method, based on laboratory flume data, for estimating flow resistance in ice-covered alluvial channels. Their method is iterative and uses the following assumptions.

(*a*) The mechanics of bedform formation essentially is the same for open water and ice-covered channels.

(*b*) Methods for predicting bedform drag in open water flow (e.g., the Einstein-Barbarossa method, or the Engelund method) can be used to predict bedform drag in ice-covered flow. This can be done by replacing the bulk drag term, $\rho g Y_{\mathrm{I}} S$, with an estimate of the actual bed shear stress in an ice-covered flow.

(*c*) The ratio of boundary shear stresses along the bed versus along the cover underside is estimated as:

$$\alpha = \tau_i / \tau_b = 0.84(\eta d/k_i)^{-0.20} \quad (7\text{-}15)$$

Equation 15 is an equation fitted to the flume data shown in Figure 7-11. The limits of the equation have yet to be determined for values of η beyond those indicated in Figure 7-11.

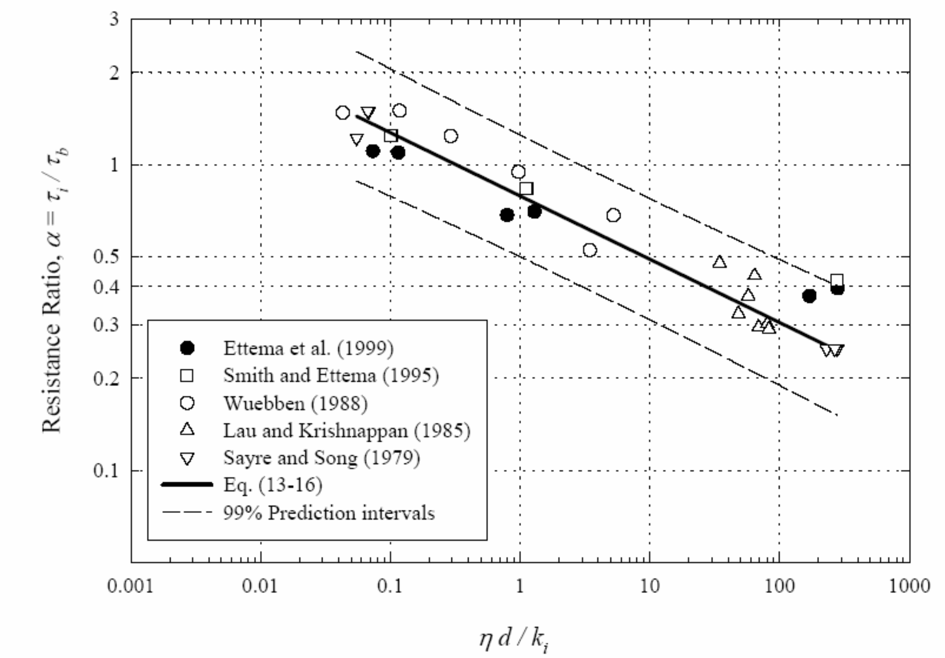


Figure 7-11. Resistance ratio, α, for an ice-covered flow in an alluvial channel.

(5) The proposed method requires the following input variables: cover roughness, k_i; median bed-sediment diameter, d; submerged specific gravity of bed sediment, $\Delta\rho/\rho$; unit discharge of water, q; channel slope, S_0; and an initial guess at flow depth, Y_I (say, $Y_I \approx 1.2Y_O$). The procedure uses the Einstein-Barbarossa method for predicting bedform resistance and predicts values of flow depth, Y_I.

e. Bed-Sediment Transport. A basic issue concerns an imbalance between rate of bed-sediment supply to an ice-covered reach, q_s, and the sediment-transport capacity of that reach, q_{sI}. This issue involves the complex problem of spatially varied flow and sediment transport, with all its repercussions on local channel slope and morphology. The sediment-transport capacity of an ice-covered channel can be expressed functionally as:

$$\frac{q_{SI}}{\sqrt{g\left(\Delta\rho/\rho\right)d^3}} = \varphi_{q_{SI}}\left(Re, Re_{*b}, S_0, \eta\frac{d}{k_i}\right) \quad (7\text{-}16)$$

This equation functionally characterizes bedload and suspended-load portions of bed-sediment transport. A fundamental issue relates directly to estimation of η or Re_{*b}. However, now cover influence on macro-turbulence becomes especially significant, because macro-turbulence affects sediment entrainment and suspension.

(1) *Laboratory Data on Bed-sediment Transport*. When examined in terms of η, or u_{*b}, laboratory data on bedload capacity of ice-covered flow concur well with the open water trend shown in Figure 7-12 for Einstein's (1950) method and Meyer-Peter and Mueller's formulation (1948). Essentially, if η can be estimated, bedload transport in an ice-covered channel can be estimated using an open water method, such as the two used in Figure 7-12.

(*a*) Estimation of suspended-load in an ice-covered channel is not as straightforward as bedload estimation. Suspended load depends not only on the bed shear stress, or u_{*b}, but also on macro-turbulence and flow distribution. As mentioned above, cover presence likely significantly alters these. So far, there is no direct way to account for macro-turbulence (notably the boils observed in sand-bed channels) effect on suspended load.

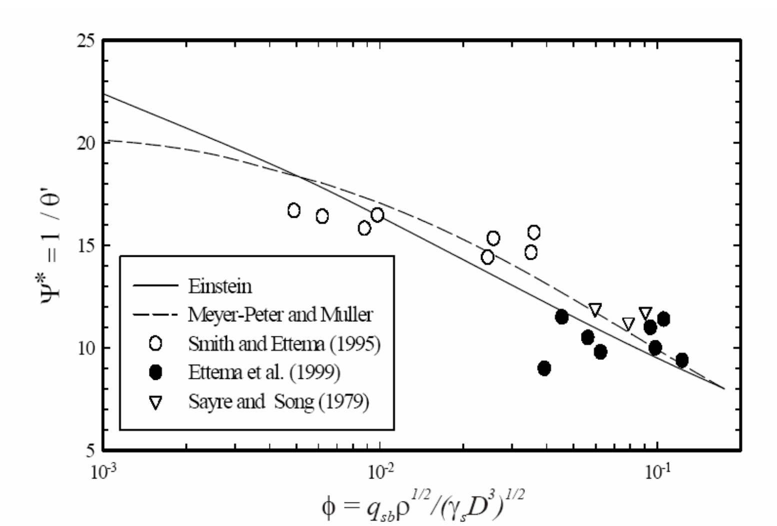


Figure 7-12. Bedload data compared with curves generated using Einstein's procedure and Meyer-Peter and Muller formula developed from openwater data. Covered-flow data conform to the same curves developed using openwater data.

(*b*) By virtue of its reduction of bulk velocity of flow, *U*, and thereby τ_b, and η, a free-floating ice cover typically reduces a channel's capacity to transport bed sediment. At certain zones within a channel, where the cover concentrates flow, sediment-transport rates may increase locally, however. Several laboratory studies have investigated cover-presence effects on sediment transport rate (Sayre and Song 1979, Wuebben 1986, Wuebben 1988a, Ettema et al. 2000). They all involved a free-floating cover that rises and subsides with changing flow rates. Their findings confirm that cover presence reduces rates of sediment transport. The rates decline rapidly with cover presence. Bedload-transport rate, for instance, can be almost halved by an ice cover that raises flow depth 15%, for a constant flow rate; this estimate assumes, reasonably, that bedload-transport rate $\propto \tau_b^2 \propto U^4$, with U decreasing by 15%; τ_b is shear stress acting on the bed, and U is bulk velocity of flow (ice-covered or open water). An important point here is that sediment eroded under an ice cover may not be transported far from the erosion location.

(2) *Field Data on Bed-sediment Transport.*

(*a*) Few field studies have been conducted in which rates of sediment transport were measured for ice-covered channels. The studies indicate the inherent difficulty of obtaining such measurements and of interpreting them. Lawson et al. (1986) conducted an extensive study of flow and sediment movement at a reach of the Tanana River, Alaska. They obtained measurements of bedload and suspended-load rates at one cross section. The rates were comparable in magnitude to rates measured during a survey conducted about a year earlier at two cross sections close to that used by Lawson et al.; Burrows and Harrold (1983) describe the earlier survey. Together, these data sets indicate a great reduction in the ratio suspended load relative to the bed-load from summer to winter. The reduction is attributed tentatively to reduced flow of melt water from glaciers drained by the Tanana River. Laboratory data obtained by Lau and Krishnappan (1985) and Ettema et al. (1999) show the opposite result, which both studies attribute to cover under-damping of turbulence generated by flow over bedforms.

(*b*) Alterations in flow distribution complicate evaluation of ice-cover effects on transport rates for many. This difficulty is evident in Figure 7-1, which shows an ice cover over the Yellowstone River, near Fallon, Montana, and from figures such as Figure 7-4, which shows non-uniform ice accumulation across the Tanana River. The series of shear lines evident in the ice cover on the Yellowstone River (Figure 7-1) indicate that the flow area has successively narrowed. Flow-width alteration is more difficult to predict than is flow depth change due to ice. The formation of subchannels within an ice-covered channel may accentuate narrowing of the flow area, especially if the channel is not prismatic. The subchannels form when accumulations of frazil slush or other ice pieces develop under the ice cover. In effect, they duct the flow in a manner that significantly alters the flow distribution from that attributable to the imposition of a level ice cover.

(3) *Field Data on Suspended Load.* The few field studies on sediment transport during ice-covered flow focused on suspended-load and do distinguish between bed sediment and washload sediment.

(*a*) The study carried out by Tywonik and Fowler (1973) focused on the measurement of suspended-sediment load in several rivers in the Canadian Prairie (e.g., Assiniboine River and Red River). They report that periods of ice cover on these rivers coincide with periods of low discharge and, therefore, low rates of suspended-sediment transport. In addition, they experienced considerable difficulty in making the suspended-load measurements, owing to frigid weather conditions and slush ice presence.

(*b*) For most cold-regions rivers, the major sediment-transport event each year occurs during the large flows associated with ice runs resulting from the dynamic breakup of an ice-cover or the release of a breakup ice jam, if a jam develops. In addition to large flow rates usually involved, these events may produce severe gouging and abrasion of banks by moving ice. The resultant sediment transport comprises a mix of bed sediment and fine sediment washed into the river during snowmelt. Bedload measurements are very difficult to obtain under ice-run conditions.

(*c*) Two studies, though, have provided some suspended-load data from individual breakup events. Prowse (1993) measured suspended-load concentrations during ice breakup of the Liard River, North West Territories. His data show a gradual increase in concentration with increasing water discharge immediately prior to breakup. When breakup occurred, suspended-load concentration increased by an order of magnitude, being comparable to concentrations associated with peak open water flows of about two to five times the peak flow at breakup. Data obtained by Beltaos and Burrell (2000) during ice breakup on the St John River, New Brunswick, show a similar trend.

f. Local Scour Beneath Ice Jams. The erosive behavior of a flow may increase locally beneath an ice jam if the jam concentrates flow, increasing the magnitude of its velocity and turbulence. Also, an ice jam may deflect flow, altering its direction in a manner so as to aggravate bank erosion or channel shifting. This mechanism locally increases flow velocity, and it may occur when flow and ice pieces are forced beneath an ice accumulation, such as an ice jam or an ice cover. Localized scour of an alluvial bed or bank of a channel may occur in the vicinity of an ice cover when the flow field at the cover locally increases flow velocities and, thereby, increases flow capacity to erode bed or bank sediment. There are several conditions under which this mechanism may operate.

(1) The most severe condition typically occurs near the toe of an ice jam (freezeup or breakup), as illustrated in Figure 7-13. There, where jam thickness is greatest and flow most constricted, increased flow velocities may locally scour the bed (Neill 1976, Mercer and Cooper 1977, Wuebben 1988b). Channel locations recurrently (nominally every year) subject to ice jams may develop substantial scour holes. Tietze (1961) and Newbury (1982), for example, suggest instances of such scour holes at sites of recurrent freezeup jams. In most circumstances, the scour hole would have no lasting or adverse effect on channel morphology, because it gradually would fill once the jam is released. It is conceivable that, in certain circumstance nonetheless, the localized scour could have a longer-term effect on channel morphology; e.g., if it promoted bank erosion at the jam site, or led to the washout of the channel feature triggering the jam, an island or bar for example.

(2) To a lesser extent, local scour of bed and bank may also occur when ice pieces collect at the leading edge of an ice cover or at some channel feature (e.g., a set of channel bars) that impedes their drift. These situations are quite marginal in extent, likely occurring more-or-less randomly along a channel, and are short-lived. However, they may potentially trigger more severe erosion in some situations.

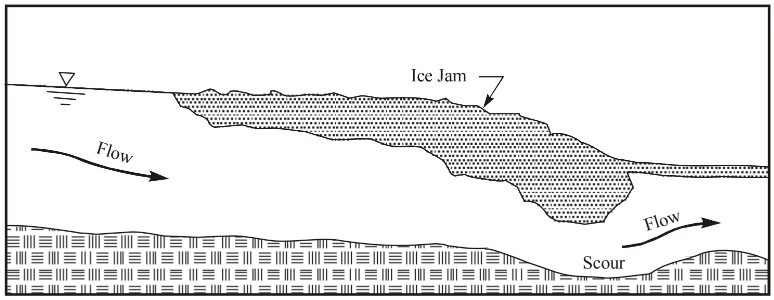


Figure 7-13. Flow acceleration and local scour beneath an ice jam.

g. Towboat Activities. As illustrated in Figure 7-14, towboat activities in ice-covered water can mobilize bed sediment. The lack of clearance beneath a towboat or barge (draft of 2.7 m [9 ft] when fully laden) causes ice rubble to be shoved as an accumulated mass ahead of it. Rubble ice is pushed down and may gouge the channel bed. If sufficient ice rubble accumulates, the towboat or barge even may become stuck on the mass of ice rubble.

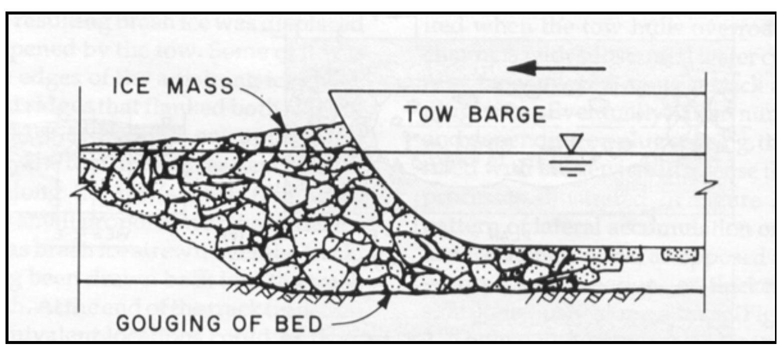


Figure 7-14. Channel bed gouged by ice rubble shoved by tow barge.

7-5. Ice Influences on Channel Morphology. The extent to which the seasonal formation and breakup of ice perturbs the stability of alluvial channels in regions subject to frigid winters is unclear. It seems from limited field observations (e.g., Mackay et al. 1974, Zabilansky et al. 2002) that river ice may potentially exert a compound impact of hydraulic and geomechanic effects that may continually de-stabilize certain plan-form geometries of channels subject to substantial, reservoir-regulated flow during frigid winters.

a. Introduction.

(1) There is considerable debate about ice influences on channel morphology and bank erosion. On one hand, some articles (e.g., Neill 1982, Blench 1986) largely dismiss the influences. On the other hand, there are fairly numerous anecdotal articles (e.g., Marusenko 1956, Lane 1957, Collinson 1971, MacKay et al. 1974, Hamelin 1979, USACOE 1983, Doyle 1988, Uunila 1997, Milburn and Prowse 1998), and the odd review article (Ettema 1999), suggesting ways in which river ice perceptibly affects channel morphology. The dismissive articles draw their conclusions from a few observations of overall plan form of a few rivers. They do not consider the impacts of reservoir regulation of flow during winter, take into account the diversity of channel morphologies, nor consider the important ephemeral impacts of ice that trigger local changes in thalweg.

(2) Several factors influence alluvial channel stability. Most of them are explainable in terms of Equation 7-16. Dependent variables of practical interest are average depth of flow, Y, hydraulic radius, R, also channel width, B, sinuosity, ζ, and shape, flow-energy gradient, S, and sediment-transport capacity, q_{sI}. Significant changes in any of the independent variables in Equation 7-16 may alter R, ζ, or q_{sI}, and may destabilize the alluvial reach. The greatest natural disturbances typically result from changes in water and sediment inflow rates q, or q_s. River-ice impacts likely become more significant when water discharge fluctuates appreciably; then, the prospects for other adverse ice influences increase, such as ice-cover break up followed by ice jamming.

b. Hydraulic Impacts. Ice may exert the following hydraulic impacts on alluvial channels:

- By reducing the sediment-transport capacity of a river reach, ice may redistribute bed sediment along the channel. Whatever local effects river ice may exert, overall river ice usually reduces the channel's overall capacity to convey the eroded sediment a significant distance from the erosion location. Consequently, bars may develop in response to flow conditions under river ice, and be washed out shortly after the cover breaks up. In situations where a significant load of bed sediment enters a long reach that has a free-floating ice cover, river ice may tend to cause mild aggradation of the channel it covers. In situations where the reach is under a fixed ice cover, local degradation may occur.
- Through its effects on lateral distribution of flow resistance and, thereby, flow and boundary drag, ice may modify channel cross-sectional shape developed under open water flow conditions.
- Congestion or jamming of ice at one channel location may divert flow into an adjoining channel, which then enlarges (anabranching or thalweg avulsion), or over-bank, which may result in a channel cutoff (avulson).
- Difficulties in ice passage through channel confluences may initiate ice jamming at confluences. In turn, an ice jam may modify confluence bathymetry.

- By imposing additional flow resistance, a free-floating ice cover diminishes the effective gradient of flow energy available for sediment transport and alluvial-channel shaping. It consequently alters channel-thalweg alignment.

Ice jams, especially breakup ice jams, likely exert the greatest ice-hydraulic impact on unregulated alluvial channels. Mackay et al. (1974), for instance, describe the significant impacts that breakup ice jams exert on the Mackenzie River. For channels regulated by reservoirs used for hydropower generation during winter, ice-cover formation and presence can exert significant effects (e.g., Zabilansky et al. 2002). In overall terms, ice impacts have yet to be rigorously investigated, or even to be assessed quantitatively. Brief discussions of the impacts ensue.

(1) *Ice-Cover Influence on Local Elevation of Channel Bed.* A basic issue concerns an imbalance between unit rate of sediment supply to an ice-covered reach, q_s, and the sediment-transport capacity of that reach, q_{sI}. This issue involves the complex problem of spatially varied flow and sediment transport, with all its repercussions on local channel slope and morphology. If the sediment-transport capacity of an ice-covered channel, q_{sI}, were less than the rate at which sediment load is supplied to the channel, q_s, the bed elevation must rise locally. Conversely, if $q_{sI} > q_s$, the bed elevation must drop locally. The former condition usually would prevail for a floating cover, because bulk velocity of flow decreases. The latter condition may occur beneath when the cover is fixed or thick, or both, because the bulk velocity of flow is forced to increase substantially under the ice cover, with some flow spilling over the cover, as indicated in Figure 7-15. An ice jam, by constricting flow, may locally scour a riverbed, especially at the jam's toe (Neill 1976, Wuebben 1988b), as shown in Figure 7-13.

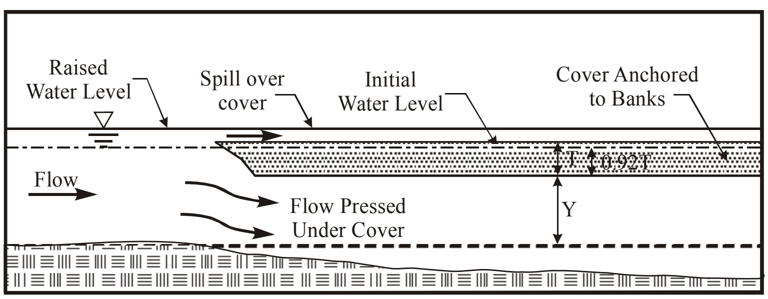


Figure 7-15. Flow in a channel reach constricted by a fixed ice cover.

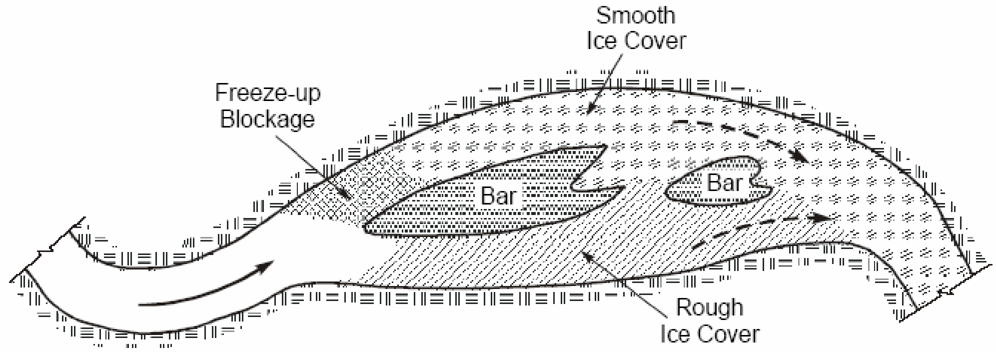
(2) *Channel Anabranching, Avulsions, and Cutoffs*. Channels with tight meander loops or with subchannels around numerous bars or islands are prone to ice-jam formation. Such channels typically have insufficient capacity to convey the incoming amount of ice. Their morphology may be too narrow, shallow, curved or irregular to enable drifting ice pieces to pass. Jam formation may greatly constrict flow, causing it to discharge along an alternate, less resistant course. Milburn and Prowse (1998), King and Martini (1984), and Dupre and Thompson (1979) suggest that ice-jam induced avulsion plays a major role in shifting the distributary channels of river deltas. Zabilansky et al.

(2002) indicate that ice-induced avulsions of subchannels may occur in sinuously braided reaches of the Missouri River.

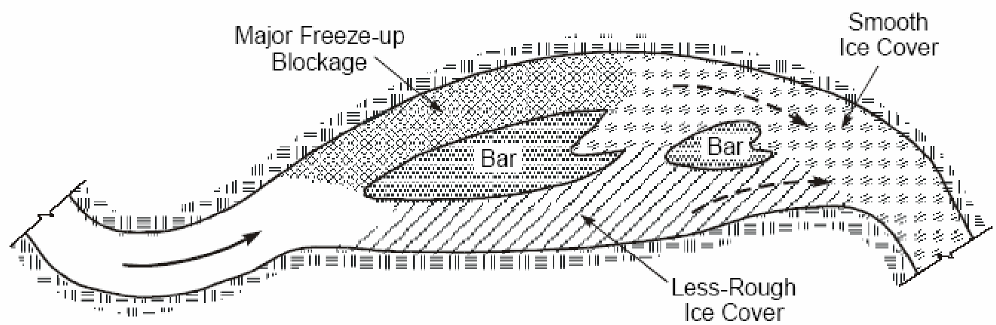
(*a*) At sites where the river flows in two or more subchannels, ice-cover formation can trigger a switch of the principal thalweg from one subchannel to the other. Figure 7-16 illustrates the processes involved. When a rougher ice cover formed in one subchannel, the cover partially diverted flow from that subchannel to the subchannel with the smoother ice cover. The subchannel with the smoother ice cover then enlarged while the rougher-covered subchannel reduced in size. Survey observations from the Fort Peck reach of the Missouri River (Zabilansky et al. 2002) suggest that thalweg switching is a recurrent process, and that switches may take a period of several winters to fully occur. Strictly speaking, such switching comprises a stochastic dynamic process that may be narrow-banded about a dominant period (e.g., a certain number of winters). It may also be broad-banded owing to several factors (e.g., variability of flow conditions during a year or during ice-cover formation).

(*b*) When an ice jam forms in a meander loop, upstream water levels may rise to the extent that flow proceeds over-bank and across the neck of a meander loop. If the meander neck comprises readily erodible sediment, and the flow is of sufficient scouring magnitude, flow diverted by the jam may result in a meander-loop neck cut, whereby a new channel forms through the neck, and the former channel is left largely cut off. A meander cut off shortens and steepens a channel reach, the consequences of which are felt upstream and downstream of the cut off reach. The net effect of ice jams, in this regard, is to reduce channel sinuosity. Mackay et al. (1974), for instance, cite examples of such events.

(*c*) If, on the other hand, the meander loop is wide and not easily eroded, over-bank flow resulting from an ice jam may have the reverse effect. Rather than the net consequence being the erosion of channel through the meander loop, over-bank flow may deposit sediment, thus raising bank height and reinforcing the meander loop. Eardley (1938) reports that ice jams cause substantial sediment deposition on the flood plain of the Yukon River. A similar event is reported in Simon et al. (1999) for the Fort Peck reach of the Missouri River. Over-bank deposition of sediment, together with ice-run gouging and abrasion of sediment erosion from the lower portion of a bank, may over-steepen riverbanks.



a. A relatively short initial accumulation of drifting ice in subchannel 1 may divert ice into subchannel 2, which then becomes extensively enveloped by a rough ice cover. Meanwhile, subchannel 1 freezes over with a smooth ice cover, or may remain partially open. The greater flow resistance in subchannel 2 causes flow to favor 1, which then enlarges.



b. A relatively long initial accumulation of drifting ice in subchannel 1 may divert ice and flow into subchannel 2, which becomes extensively covered by less rough ice. The greater flow resistance in subchannel 1 causes flow to favor subchannel 2, which then enlarges.

Figure 7-16. Ice-cover formation in a sinuous-braided channel may alternate the location of the major subchannel. Two scenarios of major subchannel were identified.

(3) *Channel Confluences*. By virtue of their role in connecting channels and, thereby, concentrating ice within a watershed, confluences are perceived as locations especially prone to the occurrence of ice jams. Fairly numerous accounts exist of jams in the vicinity of a confluence (Tuthill and Mamone 1997). Flow and ice concentration in a confluence may cause ice to jam within a confluent channel, within the confluence itself, or at some distance downstream of a confluence. Various mechanisms may trigger jams in the vicinity of confluences. Confluence bathymetry commonly leads to jam initiation, and, in turn, jamming can modify confluence bathymetry (Ettema and Muste 2001).

(4) *Cover Influence on Thalweg Alignment*.

(*a*) An ice cover reduces the effective energy gradient of flow (and thereby stream power) available for sediment transport and channel shaping. Therefore, cover formation may trigger a change in thalweg alignment. Such an influence is still a matter of conjecture, and indeed, is difficult to confirm from field or laboratory experiments because of the long durations involved. Zabilansky et al. (2002) present a hypothesis that elaborates this influence.

(*b*) The essential consideration here is that thalweg lengthening and branching are mechanisms whereby an alluvial-channel flow innately increases flow resistance (and thereby rate of energy use) to offset increased flow energy associated with a larger channel slope.

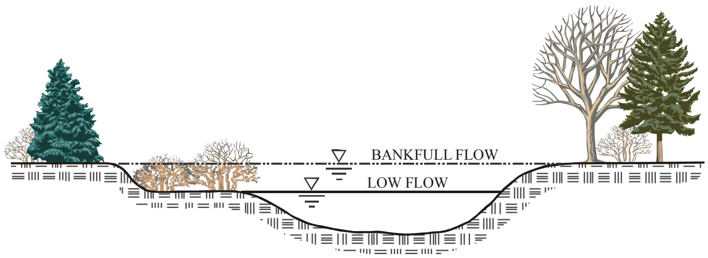
c. Impacts on Riverbanks. Ice may influence channel cross-section shape, alignment, and bed elevation through several geomechanic impacts on riverbanks:

- Reduce riverbank strength by increasing pore-water pressure or by producing rapid drawdown of bank water table during dynamic ice-cover or ice-jam breakup. This impact is part of the overall consequence of freeze–thaw behavior or riverbanks in frigid conditions.
- Tear, batter, and dislodge riverbank material and vegetation during collapse of bank-fast ice.
- Gouge and abrade riverbank material and vegetation during ice run.

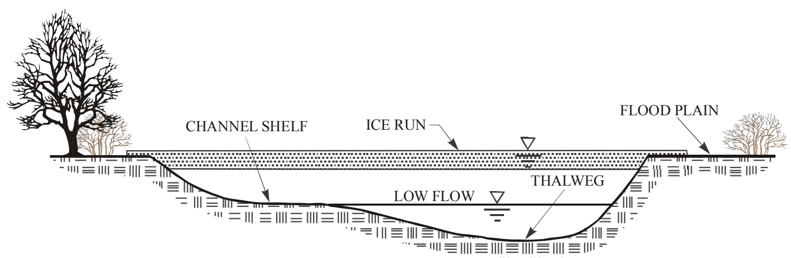
(1) *Introduction*.

(*a*) These impacts reduce riverbank resistance to erosion and increase the local supply of sediment to the channel. The first two impacts are not well studied. The third has received some attention, but the extent to which it affects channel shape is unclear. It is normal for river channels and floodplains subject to ice to be denuded of larger vegetation, as is sketched in Figure 7-17.

(*b*) Engelhardt and Waren (1991), for instance, briefly describe the consequences of such combined processes for the Missouri River in downstream of dams in Montana and North Dakota—increased rates of ice-covered flow, increased movement up and down riverbanks, bank freezing at higher elevation, and more frequent freeze–thaw cycles exacerbate bank erosion. The consequences become noticeable in early spring, when noticeably large portions of riverbanks fail. Zabilansky et al. (2002) report similar observations.



a. Rivers not subject to ice.



b. Rivers subject to ice.

Figure 7-17. Ice runs may inhibit vegetation growth along riverbanks and floodplains.

(2) *Freeze–Thaw Influences on Riverbank Strength*. It is well known that the freezing and thawing of soil affect the erosion of riverbanks adjoining rivers and lakes. Lawson (1983, 1985) and Gatto (1988, 1995), among others, provide extensive reviews of the subject. In short, because frozen soil is more resistant to erosion than is unfrozen soil, riverbanks are less erodible while frozen. The freezing and thawing of soil, however, usually weakens soils, making thawed (or thawing) riverbanks more susceptible to erosion. The net consequence on the overall rate of riverbank erosion, therefore, remains a matter of debate. Most likely, the net consequence varies regionally and from site to site.

(*a*) Freeze–thaw cycles affect soil structure, porosity, permeability, and density. These changes in soil properties can substantially reduce soil shear strength and bearing capacity; strength reductions of as much as 95% are reported (Andersland and Anderson 1990). Such adverse effects on soil strength depend on soil-particle size and gradation, moisture content, the number and duration of freeze–thaw cycles, and several other factors. Though there is no single, standard test to determine whether a soil is prone to significant weakening due to freeze–thaw (Chamberlain 1981), particle size is commonly used as an approximate indicator of soil sensitivity to freeze–thaw weakening. Soils containing fine sands and silts are especially sensitive, because they are permeable and susceptible to change in soil structure. By virtue of their particle size (about 0.1 to 0.06 mm[0.004 to 0.002 in.]), and the surface-tension property of water, fine sandy and silty soils absorb moisture more readily than do coarser or fine sediment. Clay soils are less sensitive because of their low permeability. The variability of soil properties along a riverbank, and within a specific riverbank location, causes the effects of riverbank freezing to differ along a reach.

(*b*) Gatto (1995) suggests that an eroding riverbank is especially subject to deep penetration of freezing, thereby making more of the riverbank prone to freeze–thaw weakening and erosion. The absence or stunted extent of vegetation that characterizes many eroding riverbanks results in diminished insulation protection of the riverbank and increased heat loss to air. In addition, the crest region of a riverbank experiences greatest heat loss, owing to the crest's exposure to air on at least two sides. Because of its exposure to wind, the crest may also accumulate less snow. Less snow, in turn, means deeper frost penetration during winter and faster thaw in spring. However, less snowmelt would be available to percolate into the riverbank. Questions exist about the exact manner in which border ice is anchored to the riverbank. Other factors—notably, variations in water-table (or piezometric) surface and moisture content of the top zone of the riverbank—would modify the extent of the frozen zone and its connection with river ice. Presumably, if the top portion of the riverbank and upland were dry, the riverbank crest might be the zone of least heat loss, as the distance between air and water table is greatest there.

(*c*) As the upper zone of frozen ground thaws, melt water likely drains down, over the surface of the still frozen ground. The riverbank, weakened by thaw expansion of ground and subject to the seepage pressures, is at its least stable condition.

(*d*) Several studies (e.g., Harlan and Nixon 1978, Reid 1985) have found that south-facing riverbanks experience lesser thickness of freezing, all else being equal, than do north-facing riverbanks. The explanation is that south-facing riverbanks (in the northern hemisphere) receive more insolation (energy in the form of short-wave radiation from the sun). South-facing riverbanks may also undergo more frequent diurnal freeze–thaw cycles (Gatto 1995, Zabilansky et al. 2002). The net effect on weakening of riverbank material of riverbank alignment has yet to be determined.

(3) *Reduction of Riverbank Strength.*

(*a*) Flow stage and stage fluctuations influence seepage pressures and the freeze–thaw behavior of riverbanks. Higher flow stage raises the water table in a riverbank, and a rapid drop in flow stage may momentarily reduce riverbank stability by increasing seepage pressures and, thereby, reducing the shearing resistance of the material composing the riverbank. Ice-cover formation raises flow stage, whereas cover breakup may abruptly lower it. River-ice formation, thereby, may weaken riverbanks.

(*b*) Riverbank freezing is closely linked to bankfast-ice formation along a channel, though the details of the relationship between them are unclear. They depend on riverbank condition (material, vegetation, snow, etc.), the relative elevations of water table and flow stage, and temperatures of groundwater and river water. The strength of bankfast-ice attachment to a bank depends on the relative elevations of the water table and flow stage, and on the relative water temperatures. A relatively warm (i.e., several degrees above the freezing temperature) flow of groundwater into the river will retard bankfast-ice growth and weaken its hold on the bank. The growth of a thick fringe of bankfast ice, on the other hand, may affect seepage flow through the bank, possibly constricting it, and slightly raising the water table. They are especially significant for regulated rivers, for which flows do not diminish during winter.

(4) *Bankfast-ice Loading of Bank.*

(*a*) Bankfast-ice weakening of banks is likely significant for steep banks, typically those banks comprising sufficient clay as to be termed cohesive. It is also likely significant for banks whose water table declines in elevation away from flow elevation in a channel, because the bankfast ice is less securely anchored into the bank. This erosion mechanism seems not to have been investigated heretofore but was observed—e.g., along the Fort Peck reach of the Missouri River (Zabilansky et al. 2002). When the flow stage in a channel drops, portions of an ice cover attached to a bank during the higher flow stage may be left momentarily cantilevered from the bank. The cantilevered ice soon collapses, weakening and wrenching bank material as it does so.

(*b*) Figure 7-18 illustrates how bankfast ice might weaken a bank. The ice cover freezes into the bank. The extent of the root is limited by groundwater elevation and temperature, and by the nature of the bank material. When the water level in the channel drops, and the ice cover breaks up, ice attached to the bank is cantilevered out from the bank, rotates, and tears a portion of the bank as it drops. It is difficult to get direct field observations of this mechanism for bankfast ice attached to vertical banks. For the moment, evidence for it is circumstantial.

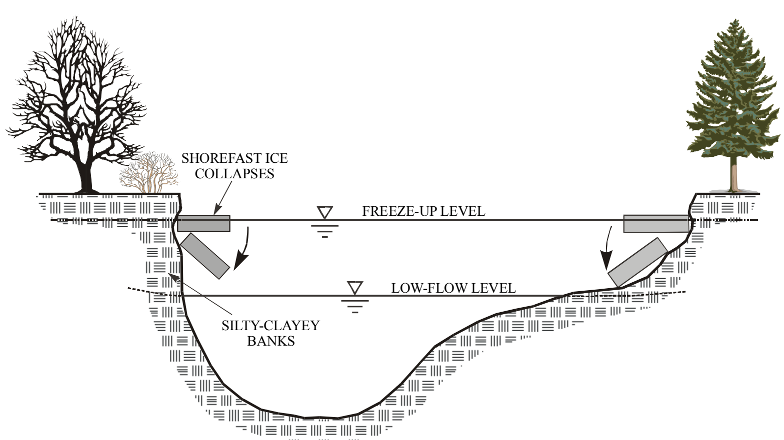


Figure 7-18. Collapse of shorefast ice may erode banks when flow stage is lowered

(5) *Gouging and Abrasion of Banks.* During heavy ice runs resulting from ice-cover breakup or ice-jam release, large pieces of ice may potentially gouge and abrade

channel banks. There exists significant evidence showing that it substantially affects channel-bank morphology subject to dynamic ice runs (Marusenko 1956, Walker 1969, Smith 1979, Hamelin 1979, Rosen 1979, Martinson 1980, Uunila 1997, Brooks 1993, Wuebben 1995, Wuebben and Gagnon 1995). Such channels are usually relatively steep and convey high-velocity flows. Moreover, their ice covers typically break up fairly dramatically in concert with a sudden rise in flow, attributable, for example, to rapid snowmelt or rain, or both. The resultant ice rubble comprises hard, angular blocks of ice.

(*a*) One study of 24 rivers in Alberta (Smith 1979) led to the intriguing hypothesis that ice runs enlarge channel cross sections at bank-full stage by as much as 2.6 to 3 times those of comparable flow rivers not subject to ice runs. The hypothesis is based on a comparison of the recurrence interval of bank-full flows in the 24 rivers and an empirical relationship between the cross-section area and flow rate for bank-full flow. The channel-widening effect of ice runs is plausible. However, the extent of widening indicated seems overly large, and requires further confirmation. Kellerhals and Church (1980), in a discussion of Smith (1979), argue against Smith's hypothesis. They suggest that other factors have led to an apparent widening of the channels analyzed by Smith; e.g., recent entrenchment of major rivers in Alberta, and ice-jam effects of flow levels. Moreover, it is possible that the banks are somewhat protected by a band of ice forming a shear wall flanking the riverbanks. It is interesting to contrast Smith's hypothesis with a further hypothesis, mentioned above, that ice jams may promote channel narrowing by causing over-bank flow (e.g., Uunila 1997). For channels whose dominant channel-forming flow coincides with ice-cover breakup, over-bank loss of flow reduces the flow rate to be accommodated by the channel.

(*b*) In many situations, notably those in which an ice run is sluggish, a shear wall of broken ice may fend moving ice from contacting the bank (Figure 7-19). The shear wall usually becomes smooth-faced, and protects riverbanks from direct ice impact or gouging. Running ice, if sufficiently thick, may still gouge the lower portion of a bank. Significant gouging may occur downstream of the toe of a jam, before the arrival of sufficient ice rubble to form shear walls. A surge front from a released jam may fracture an ice cover into large slabs, which are then set in motion. The surge front typically moves faster than the ice rubble composing the jam, but gradually attenuates. Typically, ice gouging occurs within a relatively short reach of a river.

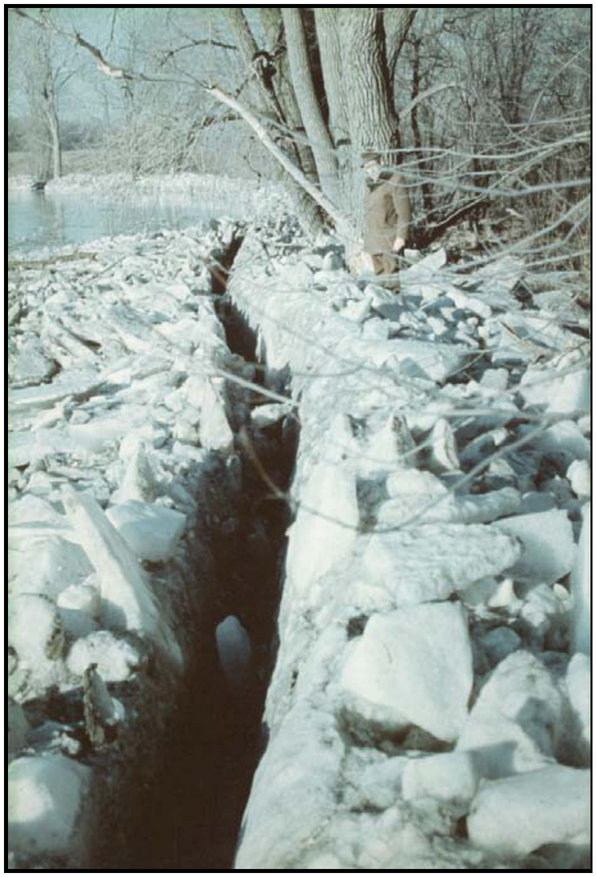


Figure 7-19. Ice shear wall along riverbank.

(*c*) Ice gouging and abrasion, though, can be severe for channel features protruding into the flow. In addition, channel locations with a substantial change in channel alignment are especially prone to ice-run gouging and abrasion; e.g., a sharp bend, point bar, and portions of a channel confluence. There is a little information on how ice runs affect the local morphology of these sites. Two features have been observed in gravely rivers—ice-push ridges and cobble pavements. Ice-push ridges form when a heavy ice run gouges and shoves sediment along the base of banks (e.g., Bird 1974). The gouged sediment piles up as ridges beneath the ice run as it comes to rest as a jam. The finer sediments eventually get washed out, leaving the more resistant gravel and boulders in ridges. The ridges usually develop in the vicinity of locations subject to recurrent ice jams.

(*d*) Cobble pavements may cover bars and the lower portion of banks subject to ice gouging and abrasion. Essentially, an over-riding mix of ice and cobbles removes the finer material from the surface of the bars or banks. The resultant cobble surface comprises cobbles whose major axis is aligned parallel to the channel and whose size gradually decreases downstream (Mackay and Mackay 1977). The resultant cobble pavement may extend for many miles along the banks of large northern rivers, such as the Mackenzie and Yukon Rivers (Kindle 1918, Wentworth 1932).

(*e*) The gouging and abrasion of the lower portion of banks, in conjunction with over-bank sediment deposition during ice-jam flooding, may produce an elevated ridge or bench feature along some northern rivers. These features have been dubbed bechevniks for Siberian rivers (Hamelin 1979). A bechevnik is the marginal strip composing the lower portion of a riverbank and exposed portion of adjoining river bed that, in days gone by, formed convenient paths for towing boats upstream manually or by horse; becheva apparently is Russian for towrope. Figure 7-20 illustrates the main features of a bechevnik, which may form partly from ice abrasion and partly from the deposition of sediment and debris left by the melting of ice rubble stranded after ice runs.

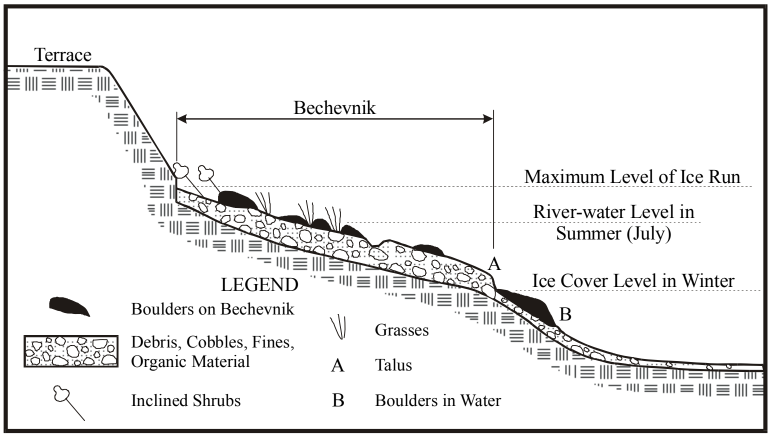


Figure 7-20. Sketch of a bechevnik (after Hamelin 1979).

(*f*) Ice-run gouging and abrasion have an important, though as yet not quantified, effect on riparian vegetation that, in turn, may affect bank erosion and channel shifting. Where ice runs occur with about annual frequency, riparian vegetation communities have difficulty getting established. Ice abrasion and ice-jam flooding may suppress certain vegetation types along banks, as illustrated in Figures 7-17 and in 7-20 for a bechevnik, possibly exacerbating bank susceptibility to erosion. This aspect of river ice has yet to be further investigated. Scrimgeour et al. (1994) and Prowse (2001) provide useful early reviews.

(*g*) Moving ice may also grind banks formed of soft rock (e.g., sandstones and mudstones) or stiff clay. Danilov (1972) and Dionne (1974), for instance, describe how moving ice has affected rock banks of rivers like the St Lawrence River. The extent of erosion, though, is less than for banks formed of alluvial sediment.

d. Combined Impacts. One hydraulic or geomechanic impact of river ice may disturb a channel, but not necessarily destabilize it. A combination of hydraulic and geomechanic impacts, though, may destabilize a channel. A shift in thalweg alignment or a bank failure, alone, may not destabilize a channel. The channel may adjust back to more or less its stable open water condition once open water conditions resume.

(1) Channels usually considered less stable in open water conditions are more likely to be adversely affected by river ice. Sinuous-point-bar, sinuous-braided, and braided alluvial channels are especially prone to river ice impact, especially if they have steep banks, formed of fine and partially cohesive sediments. The thalwegs of such channels usually lie close to the outer banks of bends, and the banks themselves are prone to bankfast-ice loading, lack of vegetation cover (typical of eroding banks), and freeze–thaw weakening. Figure 7-21 illustrates this susceptibility. The thalweg lies close to the bank, such that the flow continually erodes the bank-toe, thereby keeping the bank steep, and possibly undercutting the bank. Snow cannot protectively blanket the bank face. Frost penetration is potentially deep, the water table is held relatively high, and the channel shifts, destabilized.

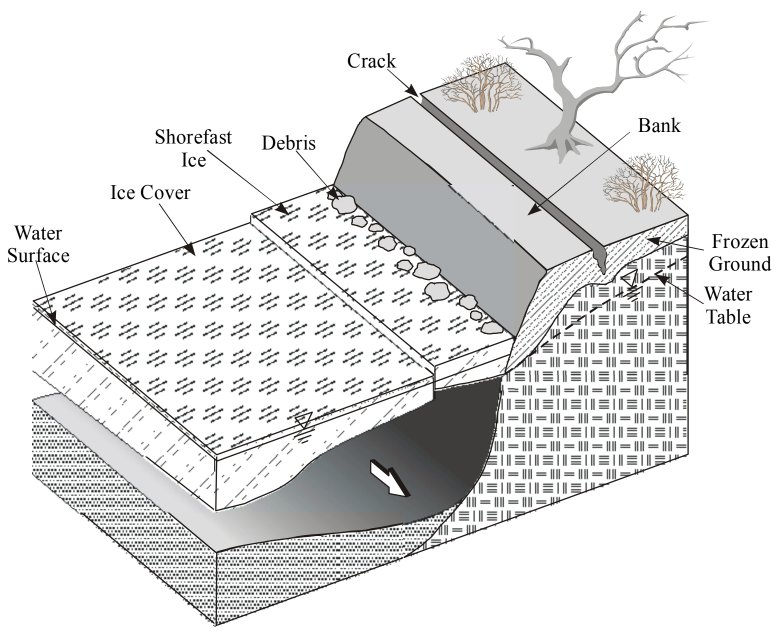


Figure 7-21. Combined hydraulic impacts (e.g., thalweg shift and bank-toe erosion) and geomechanic impacts (e.g., freeze–thaw weakening of bank material, elevated seepage pressures, bankfast-ice loading) may weaken and erode channel banks, especially along channel bends, and result in continual, overall channel destabilization.

(2) An intriguing question is whether the destabilizing impacts of river ice uniquely modify alluvial-channel morphology. An answer can only be tentatively suggested at this moment. It is likely that the major geometric parameters do not change appreciably (e.g., channel thalweg sinuosity, width, hydraulic radius, meander radius). However, river ice likely increases irregularities in channel planform and the frequencies with which channel cross section and thalweg alignment shift.

7-6. References

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None.

b. Related publications.

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Chapter 8
Bearing Capacity of Floating Ice Sheets

8-1. Introduction

In cold regions, ice covers on rivers, lakes, and seas are often used as temporary roads, bridges, airfields, and construction platforms. For these uses, it is important that there be a sufficient margin of safety between the breakthrough loads and the actual loads placed on a floating ice sheet. This chapter discusses the bearing capacity of floating ice sheets of any given thickness, or how to determine the required ice thickness for a given load.

a. The thickness of an ice sheet can be either measured by drilling holes in it or estimated for a location from atmospheric temperature data and the theoretical formulas presented in Chapter 2 of this manual.

b. At times, the actual ice thickness at a location is less than the required minimum ice thickness for a given load. A common practice to increase ice thickness is to plow the snow off the path chosen for a road. Removing the snow allows the ice sheet to grow faster, and thus increases the bearing capacity at those locations. However, the plowed snow banks become loads on the ice sheet, and they provide extra insulation to the ice at those locations, which retards ice thickness growth. Both effects can decrease safety.

c. Another common practice to increase ice thickness is by flooding and freezing in a prescribed series of steps. The literature gives examples of thickening a natural ice cover by flooding and freezing in thin layers, after which the ice has held loads as heavy as 5 meganewtons (MN) (500 tons) for 30 days and longer. However, such operations need careful planning and execution.

8-2. Bearing Capacity of Ice Blocks

The main source of bearing capacity for a floating ice sheet is its buoyancy, or the hydrostatic pressure on its bottom, because the density of ice is less than the density of liquid water. For a centrally placed or a uniformly distributed load P on an area A of an ice block (Figure 8-1), the equilibrium equation of the forces in the vertical direction is given by

$$P + Ah\gamma_i = Az\gamma_w \qquad \text{for } z < h \tag{8-1}$$

where

γ_i = specific weight of ice
γ_w = specific weight of water
h = ice thickness
z = depth of submergence.

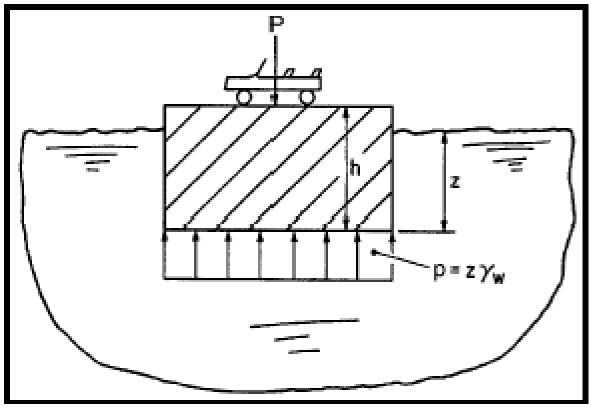

Figure 8-1. Equilibrium of forces on an ice block.

When $P = 0$, we get the depth of submergence z_o under no load, and it is given by:

$$z_o = (\gamma_i/\gamma_w)h.$$

The difference $h - z_o$ is known as the freeboard, which is associated with the bearing capacity of an ice block. When $z = h$, we get the maximum load P_{max} that can be placed on the ice block without submergence, and it is given by:

$$P_{max} = Ah(\gamma_w - \gamma_i). \qquad (8\text{-}2)$$

a. When the resultant of the load is not centrally placed on the ice block, the ice block will tilt. This will result in a linearly varying pressure p at the bottom surface of the block. The bearing capacity for this case may be determined as done previously, except that now, in addition to vertical equilibrium, the moment equilibrium has to be considered. Note that when the eccentricity of the load resultant exceeds a certain limit, namely when the loading moment is larger than the restoring moment, the ice block will tip over. When the load is dynamic, the analysis is more involved. Then, the equations of motion for the ice block have to be coupled with the dynamic equations for the fluid base.

b. To illustrate the use of the above equations, let us determine the bearing capacity of an ice block having a thickness of 1 meter (3.28 feet) and an area of 10 meters^2 (107.6 feet^2). The specific weights of water and ice are given by

$$\gamma_w = \rho_w g$$

$$\gamma_i = \rho_i g$$

where

ρ_w = density of water
ρ_i = density of ice
g = gravitational acceleration.

Assuming ρ_w = 1000 kg/m^3, ρ_i = 918 kg/m^3 and g = 9.81 m/s^2 (or, $\rho_w g$ = 62.4 lbf/ft^3 and $\rho_i g$ = 57.3 lbf/ft^3), we get the bearing capacity of the ice block P_{max} = 8.04 kN (1808 lbf) from Equation 8-2.

c. Another example to illustrate the use of Equation 8-2 is to find the area of a 0.6-meter-thick (2-feet-thick) ice block needed to safely carry a load of 13.34 kN (3000 lbf). Using the same values for specific weights, we get

$$A = 13340/\{0.6 \times (1000 - 918) \times 9.81\} = 27.65 \text{ m}^2 \text{ (297 ft}^2\text{)}$$

which is a square area of about 5.26 meters (17.25 feet) per side.

8-3. Bearing Capacity of Floating Ice Sheets

When a large floating ice sheet is loaded vertically over an area, the deformation of the ice in the vicinity of the applied load causes slightly higher water pressure $p(x,y)$ under the ice sheet than the pressure p_o (=$\rho_i gh$) at farther distances (Figure 8-2). With Archimedes' principle, it can be shown that, for large ice sheets, the applied load is equal to the weight of displaced water caused by the deformation of the floating ice sheet. For quasi-static loading, this condition of equilibrium is satisfied at all times. Thus, the buoyancy force supports the load, and the ice sheet merely deforms to distribute the load over a large area. The deformation of the ice sheet generates stresses that can lead to its failure, and thus destroy the ability of the ice sheet to distribute the load.

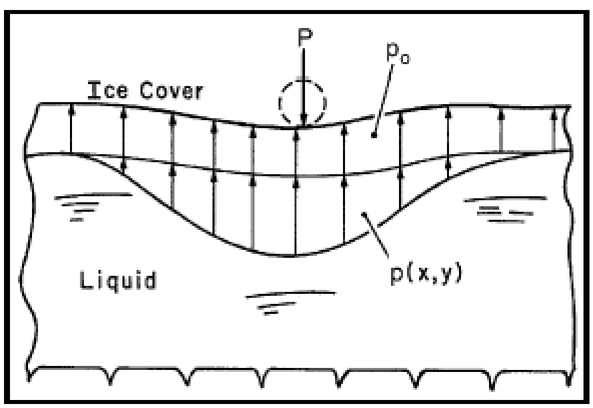

Figure 8-2. Hydrostatic pressure from a load on an floating ice sheet.

a. Because floating ice sheets exist at temperatures close to ice's melting point, it is a common experience that ice responds to applied loads by elastic and creep deformations simultaneously. During uniaxial tests at low strain rates (below 10^{-4} s^{-1} in compression and 10^{-5} s^{-1} in tension), ice deforms mostly by creep, and creep strains are generally larger than elastic strains. At high strain rates during uniaxial tests, most of the deformation in ice is elastic (because it takes time to develop creep deformation), and the failure of ice specimens is by fracture. The interplay between creep and elastic deformations, coupled with the low fracture energy required to propagate a crack, causes ice to fail in both the ductile and brittle manners with a strong dependence on strain rate, making predictions of the bearing capacity of floating ice covers very complex.

b. Because of the creep and elastic deformations and the inertial effects of underlying water, the loading on a floating ice sheet can be categorized as one of the following three types:

(1) Short-term loads, such as those imposed by slowly moving vehicles or by the placement of a load by a crane for a short time.

(2) Moving loads that are fast enough to excite the ice–water system to deflect much more than would be the case for a static load.

(3) Long-term loads, such as those imposed by parked vehicles, stored material, or drilling rigs.

In the following paragraphs, each of the three types of loading is separately discussed because of significant differences in the response of the ice sheet to these loads.

8-4. Analytical Methods for Short-Term Loads

Under this type of loading, ice behaves as an elastic, brittle material, and the ice–water inertial forces are negligible. The floating sheet can be thought of as an elastic plate resting on an elastic foundation, and its deflection is governed by the differential equation

$$D\nabla^4 w + \gamma_w w = q \qquad (8\text{-}3)$$

where

D = $Eh^3/[12(1-\nu^2)]$ (flexural rigidity of the plate)
E = effective elastic modulus of ice
h = ice thickness
ν = Poisson's ratio for ice
∇^4 = biharmonic operator [e.g., $(\partial^4/\partial x^4) + 2(\partial^4/\partial x^2\partial y^2) + (\partial^4/\partial y^4)$ in Cartesian coordinates]
w = vertical deflection of a point on the ice sheet
γ_w = specific weight of water
q = load per unit area on the ice sheet.

Equation 8-3 leads to the definition of characteristic length:

$$L=(D/\gamma_w)^{1/4}. \qquad (8\text{-}4)$$

Figure 8-3 shows plots of L versus h for various values of the effective elastic modulus E, for a value of Poisson's ratio $\nu = 0.3$.

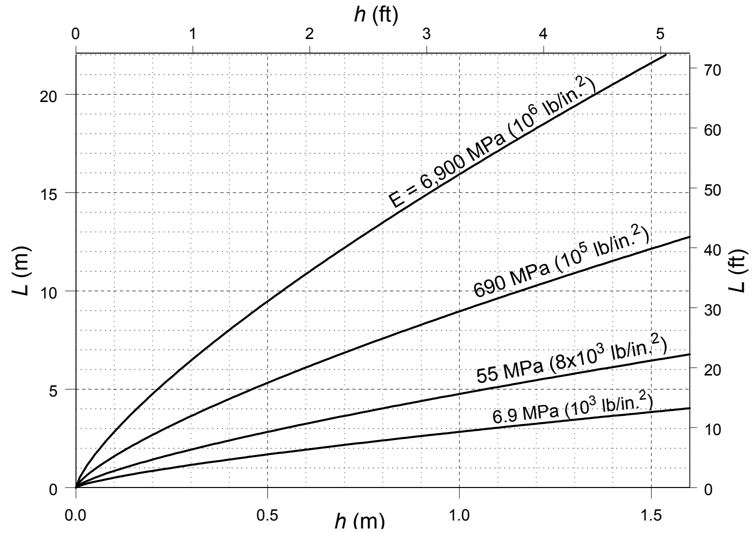

Figure 8-3. Plots of *L* versus *h* for various values of *E*.

a. A solution for Equation 8-3, which satisfies a given set of boundary conditions, can be obtained for a particular loading q, and the stresses can be obtained from the solution. The maximum tensile stress σ_{max} at the bottom of an infinite plate on elastic foundations is given by:

$$\sigma_{max} = CP/h^2 \qquad (8\text{-}5)$$

where

P = total, downward acting load uniformly distributed over a circular area of radius a

h = plate (ice) thickness

C = $0.275(1 + \nu) \log_{10} \{(Eh^3)/(\gamma_w b^4)\}$

b = $(1.6a^2 + h^2)^{1/2} - 0.675h$, when $a < 1.724h$, or $b = a$, when $a > 1.724h$.

The coefficient C is obtained from the theory of thick plates, and it does not go to infinity for concentrated loads as in the case of results from the theory of thin plates. Figure 8-4 shows plots of C versus a/L for $\nu = 0.3$ and various ratios of h/L. As shown in Figure 8-4, the maximum stress σ_{max} decreases with increasing radius a for the same load and ice thickness.

b. If a load P is applied uniformly over a square area, a by a, at the edge of a semi-infinite floating ice sheet, the maximum tensile stress can be obtained by Equation 8-5, but the constant C in Figure 8-4 is much higher than that for infinite ice sheets. If there are any wet cracks in the ice sheet, it should be treated as semi-infinite. If a load moves onto the edge of a floating ice sheet, care must be exercised to make sure that it is not large enough to create a crack at and perpendicular to the edge. The plot in Figure 8-4 also shows a decrease in the maximum stress at the edge if the load is distributed over a larger area.

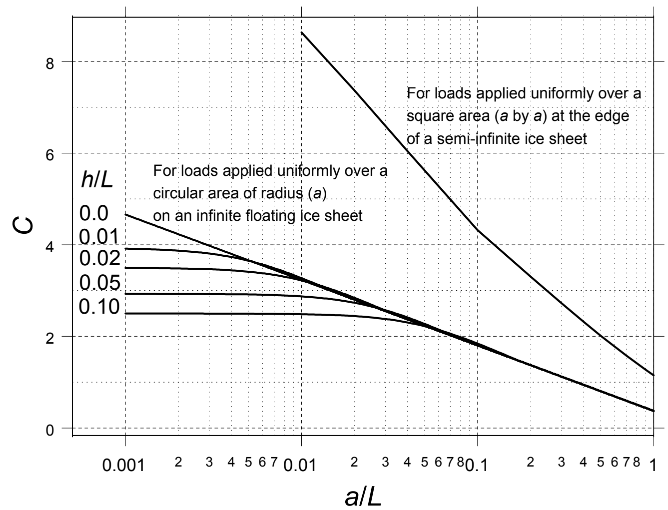

Figure 8-4. Plots of *C* versus *a*/*L* for various values of *h*/*L*.

c. To superpose the stresses from many loads on an infinite floating ice sheet, use the following procedure. The stress σ caused by a load applied at a distance x from the point of loading is given by:

$$\sigma = \sigma_{max} \exp\left(-\frac{x}{0.691L}\right) \tag{8-6}$$

The total stress at a point attributable to loads P_0, P_1, P_2, ..., P_n located at distances $x_0(= 0)$, x_1, x_2,..., x_n is obtained at the point x_0 by adding the stress contributions from all loads:

$$\sigma_{total} = \sigma_0 + \sum_{i=1}^{n} \sigma_i \exp\left(-\frac{x_i}{0.691L}\right) \tag{8-7}$$

d. A safe, proven value of the maximum stress of 550 kPa (80 psi) has worked for the designs of floating platforms of sea ice, but a value of 690 kPa (100 psi) can be assumed for freshwater ice. Field experience with drilling platforms suggests the following values of the effective elastic modulus: 690 MPa for calculations of deflections and stresses immediately after placement of a load and 55 MPa for calculations of deflections at a long time after placement of a load (these values of effective elastic moduli are close to those measured by 3-meter-long [10 foot-long] strain gages used at five levels in a 7-meter-thick [22-foot-thick] ice platform). The maximum tensile stress, which depends on the distributions and distances of the loads from each other, is the immediate elastic response to a load placement, and it decreases with the passage of time because of the creep deformation of ice.

e. To illustrate the above procedure, let us determine the load-carrying capacity of a 30.5-centimeter-thick (12-inch-thick) freshwater ice sheet, assuming that the flexural strength and effective elastic modulus of ice are, respectively, 690 kPa (100 psi) and 690 MPa (10^5 psi) and that the load is distributed over a circular area of radius 100 centimeters (40 inches). From Figure 8-4, we get a value of L = 3.7 meters (12 feet) for h = 0.305 meters (12 inches) and E = 690 MPa (10^5 psi). For values of a/L = 0.1/3.7 = 0.27 and h/L = 0.305/3.7 = 0.083, we get a value of C = 1.19. Substituting values of C = 1.19, σ_{max} = 690 kPa (100 psi) and h = 0.305 meters (12 inches) in Equation 8-5, we get an estimate of the safe load P = 54.11 kN (12160 lbf).

f. To see the effect of load distribution on the bearing capacity, let us now determine the load-carrying capacity of the same ice sheet as in the above example, except that the load is distributed over a circular area of radius 10 centimeters (4 inches) instead of 100 centimeters (40 inches). The value of L = 3.7 meters (12 feet), as given above. For values of a/L = 0.1/3.7 = 0.027 and h/L = 0.305/3.7 = 0.083, we get a value of C = 2.5. From Equation 8-5, we get an estimate of the safe load $P = (690 \text{ kN m}^{-2})(0.305 \text{ m})^2/2.5$ = 25.67 kN (5772 lbf), which is less than half the value of safe load obtained above.

g. To estimate a load P that is uniformly distributed over a square area (20 × 20 centimeters [8 × 8 inches]) at the edge of a semi-infinite ice sheet, we get a value of C equal to 5.5 for the value of a/L = (0.2/3.7) = 0.054. The safe load P placed at the edge of a semi-infinite ice sheet is only 11.67 kN (2624 lbf) for σ_{max} = 690 kPa (100 psi).

h. The analytical methods for short-term loads presented in this paragraph compute the maximum tensile stress immediately after placement of a load on a floating ice sheet, and the use of these procedures can only lead to prediction of the loads to cause the first crack in the sheet. If the elastic stress exceeds the tensile strength, radial cracks form around the load. If the load on an ice sheet continues to increase, several circumferential cracks form before breakthrough takes place. For safe placement of loads during any operation on floating ice sheets (i.e., to prevent radial cracks from forming under the load), plans should include estimating the maximum tensile stresses, which should not exceed the tensile strength of the ice. This is a conservative approach to estimating the bearing capacity of floating ice sheets, because the breakthrough loads are generally higher than the load necessary to cause the first crack in the ice sheet.

8-5. Empirical Methods for Short-Term Loads

Data compiled on the failure loads and thicknesses of ice covers during logging and other operations indicate that breakthrough loads depend on the square of the ice thickness. By having an adequate factor of safety, a safe short-term load on a floating ice sheet can be obtained from the breakthrough loads. A load obtained by this procedure may produce radial cracks in the ice sheets, but the wedging action of a radially cracked ice sheet supports the load for a short duration of time.

a. A simple empirical formula for the loads created by single vehicles is

$$P = Ah^2 \quad (8\text{-}8)$$

where

P = allowable load
h = effective ice cover thickness

A = coefficient that depends on the quality of the ice, the ice temperature, the geometry of the load, the kind of units used, and the factor of safety.

b. To ensure safe movement of single vehicles crossing lake or river ice at temperatures below 0°C (32°F), the straightforward and practical formulas $P = h^2/16$ or $h = 4\sqrt{P}$ have been used for decades. These formulas are for English units in which P is in tons (2000 lbf) and h is in inches. Although not strictly equivalent, similar practical formulas for SI units are $P = h^2/100$ or $h = 10\sqrt{P}$, where P is in metric tons (1000 kgf, or 2205 lbf) and h is in centimeters, and $P = h^2$ or $h = \sqrt{P}$, where P is in meganewtons (MN) and h is in meters. All these formulas are for black ice below 0°C (32°F), and appropriate adjustments to thicknesses to account for snow ice should be computed as given below. The following are illustrative examples of Equation 8-8.

c. Determine the allowable load of an ice cover with the smallest ice thickness h = 25.4 centimeters (10 inches).

$$P = \frac{h^2}{16} = \frac{10^2}{16} = 6.25 \text{ tons.}$$

In metric units, this is

$$P = \frac{25.4^2}{100} = 6.45 \text{ metric tons.}$$

d. Determine the smallest ice thickness needed to safely carry one person of weight P = 200 lbf = 0.1 ton (90.7 kgf = 0.0907 metric ton).

$$h = 4\sqrt{0.1} = 1.26 \text{ inches}$$

Expressed in metric units, the required thickness is

$$h = 10\sqrt{0.0907} = 3 \text{ centimeters.}$$

e. Based on Equation 8-8, Table 8-1 lists the safe minimum values of ice thickness for tracked and wheeled vehicles on clear, sound ice. The last column of Table 8-1 lists the safe distance that should be maintained between vehicles to avoid superposition of stresses from two loads. These distances are about 100 times the required minimum ice thickness. For an ice thickness greater than the minimum required thickness, the spacing between the loads can be reduced. When driving a vehicle on an ice sheet, checking the ice thickness at regular intervals along the intended path is recommended. This should be done every 45 meters (150 feet), or more frequently, if the ice thickness is quite variable. There are several additional points to consider.

(1) If white, bubble-filled ice makes up part of the ice thickness, this part should be considered equivalent to half as much clear ice. For example, if a 76.2-centimeter-thick (30-inch-thick) ice sheet is composed of 25.4 centimeters (10 inches) of white ice and 50.8 centimeters (20 inches) of clear ice, the white ice should only be considered as 12.7 centimeters (5 inches) thick, giving an equivalent thickness of clear ice to be 50.8 + 25.4/2 = 63.5 centimeters (20 + 10/2 = 25 inches) for the computation of the safe load on that ice sheet.

(2) If there has been a large snowstorm, the snow represents a new load on the ice. If the new snow is sufficiently heavy, it will depress the whole ice sheet to a level where the top surface of the ice sheet is below the water level. Water then usually seeps through the cracks in the ice sheet and saturates the lower layers of the snow cover. Stay off the ice sheet until this slush freezes completely. When that happens, the frozen slush becomes an added thickness of white ice.

(3) Contrary to what many think, a rapid and large drop in air temperature causes an ice sheet to become brittle, and it may not be safe to use the ice sheet for 24 hours.

(4) If the air temperature stays above freezing for 24 hours or more, the ice begins to lose its strength, and the values given in Table 8-1 do not represent safe values. This becomes the general condition during springtime. No quantitative guidance can be offered for this situation. When this happens, any ice cover is unsafe for any load.

Table 8-1
Approximate Ice Load-Carrying Capacity (Note: Read the text before using this table)

Type of Vehicle	*Total Weight Metric tons (tons)*	*Necessary thickness* at average ambient temperatures for three days cm (in.)*		*Distance between vehicles m (ft)*
		0 to –7°C (32 to 20°F)	*–9°C and lower (15°F and lower)*	
Tracked	6 (6.6)	25.4 (10)	22.9 (9)	15.2 (50)
	10 (11.0)	30.5 (12)	27.9 (11)	19.8 (65)
	16 (17.6)	40.6 (16)	35.6 (14)	24.4 (80)
	20 (22.0)	45.7 (18)	40.6 (16)	24.4 (80)
	25 (27.6)	50.8 (20)	45.7 (18)	30.5 (100)
	30 (33.1)	55.9 (22)	48.3 (19)	35.1 (115)
	40 (44.1)	63.5 (25)	55.9 (22)	39.6 (130)
	50 (55.1)	68.6 (27)	63.5 (25)	39.6 (130)
	60 (66.1)	76.2 (30)	71.1 (28)	45.7 (150)
Wheeled	2 (2.2)	17.8 (7)	17.8 (7)	15.2 (50)
	4 (4.4)	22.9 (9)	20.3 (8)	15.2 (50)
	6 (6.6)	30.5 (12)	27.9 (11)	19.8 (65)
	8 (8.8)	33.0 (13)	30.5 (12)	32.0 (105)
	10 (11.0)	38.1 (15)	35.6 (14)	35.1 (115)

* Freshwater ice.
When the temperature has been 0°C (32°F) or higher for a few days, the ice is probably unsafe for any load.

8-6. Moving Loads

a. When a load moves on an ice sheet fast enough (more than 15 km/hr or 10 mph), the inertia forces generated by the movement of the ice sheet and the underlying water modify the deflections and stresses obtained from Equation 8-3 for the short-term load. For a slow-moving load, the deflection bowl in the ice sheet moves with it, and the underlying water must continually be moved aside by the bowl in a way similar to a shallow-draft boat. As for a boat, movement of the deflection bowl generates waves in the ice–water system. If the celerity of these waves is the same as the vehicle speed, the deflection and the stresses in the ice sheet are amplified, similar to resonance in an oscillating system. The critical speed at which such amplifications take place depends on the water depth H and the characteristic length L of the floating ice sheet. For deep water ($H>L$), the critical speed $u_c = 1.25\ (gL)^{1/2}$, where g is the gravitational acceleration. For shallow water ($H<L$), the critical speed $u_c = (gH)^{1/2}$. The critical speed u_c depends on the characteristic length L, which depends on the ice thickness. However, it is independent of the ice thickness in shallow water, in which water depth H is less than the characteristic length L. Because of the amplification of deflections and stresses in the ice sheet, vehicles should not approach the critical speeds.

b. As an example, let us consider 0.305-meter-thick (1-foot-thick) ice sheet, and its effective elastic modulus is 690 MPa (10^5 psi). From Figure 8-3, we get the value of characteristic length L equal to 3.7 meters (12 feet). For deep water, the critical speed of the ice–water system $u_c = 1.25(gL)^{1/2} = 7.5$ m/s (27 km/h or 16.8 mph). For water depth equal to 2 meters (shallow water), the critical speed $u_c = (gH)^{1/2} = 5.5$ m/s (20 km/h or 12.4 mph).

8-7. Long-Term Loads

When a load is placed for a long time on a floating ice sheet, there is an immediate elastic deformation of the ice, followed by permanent creep deformation. The long-term effect of creep deformation is that the vertical deflection of the loaded area increases with time, and the deflection rate is a nonlinear function of the applied load. If the load is not large, the displacement rate is small, leading to safe placement of the load for a long time. However, a high deflection rate for a large load may lead to the failure of ice sheets after a certain time. There is a need to determine the duration of time that a particular load can safely be placed on an ice sheet.

a. For time-dependent deflections less than the freeboard, elastic equations (e.g., Equation 8-3) describe the deflections of the ice sheet in the vicinity of a load, but the characteristic length, which depends on the elastic modulus E, decreases continuously with time. The maximum elastic deflection δ under a load P is given by:

$$\delta = P/(8\rho_w g L^2). \qquad (8\text{-}9)$$

b. For example, let us again consider a 30.5-centimeter-thick (12-inch-thick) ice sheet with a load P equal to 25.67 kN (5772 lbf). The short-term deflection at the load is estimated by assuming the effective elastic modulus to be 690 MPa (10^5 psi), and we get L= 3.67 meters (12 feet), and $\delta = (25{,}670)/(8 \times 9806.6 \times 3.67^2) = 0.024$ meters (6.95 inches), which is almost equal to 0.08*h*, the freeboard of the ice sheet. If this load were to be left on that ice sheet for any length of time, the permanent deflection after the elastic deflection takes place would cause the top surface to be below the water surface, creating the possibility of water seeping through cracks and flooding the loaded area. To estimate the long-term deflection, we assume the effective elastic modulus $E = 55$ MPa, and we get $L = 1.95$ meters. Limiting the maximum deflection δ to the freeboard, which is assumed to be 0.08 times the ice thickness, we get an estimate of the long-term load for the ice sheet $P_{\text{long-term}} = 8\rho_w g L^2(0.08h)$. = (8)(1000 kg/m^3)(9.81 m/s^2)(3.7 m)^2(0.08×0.305 m) = 7.3 kN (1640 lbf). These estimates of the loads indicate that the long-term load is about three to four times smaller than the short-term load on an ice sheet.

c. According to available field observations, limiting the maximum deflection of a statically loaded ice cover to the freeboard results in a safe condition. In a field situation, one needs to continuously monitor the remaining freeboard of an ice sheet for long-term storage of a load. A recommended field practice is to drill a hole in the ice sheet near the load and check the freeboard, which is the distance between the water level in the hole and the top surface of the ice sheet. If the water begins to flood the top surface of the ice sheet, it is necessary to move the load immediately to prevent breakthrough attributable to long-term creep deformation of the ice. Another method for predicting the onset of failure is based on the energy method, which requires measurement of the deflection of the ice sheet at the load and keeping a record of the load placed on it. The results of such monitoring effort also give estimates of the safe storage time.

8-8. References

a. Required Publications.

None.

b. Related Publications.

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Ice Engineering Exchange Bulletin, Number 13, U.S. Army Cold regions Research and Engineering Laboratory, Hanover, New Hampshire

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Chapter 9
Model Tests in Ice

9-1. General

a. The need for physical modeling of a river hydraulic problem arises when the available analytical or numerical solution techniques are inadequate to describe either the processes involved or important details of those processes. Such instances may be ascribable to complex boundary conditions, multi-dimensional flow patterns, or imprecisely understood processes. Physical modeling may then provide a useful alternative, either by itself or in a hybrid approach using both numerical and physical modeling.

b. Small-scale laboratory modeling of hydraulic structures (locks, dams, weirs, spillways, etc.) and vessels under open-water conditions is now common, and the modeling laws, criteria, and techniques are well established (Yalin 1971, USDI 1980). The presence of ice brings serious complications to small-scale modeling because it adds a boundary at the top of the water body having surface characteristics that are different from those of the bed of the waterway. Moreover, whenever the mechanical properties of ice affect the problem under study, these must be reproduced in the model. The basic principle of dynamic similitude or modeling is to reproduce in the model the forces that govern the problem under consideration. The ratio between any two forces (gravity forces, inertia forces, viscous forces, shear forces, mechanical forces, etc.) should be the same in the model as in the prototype. Except for a few cases, all these forces usually play some role in the actual physical phenomena of interest. Thus, strict adherence to the principle of dynamic similitude will lead to the conclusion that the phenomena can only be studied at full scale. It then becomes necessary to relax the principle of similitude, and to choose to model exactly only those forces that primarily affect the problem under consideration. Simultaneously, the "scale effects," or errors introduced by imperfect modeling of the secondary forces, are held to a minimum by judicious model design. Therefore, it is important at the outset to correctly identify the primary forces that govern a particular phenomenon before attempting to study it in a physical model. This must be done to decide whether the necessary modeling techniques are available and how the model data can be extrapolated to full scale. In the present state of the art of ice modeling, phenomena that are strongly affected by heat transfer—e.g., refreezing of broken ice, icing of structures, and the like—are not amenable to physical modeling.

9-2. General Similitude Considerations

A model is said to be in complete similitude if it is geometrically, kinematically, and dynamically similar to the prototype. Geometric similarity requires that each linear dimension of the prototype, L_p, be equal to the corresponding model dimension, L_m, times the scale factor, λ_l:

$$L_p = \lambda_l \; L_m \; . \qquad (9\text{-}1)$$

a. Kinematic similarity requires the similarity of motion. This implies that corresponding velocities and paths of motion are similar. This is most commonly stated in terms of a velocity ratio, λ_v:

$$V_p = \lambda_v \; V_m \quad . \tag{9-2}$$

For dynamic similarity, the ratio of corresponding masses and mass accelerating forces must be similar:

$$M_p = \lambda_m \, M_m \tag{9-3a}$$

$$F_p = \lambda_f \; F_m \quad . \tag{9-3b}$$

b. Turbulent open channel flows are driven by the force of gravity and resisted by friction. This leads to at least three types of forces that must be accounted for in such flows: gravity, friction, and inertia. In terms of force ratios, this requirement suggests that both Froude and Reynolds scaling must be obeyed. To satisfy more than one model law in a physical model, however, typically requires the ability to vary the properties of the testing fluid over a relatively broad range. Since it is generally not practicable to use a fluid other than water in a physical model, similitude in models of river hydraulics is generally based on Froude scaling, while trying to minimize viscous effects (Reynolds number independence) by maintaining a high enough Reynolds number to ensure fully rough turbulent flow.

c. For free surface flows, the transition from laminar to turbulent flow occurs between Reynolds numbers (based on hydraulic radius) of 500 to 2000. In this transition range, resistance to flow shifts from a primary dependence on viscous shear to a dependence on the relative roughness of the channel or form drag. For physical models of free surface flow, the viscous effects have often been minimized by maintaining a Reynolds number, based on hydraulic radius, of 1400 to 2500. An alternate criterion that is often employed is the roughness Reynolds number:

$$\mathrm{Re}^* = V^* \, k/\upsilon > 100 \tag{9-4}$$

where V^* is the shear velocity, k is a composite hydraulic roughness corresponding to an equivalent sand grain roughness, and υ is the kinematic viscosity of water. In the case of river ice models, an additional constraint is imposed, since the addition of a continuous, stationary ice cover to a wide channel effectively doubles the wetted perimeter and halves the hydraulic radius. In that case, the Reynolds number criterion must likewise be increased.

d. In addition to gravitational and viscous forces, surface tension must also be considered in the design of river ice models. The importance of surface tension can be reflected through the Weber number, which is a ratio between surface energy forces and inertia. As in the case of the Froude number, the Weber number deals with the interface between two fluids (or in some cases a fluid and a solid boundary), but like the Reynolds number it is of primary significance in flows of small depths and velocities. Surface tension effects are typically overcome by providing sufficient flow depths in areas of interest, but alternatives include controlling the surface texture of the boundaries or chemical additives to the fluid.

e. When sheet ice failure is to be modeled, such as in ice–structure interaction studies—e.g., ice forces on piers or icebreaker model tests—the ice's relevant physical and mechanical properties, such as thickness h, density ρ_i, friction factor f_i, flexural strength σ_f, crushing strength σ_c, and elastic modulus E, must be properly modeled. The ice's mechanical properties at prototype and model scales are related by:

$$\sigma_p = \lambda_\sigma \sigma_m \quad (9\text{-}5a)$$

$$E_p = \lambda_E E_m \quad (9\text{-}5b)$$

$$(\rho_i)_P = (\rho_i)_M \quad (9\text{-}5c)$$

$$(f_i)_P = (f_i)_M \quad (9\text{-}5d)$$

so that the following relationships are satisfied

$$(E/\sigma)_p = (E/\sigma)_m \quad (9\text{-}5e)$$

$$(\sigma/\rho g h)_p = (\sigma/\rho g h)_m \quad (9\text{-}5f)$$

where g is gravity.

f. Similitude relationships for river ice modeling have been presented by numerous authors (e.g., Ashton 1986). Since these texts and references and reports are widely available and in general agreement, their development will not be repeated here. The scaling ratios are presented in Table 9-1, which adopts the convention that the ratios are prototype values divided by the model values so that the geometric length scales are always greater than one. Also, for the sake of simplicity, the density ratios of the water and the ice modeling material are assumed to be unity. More details can be found in Ashton (1986).

9-3. Undistorted Models

Undistorted models are those in which all geometric lengths are scaled by the same ratio, and the first several items in Table 9-1 are simply scaled as products of the geometric length ratio. Since the significant processes in most open channel flow problems are dominated by the forces of gravity and inertia, the remaining ratios are the consequence of requiring that the Froude numbers of the model and prototype be equal:

$$\{V/(g\,D)^{0.5}\}_p = \{V/(g\,D)^{0.5}\}_m \quad (9\text{-}6)$$

where V and D are the average flow velocity and flow depth, respectively. Since gravitational acceleration is relatively constant, Equation 9-6 reduces to:

$$\lambda_v = V_p/V_m = (D_p/D_m)^{0.5} = \lambda^{0.5}\ . \quad (9\text{-}7)$$

Table 9-1.
Scaling Laws for Ice Physical Models

Variable	Symbol	Scaling ratio Distorted	Scaling ratio Undistorted ($\beta=\lambda$)
Length, horizontal	X	λ	λ
Length, vertical	Z	β	λ
Area, horizontal	A_x	λ^2	λ^2
Area, vertical	A_z	$\lambda\beta$	λ^2
Volume, Mass	$\forall$, M	$\lambda^2\beta$	λ^3
Velocity	V	$\beta^{1/2}$	$\lambda^{1/2}$
Discharge, horizontal	Q_x	$\lambda\beta^{3/2}$	$\lambda^{5/2}$
Discharge, vertical	Q_z	$\lambda^2\beta^{1/2}$	$\lambda^{5/2}$
Time, horizontal	T_x	$\lambda/\beta^{1/2}$	$\lambda^{1/2}$
Time, vertical	T_z	$\beta^{1/2}$	$\lambda^{1/2}$
Acceleration, horizontal	a_x	β/λ	1
Acceleration, vertical	a_z	1	1
Force, horizontal	F_x	$\lambda\beta^2$	λ^3
Force, vertical	F_z	$\lambda^2\beta$	λ^3
Ice strength, compressive	σ_c	β	λ
Ice strength, flexural	σ_f	λ^2/β	λ
Ice strength, shear (vertical)	σ_s	λ	λ
Modulus of Elasticity			
Flexure	E_f	λ^4/β^3	λ
Compression	E_c	β	λ
Buckling	E_b	β	λ

a. For dynamic similarity, forces must also be appropriately scaled. Since Froude scaling is based on keeping the ratios of inertial to gravity forces constant from model to prototype:

$$\{F_i/F_g\}_p = \{F_i/F_g\}_m \tag{9-8a}$$

or

$$\rho_p/\rho_m\, \lambda^3\, a_p/a_m = \rho_p/\rho_m\, \lambda^3\, g_p/g_m \tag{9-8b}$$

where a is the acceleration. Because we cannot effectively vary gravity, Equation 9-8b reduces to:

$$a_p/a_m = g_p/g_m = 1 \tag{9-8c}$$

so that the force ratio may be expressed as

$$F_r = F_p/F_m = \lambda^3. \tag{9-9}$$

b. The stress ratios that follow in Table 9-1 are a direct consequence of applying a force, scaled as λ^3, over an area, λ^2. We can also examine the roughness required in the model by referring to the Darcy-Weisbach equation for the frictional head loss H_f in a pipe of length L and diameter D:

$$H_f = f\,(L/D)\,(V^2/2g)\ . \qquad (9\text{-}10)$$

Substituting $4R_h$ (hydraulic radius) for the pipe diameter, slope S for H_f/L, rearranging and taking the ratio of Equation 9-10 for prototype and model conditions gives the following expression for the slope ratio S_r in terms of the Froude number ratio Fr:

$$S_r = f_r\,\mathrm{Fr}_r^{\,2}\ . \qquad (9\text{-}11a)$$

Similarly, using the Manning equation it can be shown that

$$S_r = \{n_r^{\,2}/R_h^{\,1/3}\}\ \mathrm{Fr}^2 \qquad (9\text{-}11b)$$

where n is Manning's roughness coefficient and R_h is the hydraulic radius. For a wide channel R_h is approximately equal to the depth D.

c. Because the modeling is based on equality of Froude numbers for model and prototype ($\mathrm{Fr}_r = 1$), and since the slope ratio in an undistorted model is also unity, the boundary friction factor should be equal in model and prototype. If the model is designed to operate under Reynolds number independence, then the friction factor should be governed primarily by the relative roughness of the boundary surface, k/R_h (where k is the composite roughness of the channel). If the model flow is in the transitional regime where boundary resistance varies with Reynolds number, it may be necessary to distort the relative roughness empirically. Similar reasoning indicates that the friction between the ice and solid boundaries or other ice pieces should also be the same in model and prototype.

9-4. Distorted Models

While undistorted models, i.e., models with the same scale in both the horizontal and vertical directions, are by far preferable, distorted hydraulic models may have to be used when modeling long reaches of wide rivers. This is accomplished by exaggerating the vertical scale relative to the horizontal scale. In some cases, there may be different scaling ratios for all three geometric lengths, or there may be a distortion of the channel slope that is distinct from the length scale ratios (tilting). In the case of river ice models, a separate length scale for ice thickness, distinct from the vertical length scale, has also been proposed (Michel 1975).

a. The need for a distorted model may also arise from limitations on the available space in which to construct the model, or because of a lack of control over the modeling materials and conditions. The size of the modeling facility often limits model scales because most water bodies are relatively shallow in comparison to their plan dimensions. If the prototype area to be modeled is large, the scale reductions necessary to fit the model within the available (or economically feasible) space may be so great that vertical dimensions cannot be measured with adequate resolution, or viscous and surface tension effects become dominant. In this case, the vertical scale may be distorted relative to the horizontal scale provided that appropriate modifications are made to the remaining scale ratios, as shown in Table 9-1.

b. The second reason for distorted models arises from the limitations on modeling materials and conditions. As mentioned previously, for large-scale physical models, it is rarely practical to use a model fluid other than water, and gravitational forces are essentially equal in model and prototype. For cases where the mechanical properties of ice are important, the practical limitations of available artificial ice materials have limited undistorted models to geometric scale ratios no greater than 20 (Michel 1978). Timco (1979) reported that doped real ice may be used at scales up to 50 (see Paragraph 9-5*b*).

c. While model distortion is often required because of either scaling or economics, it must be recognized that the distortion leads to improper conversions between potential and kinetic energy. Distortion is reasonable for flows that are largely two dimensional and that exhibit essentially hydrostatic pressure distributions. If flows have significant three-dimensional qualities, however, distortion presents significant limitations since vertical accelerations are not properly reproduced. In general, distorted models are not well suited to situations where there is significant curvature of the water surface.

d. When a model is distorted, the distortion must be planned to accomplish a specific goal (such as the prediction of water levels); however, the replication of other model characteristics (such as velocity distributions or forces on structures) may be significantly impaired despite the use of distorted scaling ratios. Scaling ratios for even basic quantities such as the hydraulic radius and boundary roughness become cross-section- or reach-specific, since they depend on cross-sectional shape. For small particles, their interaction may not distort items such as the angle of repose or internal friction. What does and does not distort properly is not always clear.

e. The scaling ratios for the case of a distorted model can be developed in a fashion similar to that used above for the undistorted case, but the task is far more complex. A detailed review of distortion in river ice models is beyond the scope of this chapter, and the reader is referred to other texts such as Michel (1978), Ashton (1986), and Wuebben (1995). If properly applied, distorted Froude scaling will ensure proper ratios of inertia to gravity forces taken separately in the vertical and horizontal directions. However, numerous scale effects will arise owing to dilatation resulting from forces scaling by different ratios in the vertical and horizontal directions. A literature review of previous river ice models has shown that distortions have typically been limited to four or fewer (Wuebben 1995).

9-5. Model Ice Materials

a. Modeling Broken Ice. In phenomena that do not involve a solid ice sheet but only ice floes or brash ice, the main forces to consider are usually gravity forces, but they also may include buoyancy forces, inertia forces, and possibly shear forces ascribable to water flowing underneath the stationary floes (e.g., ice held at a retaining structure such as an ice boom). If ice-on-ice friction is not thought to be critical, artificial ice floes can be used instead of real ice floes in the model, as long as the density of the material is equal to that of ice (e.g., polyethylene). The model study can then be made in an unrefrigerated facility with significantly reduced costs.

Several types of model brash ice have been used, usually made of pieces or crushed plastic material of a density equal or very close to that of real ice (Zufelt and Ettema 1996). An example of a model study using this type of material is found in Larsen et al. (1994) and shown in Figure 9-1.

Figure 9-1. Model of Niagara River using crushed polyethylene as model ice.

b. Modeling Sheet Ice. When the phenomenon to be studied involves the failure or breaking of an initially intact ice cover (e.g., ice forces on structures), or the secondary breaking of large floes, the mechanical properties of ice (bending strength, crushing strength, shear strength, and ice friction) become important and must be properly modeled in the laboratory. To achieve correct mechanical properties, most model ice is grown from a solution of salt, urea, glycol, or some other dopant in water. The achievable model properties, however, impose a minimum limit to the model scale. This limiting scale will depend upon the mode of failure of the ice sheet (e.g., the limiting scale is approximately 1:40 for ice failing in bending). A refrigerated facility is necessary for this type of modeling and a discussion of such a model study is given in Gooch and Deck (1990). Figure 9-2 shows a model using real ice in the CRREL refrigerated model area. Some artificial materials have been developed that are claimed to reproduce the properties of real ice, but their composition is proprietary, their handling is often messy, and even though they can be used in a warm environment, the cost of the experiments is similar to those in refrigerated facilities.

Figure 9-2. Model of ice jam control structure for Cazenovia Creek, New York.

9-6. Model Calibration

Once a modeling technique has been chosen and the physical model built, it should be calibrated or verified. This process usually consists of the following steps: adjustment of bed roughness to reproduce the water surface profile without ice (this is the normal model verification for conventional hydraulic models); verification of head losses with a simulated ice cover for known field conditions; and verification of the similitude of ice processes for known field conditions, such as ice breakup, ice drift pattern, and velocity. Even if this last verification is only qualitative, it is necessary to ascertain that the model is simulating observed natural phenomena. The objective of the calibration of a hydraulic model is to reproduce more or less normal field conditions, so that the model can be used to predict the effects of *abnormal* conditions or those produced by man-made changes with a good degree of confidence. In an ice–hydraulic model, it is not sufficient to reproduce water levels at various discharges as in a conventional hydraulic model. The ice phenomena also have to be correctly simulated. Many ice phenomena are not fully understood. If they are not carefully observed and documented at the particular field site to be modeled, it is unlikely that they can be simulated correctly in the model.

9-7. Considerations in Choosing Modeling

While proper physical hydraulic modeling must follow some basic scientific and engineering principles, it still remains as much an art as a science. This is even more true when ice effects are involved. In this regard, the experience of the engineer in charge of a model study is critical to the success of the study and to the reliability of its results. Physical modeling can be a very powerful tool in deciding among various potential designs for a project or among proposed solutions to a particular problem, in optimizing an initial design, in providing rational answers to objections to a proposed design or project, and in detecting potentially undesirable effects of a proposed design or solution, which may not have been foreseen otherwise, or not predicted by numerical modeling. While a physical model study often is a costly endeavor, when properly conducted, it can point the way to design or construction savings that often will more than offset its cost (Figure 9-3).

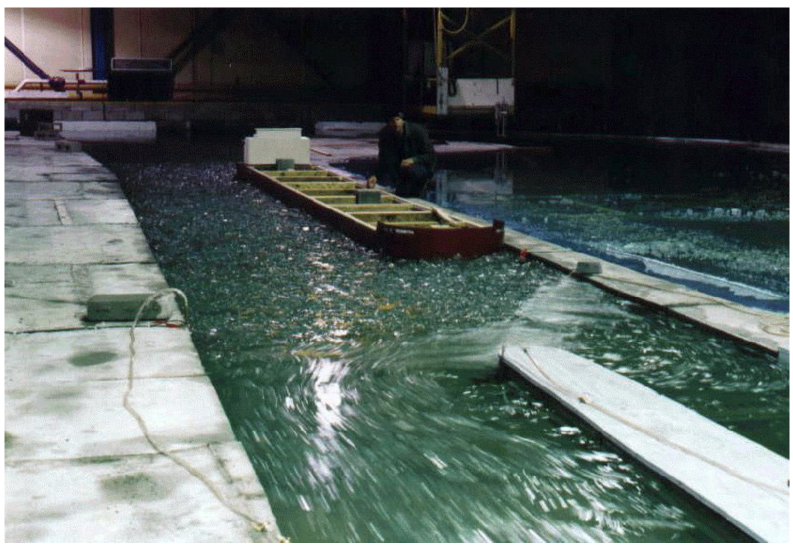

Figure 9-3. Model of Soo Locks, Michigan—ice control in upper lock approach.

9-8. References

a. Required publications.

None.

b. Related publications.

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Part II: Ice Jams and Mitigation Measures

Chapter 10
Ice Jam Flooding in the United States

10-1. General

Flooding and flood-related events cause greater damage and more fatalities than any other natural disaster. About 80 percent of all presidential disaster declarations are the result of flooding (Federal Emergency Management Agency 1992a). Flood damages averaged $3.3 billion and flood-related fatalities averaged about 100 annually over a recent 10-year period (U.S. Army 1993, 1994). The most common type of flood is the result of a major rainfall or snowmelt. A second type of flood happens suddenly, as in the case of dam failures or intense rainfall that generates a flash flood. A third category of flood results from an ice or debris jam.

a. Flood stages during an ice jam (Figure 10-1) can increase more rapidly and attain higher levels than those associated with open-water conditions. Ice jam flooding may take place outside the regulatory floodplain, often when the river flow would not otherwise cause problems. Although no specific damage figures are available, it is estimated that ice jams cause over $100 million in damages annually in the United States. Roads may be flooded and closed to traffic, and bridges weakened or destroyed, limiting emergency and medical relief to the affected areas. The potential exists for death or serious injury from jam and flood conditions, or during evacuations. Ice covers and ice jams also block hydropower and water supply intakes; delay or stop navigation; damage riverine structures, such as locks, dams, bridges, dikes, levees, and wingwalls; and decrease downstream discharge. In addition, ice movement and ice jams can severely erode streambeds and banks, with adverse effects on fish and wildlife habitat. Many laws and regulations have been developed to reduce national vulnerability to flooding.

b. Most American communities have floodplain regulations designed to prevent future development in areas subject to conventional open-water flooding. Some communities are protected by structural controls, such as dikes, levees, and flood control dams. Mitigation measures specifically designed to protect against ice jam flooding are used less commonly.

Figure 10-1. March 1999 breakup ice jam, Tunbridge, Vermont.

10-2. Ice Jam Flooding

In many northern regions, ice covers the rivers and lakes annually. The yearly freezeup and breakup commonly take place without major flooding. However, some communities face serious ice jam threats every year, while others experience ice-jam-induced flooding at random intervals. The former often have developed emergency plans to deal with ice jam problems, but the latter are often ill-prepared to cope with a jam. In a 1992 survey, Corps District and Division offices reported ice jam problems in 36 states, primarily in the northern tier of the United States (Figure 10-2). However, even mountainous regions as far south as New Mexico and Arizona experience river ice. Of the 36 states, 63 percent reported that ice jams occur frequently, and 75 percent rated ice jams as being serious to very serious (White 1992). Ice jams affect the major navigable inland waterways of the United States, including the Great Lakes. A study conducted in Maine, New Hampshire, and Vermont identified over 200 small towns and cities that reported ice jam flooding over a 10-year period (U.S. Army 1980). In March 1992 alone, 62 towns in New Hampshire and Vermont reported ice jam flooding problems after two rainfall events. Table 10-1 lists some of the major ice jams recently recorded.

Table 10-1
Recent Major Ice Jams in the United States

Place	*Date*	*Type (Damages)*
Safe Harbor, Pennsylvania	March 1996	Breakup (>$14 million)
Western Montana	February 1996	Breakup (>$2 million)
Ashland to Columbus, Nebraska	March 1993	Breakup ($25 million)
Montpelier, Vermont	March 1992	Breakup ($5 million)
Allagash, Maine	April 1991	Breakup ($14 million)
Mississippi River/ Missouri River Confluence	December 1989	Breakup (>$20 million)
Salmon, Idaho	February 1984	Freezeup ($1.8 million)
Port Jervis, New York/ Matamoras, Pennsylvania	February 1981	Breakup ($14.5 million)
Ashland to North Platte, Nebraska	February 1978	Breakup ($18 million)

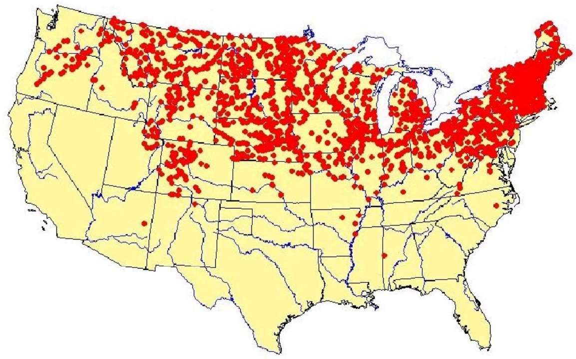

Figure 10-2. Ice events in the continental United States reported in the CRREL Ice Jam Database.

a. Characteristics of Ice Jams and Ice Jam Flooding. Because ice jam floods are less common and more poorly documented than open-water floods, it is more difficult to characterize these events compared to open-water flooding. In addition, because of the complex processes that cause ice jams to form and progress, and the highly site-specific nature of these jams, these events are more difficult to predict than open-water flooding. The rates of water level rise can vary from feet per minute to feet per hour during ice jam flooding. In some instances, communities have many hours of lead time between the time an ice jam forms and the start of flooding. In other cases, the lead time is as little as 1 hour. Although the actual time of flooding may be short compared to open-water floods lasting days to weeks, significant damage can result. The winter weather that often accompanies ice jams also adds to the risks and damages caused.

b. Example from Montpelier, Vermont, 1992. In March 1992, an ice jam developed at 0700 in Montpelier, Vermont. By 0800 the downtown area was flooded (Figure 10-3). During the next 11 hours, the business district was covered with an average of 1.2 to 1.5 meters (4 to 5 feet) of water. The flood happened so quickly that there was not sufficient time to warn residents so that they could protect their property and possessions. Even after water levels dropped, damage related to the flooding continued as cold weather caused freezing of wet objects. Damages of less than 1 day were estimated at more than $5 million (FEMA 1992b).

a. Winooski River.

Figure 10-3. Views of Montpelier, Vermont, ice jam (March 1992).

b. Downtown area.

Figure 10-3 (cont'd). Views of Montpelier, Vermont, ice jam (March 1992).

10-3. Ice Jam Flood Losses

a. Loss of Life. Ice jam flooding is responsible for loss of life, although the number of fatalities in the United States is considerably lower than that from open-water flooding. The CRREL Ice Jam Database (White and Eames 1999) reports 22 ice-event related deaths. Six of these deaths occurred during rescue attempts. Other deaths have occurred when residents delayed evacuation until it was too late. Often, rescue attempts are carried out at night, with both flood conditions and large ice pieces present, increasing the danger. This was the case for the neighborhood containing the home shown in Figure 10-4; fortunately, no deaths or injuries were reported.

b. Dollar Costs. Ice jams in the United States cause approximately $125 million in damages annually, including an estimated $50 million in personal property damage and $25 million in operation and maintenance costs to Corps navigation, flood control, and channel stabilization structures.

Figure 10-4. Damage from January 1996 breakup jam, Saranac River near Plattsburgh, New York.

Figure 10-5. Towboats and barges in ice.

c. Interference with Navigation. Ice jams have suspended or delayed commercial navigation, adversely affecting the economy (Figure 10-5). Although navigational delays are commonly short, they may result in shortages of critical supplies, such as fuel, coal, and industrial feedstocks, and lead to large costs from the operation of idle vessels (U.S. Army 1981). The costs associated with delays and stoppages of navigation by ice are difficult to determine, as there appears to be no central clearinghouse for such information. A search of Corps reports and newspapers in the St. Louis District revealed damage estimates for only 5 years: 1909 (more than $80,000), 1951 ($760,000), 1958 ($961,000), 1962 (more than $800,000 in shipping alone), and 1977 ($6.75 million in structural damage and shipping). These are reported in contemporary dollars and, except for 1977, are thought to be conservative, as they do not include all types of damage (e.g., increased operation and maintenance, structural damage, loss of perishable goods, flood-fighting efforts, damage to towboats and barges, etc.). In many years, as was reported in 1977 (Cairo Evening Citizen 1977):

> The tow vessels are under tremendous economic pressure to get the river open and moving again [St. Louis District public information officer Mel] Doernhoeser said. He said that each day a vessel is tied up it could mean from $3–5,000 to the company… the inland water transport system transports about 16 percent of the total shipping in the nation and that some of the more valuable commodities are primarily shipped by boat. Many of the places where the barges are docked are inaccessible from land and that even if rail or trucking facilities could reach them, they would not be able to handle the excess cargo…[since] one barge holds 15 rail cars of cargo.

Ice jams also cause structural damages to dams, gates, locks, mooring areas, and fleeting areas. Ice-related damage can occur even when ice is not the actual damaging force, as was the case in 1962. That year a large ice jam formed on the Mississippi River, trapping about 250 barges near Cairo. Somehow, a group of barges came loose, creating a domino effect that eventually loosed over 150 barges, sinking at least two, damaging harbor facilities, and heavily damaging a tow boat in the rescue effort. Contemporary newspapers reported that at a cost of about $65,000 for each barge, and perhaps double that when the cargo was included, nearly $1 million in damages resulted. Both the Corps of Engineers and members of the navigation industry, in addition to the Coast Guard, have contributed time and resources to combat ice jams on the Mississippi and Illinois Rivers. Historical records contain numerous reports of towboats, including those operated by the Corps, attempting to loosen ice and create navigation channels. Figure 10-6 shows a typical operation: two tows breaking ice in a lock forebay. In 1979, the cost of ice operations by towboats was estimated at about $1000 to $1500 per day, not including damage.

Figure 10-6. Towboats *H.L. Frieberg* (left) and *Dan Luckett* (right) breaking ice in the upper lock forebay, Lock and Dam 26, February 1966.

d. Reduced Power Production. Ice jams also affect hydropower operations, stopping hydropower generation by blocking intakes, causing high tailwater, making reduced discharge necessary, or damaging intake works (Figure 10-7). Lost power revenue attributable to such shutdowns can be substantial. In one such instance, power production at Oahe and Big Bend Dams (North Dakota) was curtailed during the period 10–12 January 1997 to avoid ice-related flooding in the Pierre–Fort Pierre area. Forgone energy generation was estimated at 6800 MWh, with a cost of about $270,000. Frazil blockage of intakes can affect other forms of power production in addition to hydropower. For example, in late January 1996, frazil ice blocked one, and partially blocked a second, emergency cooling water intake at the Wolf Creek Nuclear Power Plant located in Burlington, Kansas. This resulted in a plant shutdown, which in turn caused refueling to begin earlier than planned. It was estimated that the plant probably lost 2 to 3 weeks of power production because of the frazil blockage, at a cost of between $15 and $20 million.

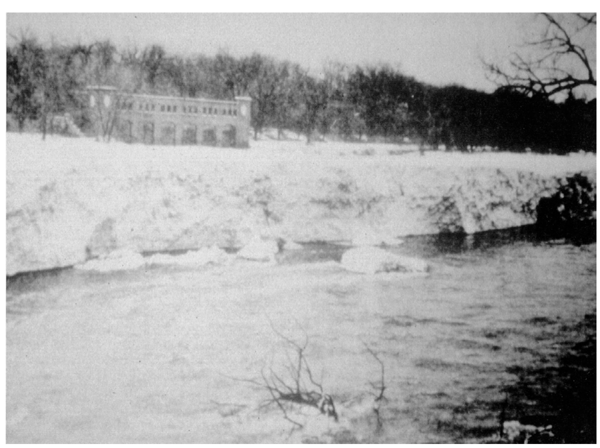

Figure 10-7. Jam immediately downstream of power plant, Fox River, near Ottawa, Illinois.

e. Channel Erosion and Damage to Channel Training Structures. The presence of an ice cover or ice jam can result and river bed scour and bank erosion that may lead to bridge or river bank failure (Figure 10-8). Winter monitoring on the upper Missouri River in Montana revealed nearly 12 meters (40 feet) of bank loss at one location during the ice-covered period of the winter of 1998–1999. Over a half meter (2 feet) of ice-induced bed scour was measured at a nearby site during the breakup period (Zabilansky and Yankielun 2000). Ice jams can damage stream channels and improvements, so that the overall vulnerability to flooding is increased. Riprap can be undermined or moved out of place. Ice-jam-related damage to river training structures costs millions of dollars each year. White (1999) reports that damage to river training structures near the Mississippi–Missouri confluence cost approximately $10 million as a result of the December 1988–January 1989 ice jam.

f. Indirect Costs. Ice jams can destroy fish and wildlife and their habitat, such as eagle roosting trees, and they can mobilize toxic materials buried in sediment. For example, the February 1996 Blackfoot River ice jam in Montana mobilized bed sediments containing high concentrations of mining wastes that are toxic to fish. This event resulted in a significant fish kill (Eames et al. 1998). As with any natural process, some of the scour associated with ice jams may be beneficial to wildlife habitat. Shallow, vegetation-choked wetlands may be opened, allowing for fish and waterfowl spawning and brood habitat.

Figure 10-8. Bank scour caused by a breakup jam near Dickey, Maine.

10-4. Ice Jam Database

a. While much information has been collected and compiled for open-water floods, documentation on ice jams and other ice events, such as freezeup and ice cover breakup, is not often readily available in the United States. Additionally, while open-water stage can be determined at a site by flood routing from other sites upstream or downstream, the complex nature of ice jams requires highly site-specific methods of estimating flood stage. The relatively small quantity and limited availability of ice event data reflect the facts that ice events usually occur less frequently, are of shorter duration, and adversely affect only short reaches of river, compared to open-water floods, which can affect long reaches for up to several weeks.

b. In the past, the lack of readily available information on historical ice events has hindered the rapid, effective response to ice jam flooding and other ice-related damage. Collecting information specifically related to ice events, such as stage, flooded area, and previous mitigation methods, has generally required a time-consuming search of a variety of potential data sources. During emergencies, this is rarely possible. Information that might have assisted the emergency response effort may not be found until after the event, if at all.

c. The need for an accessible collection of ice data was particularly evident to personnel in the U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (CRREL), Ice Engineering Research grou), who are involved in research on the hydraulics of ice, including ice cover formation and breakup, bed and bank erosion caused by ice, ice effects on riverine structures, and ice jam initiation, prediction, mitigation, and control, and who are called on to advise during ice jam flooding emergencies. The CRREL Ice Jam Database was developed in response to this need (White and Eames 1999). The database provides quick access to general information on nearly 12,000 specific ice jam events in the United States. These historical data are crucial during emergency situations where information about jam locations or stages would be helpful. Database entries include the name of the water body; the city and state where the ice event took place; the month, year, and date of the ice event; the ice event type, if known; a brief description of damage; the names of IERD and Corps personnel familiar with the event or site (points of contact); whether IERD files contain visual records of the event; latitude and longitude; the USGS gage number, if available; and hydrologic unit code. Records also contain narrative descriptions of ice events (which can be several pages long) and a list of information sources. There is a separate database entry for each discrete ice event at a given location.

d. The CRREL Ice Jam Database is constantly enlarging as historical ice event data are collected and entered. It is maintained by IERD personnel using the ORACLE database manager. The inclusion of geographical information will allow future development of GIS applications. USGS hydrologic unit codes allow searches by Corps Districts and Divisions, many of which are delineated by watershed boundaries. The database may be accessed via the CRREL web site at http://www.crrel.usace.army.mil. The user interface allows for database queries that are displayed in a manner that allows additional data screening and processing.

e. This new database is useful, not only as a centralized record of ice events, but also for the many potential applications of the information. These include rapid identification of potential ice jam stages, flooded areas, and mitigation methods at some known ice jam locations. The listing of sources and contacts may aid in the search for additional information about particular ice events. The ice event data provided can be evaluated with other meteorological and hydrological data to characterize the conditions most likely to cause ice events at a particular location. The database is useful for reconnaissance level evaluation, for detailed studies of a problem area, and for designing ice control techniques, as well as for emergency responses to ice jam events. CRREL plans to prepare summaries of ice jam data for all affected states and has completed brief summaries for New Hampshire and Vermont (White 1995), Alaska (Eames and White 1997), and Montana (Eames et al. 1998) to date. Annual ice jam summaries are available beginning in 1996.

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Chapter 11
An Ice Jam Primer

11-1. Review of Ice Types

Ice forms in freshwater bodies whenever the surface water cools to 0ºC (32ºF) or a fraction of a degree lower. There are many types of ice, depending on the precise mode of formation and evolution (Ashton 1986). See Chapter 2 for a thorough review.

a. Sheet ice. The ice that forms in calm water, such as lakes or reservoirs, or in slow-moving river reaches where the flow velocity is less than 0.5 m/s (1.5 ft/s), is termed sheet ice. Ice crystals formed at the water surface freeze together into skim ice that gradually thickens downward as heat is transferred from the water to the air through the ice layer. Sheet ice usually originates first along the banks and expands toward the center of the water body. In slow rivers, the sheet ice cover may also be created by the juxtaposition of incoming frazil pans generated in faster reaches upstream. Sheet ice that grows statically in place is often called black ice because of its appearance. An ice cover may also thicken at the top surface when water-soaked snow freezes to form snow ice that has a milky white appearance because of small air bubbles.

b. Frazil ice. Frazil ice (Figure 11-1) consists of small particles of ice formed in highly turbulent, supercooled water, such as river rapids or riffles, during cold, clear winter nights when the heat loss from the water to the atmosphere is very high. As the frazil particles are transported downstream, they join together to form flocs that eventually rise to the surface where they form frazil pans or floes. Frazil is often described as slush ice because of its appearance.

Figure 11-1. Frazil ice and frazil pans, Salmon River, Idaho

c. Fragmented ice. This type of ice is made up of ice pieces that originated as consolidated frazil ice pans or from the breakup of sheet ice growing at the surface of slow-moving water.

d. Brash ice. Brash ice is an accumulation of ice pieces up to about 2 meters (6 feet) in maximum dimension, resulting from the breakup of an ice cover by increasing water flow or by vessel passage. It is of particular concern in navigation channels and lock approaches.

11-2. Types of Ice Jams

An ice jam is a stationary accumulation of ice that restricts flow. Ice jams can cause considerable increases in upstream water levels, while at the same time downstream water levels may drop, exposing water intakes for power plants or municipal water supplies. Types of ice jams include freezeup jams, made primarily of frazil ice; breakup jams, made primarily of fragmented ice pieces; and combinations of both.

a. Freezeup jams. Freezeup jams are composed primarily of frazil ice, with some fragmented ice included. They occur during early winter to midwinter. The floating frazil may slow or stop because of a change in water slope from steep to mild, because it reaches an obstruction to movement such as a sheet ice cover, or because some other hydraulic occurrence slows the movement of the frazil (Figure 11-2). Jams are formed when floating frazil ice stops moving downstream, makes the characteristic "arch" across the river channel, and begins to accumulate. Freezeup jams are characterized by low air and water temperatures, fairly steady water and ice discharges, and a consolidated top layer of ice.

Figure 11-2. Frazil pans slowing down, being compressed, and breaking off in an arch shape. *The downstream movement of the pans will eventually stop. Flow is from right to left*

b. Breakup jams. Breakup jams happen during periods of thaw, generally in late winter and early spring, and are composed primarily of fragmented ice formed by the breakup of an ice cover or freezeup jam (Figure 11-3). The ice cover breakup is usually associated with a rapid increase in runoff and corresponding river discharge attributable to a significant rainfall event or snowmelt. Late season breakup is often accelerated by increased air temperatures and solar radiation.

Figure 11-3. Initial breakup of sheet ice

(1) The broken, fragmented ice pieces move downstream until they encounter a strong, intact downstream ice cover, other surface obstruction to flow, or other adverse hydraulic conditions, such as a significant reduction in water-surface slope. Once they reach such a jam initiation point, the fragmented ice pieces stop moving, begin to accumulate, and form a jam (Figure 11-4). The ultimate size of the jam (i.e., its length and thickness) and the severity of the resulting flooding depend on the flow conditions, the available ice supply from the upstream reaches of the river, and the strength and size of the ice pieces.

(2) Midwinter thaw periods marked by flow increases may cause a minor breakup jam. As cold weather resumes, the river flow subsides to normal winter level and the jammed ice drops with the water level. The jam may become grounded as well as consolidated or frozen in place. During normal spring breakup, this location is likely to be the site of a severe jam.

c. Combination jams. Combination jams involve both freezeup and breakup jams. For example, a small freezeup jam forms in a location that causes no immediate damage. Before the thaw, the jam may provide a collecting point for fragmented ice that floats downstream. On the other hand, it could break up at the same time as the remainder of the river. Since the jam is usually much thicker than sheet ice, it significantly increases the volume of ice available to jam downstream.

Figure 11-4. Breakup jam

d. Other factors. In some rivers, frazil ice does not cause freezeup jams; instead, it deposits beneath sheet ice in reaches of slow water velocities. These frazil ice deposits, called hanging dams, are many times thicker than the surrounding sheet ice growth, and will tend to break up more slowly than thinner ice. Such a frazil deposit could also provide an initiation point for a later breakup jam, as well as increase the volume of ice available to jam downstream.

11-3. Causes of Ice Jams

River geometries, weather characteristics, and floodplain land-use practices contribute to the ice jam flooding threat at a particular location. Ice jams initiate at a location in the river where the ice transport capacity or ice conveyance of the river is exceeded by the ice transported to that location by the river's flow.

a. Change in slope. The most common location for an ice jam to form is in an area where the river slope changes from relatively steep to mild. Since gravity is the driving force for an ice run, when the ice reaches the milder slope, it loses its momentum and can stall or arch across the river and initiate an ice jam. Water levels in reservoirs often affect the locations of ice jams upstream as a result of a change in water slope where reservoir water backs up into the river. Islands, sandbars, and gravel deposits often form at a change in water slope for the same reasons that ice tends to slow and stop. Because such deposits form in areas conducive to ice jamming, they are often mistakenly identified as the cause of ice jams. While these deposits may affect the river hydraulics enough to cause or exacerbate an ice jam, the presence of gravel deposits is usually an indication that the transport capacity of the river is reduced for both ice and sediment. Ice jams located near gravel deposits should be carefully studied to determine whether the gravel deposit is the cause of the jam or a symptom of the actual cause.

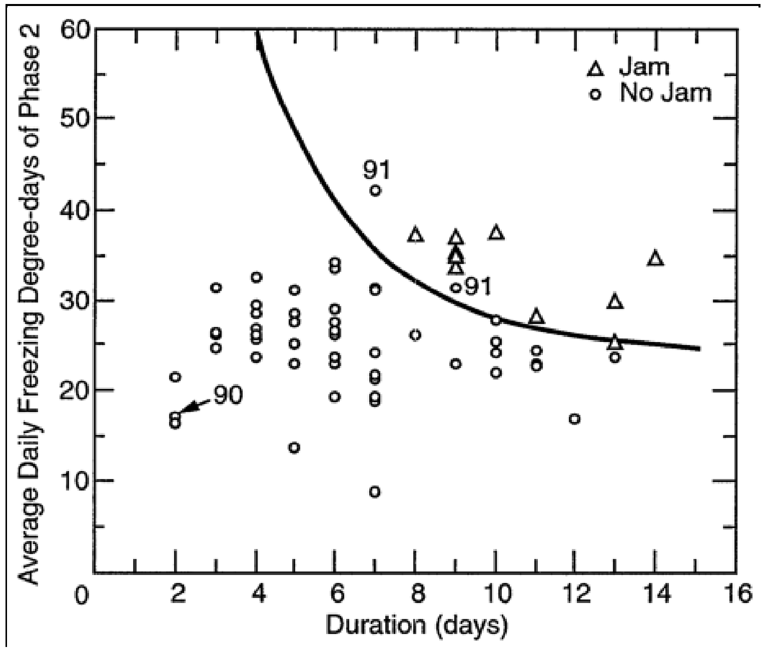
b. Confluences. Ice jams also commonly form where a tributary stream enters a larger river, lake, or reservoir. Smaller rivers normally respond to increased runoff more quickly than larger rivers, and their ice covers may break up sooner as a result of more rapid increases in water stage. Ice covers on smaller rivers will typically break up and run until the broken ice reaches the strong, intact ice cover on the larger river or lake, where the slope is generally milder. The ice run stalls at the confluence, forming a jam, and backing up water and ice on the tributary stream.

c. Channel features. Natural and constructed features in a river channel may play a role in the locations of ice jams. River bends are frequently cited as ice jam instigators. While river bends may contribute to jamming by forcing the moving ice to change its direction and by causing the ice to hit the outer shoreline, water slope is often a factor in these jams as well (Wuebben and Gagnon 1995, Urroz and Ettema 1994). Obstructions to ice movement, such as closely spaced bridge or dam piers, can cause ice jams. In high runoff situations, a partially submerged bridge superstructure obstructs ice movement and may initiate a jam. In smaller rivers, trees along the bank sometimes fall across the river causing an ice jam. Removing or building a dam may cause problems. In many parts of the country, small dams that once functioned for hydropower have fallen into disrepair. Communities may remove them as part of a beautification scheme or to improve fish habitat. However, the effects of an existing dam on ice conditions should be considered before removing or substantially altering it. It is possible that the old dams control ice by delaying ice breakup or by providing storage for ice debris. Dam construction can also affect ice conditions in a river by creating a jam initiation point. On the other hand, the presence of a dam and its pool may be beneficial if frazil ice production and transport decrease as a result of ice cover growth on the pool.

d. Operational factors. Some structural or operational changes in reservoir regulation may lead to ice jams. For example, changes in hydropower operations can inadvertently cause ice jam flooding. Sudden releases of water, such as those characteristic of peaking plants, may initiate ice breakup and subsequent jamming. On the other hand, careful reservoir regulation during freezeup or breakup periods can reduce ice jam flood risks.

11-4. Predicting Ice Jams

Very few methods for predicting ice jams exist, and those that do are highly site-specific, requiring knowledge of the location of the jam initiation point. Because freezeup jams rely heavily on periods of intense cold that produce large quantities of frazil, they can be somewhat easier to predict than breakup jams, which are caused by a site-specific combination of complex physical processes. Evaluation of historical ice, meteorological, and hydrological records is necessary for developing a prediction method for either type of jam. For example, Zufelt and Bilello (1992) used historical records, along with river geometry, to develop a method to predict the progression of freezeup jams in Idaho. Their model results showed that ice jam flooding at that location could be related to the accumulated freezing degree-days and the duration of periods of extreme cold (Figure 11-5). Wuebben and Gagnon (1995) ranked meteorological and hydraulic parameters for known jam and no-jam events in North Dakota to determine the likelihood of breakup jam flooding, with good results. They selected model parameters after studying the physical processes at the site, and all relate to the stage and ice thickness the time of breakup. Table 11-1 presents the parameters and their assigned weighting factors.



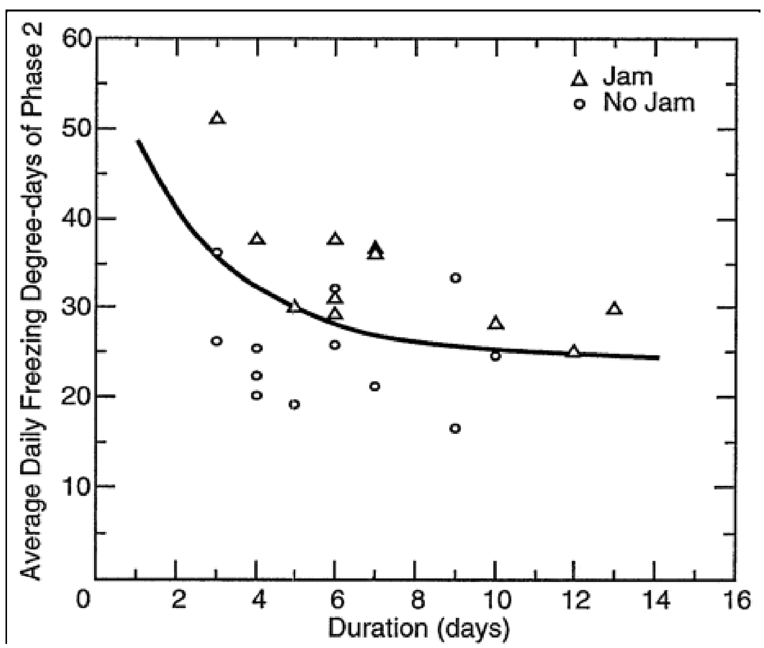


Figure 11-5. Example freezeup prediction model for Salmon River, Idaho. *The curves apply to antecedent periods (Phase I) of less than 500 (Fahrenheit) or 278 (Celsius) AFDD (left) and more than 500 (Fahrenheit) or 278 (Celsius) AFDD (right)*

Table 11-1
Upper and Lower Threshold Limits and Weighting Factors in Wuebben's Complex Threshold Model for Prediction of Ice Jams at Williston, North Dakota

Parameter	*Lower Threshold*	*Upper Threshold*	*Weight*
ΣFDD_{max}, °F days (°C days)Σ	1700 (944)	2600 (1444)	2
Q_{max}, ft^3/s (m^3/s)	< 25000 or > 86800 (<708 or > 2458)	30000 < xi < 70000 (850, xi < 1982)	1
Julian day of ΣFDD_{max}	150	165	1
Julian day of Q_{max}	155	170	1
Julian day of ΣFDD_{max} - Julian day of Q_{max}	<-8 or > 10	-5 < xi < 7	2
Lake Sakakawea stage, ft MSL (m MSL)	1835 (559.3)	1840 (560.8)	1
Total snowfall, in (cm)	20 (50.8)	40 (101.6)	2
Timing of snowfall, in (cm)	< 5 (12.7) after JD = 90	> 10 (25.4) after JD = 90 or > 5 (12.7) after JD = 120	1 1

11-5. References

a. Required publications.

None.

b. Related publications.

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Ashton, G.D., ed. 1986. *River and Lake Ice Engineering*, Water Resources Publications, Littleton, Colorado.

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Urroz, G.E., and R. Ettema. 1994. "Application of Two_Layer Hypothesis to Fully Developed Flow in Ice_Covered Curved Channels," *Canadian Journal of Civil Engineering*, Vol. 21, no. 1, pp. 101_110.

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Wuebben, J.L., and J.J. Gagnon. 1995. *Ice Jam Flooding on the Missouri River near Williston, North Dakota,* CRREL Report 95-19, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Zufelt and Bilello 1992
Zufelt, J.E., and M.A. Bilello. 1992. *Effects of Severe Freezing Periods and Discharge on the Formation of Ice Jams at Salmon, Idaho,* CRREL Report 92-14, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Chapter 12
Ice Jam Mitigation Techniques

12-1. Ice Jam Flood Control

a. General. Until the 1970s, flood control concentrated largely on open-water flood events and was considered primarily a Federal responsibility. Large structural solutions such as levees or flood-control dams were built. Now, the Federal Government requires local and State governments to share the costs, and Government policies favor small-scale, locally funded projects. In light of significantly reduced budgets, innovative ice jam mitigation techniques that require low maintenance and low up-front costs, have low environmental impacts, and yield excellent results in terms of reduced flooding damages are being developed. Many of these are appropriate for design and implementation in smaller cities and towns.

b. Effects of flood insurance. In 1990 the Federal Emergency Management Agency (FEMA) initiated the Community Rating System to reward local hazard mitigation efforts by reducing flood insurance premiums in communities that adopt relocation, hazard area acquisition, and other mitigation policies. "Clearly, Federal flood hazard policy is demonstrating an increasing emphasis on mitigation. Mitigation works to change the nature of the threat, decreases vulnerability to damage and reduces exposure to the hazard" (Drabek and Hoetmer 1991).

12-2. Types of Mitigation Measures

A number of ice jam flood mitigation measures are possible. These measures can be of a structural or nonstructural nature, appropriate to control breakup jams or freezeup jams. Some are permanent, some are deployed in advance of an anticipated flood threat, while others are deployed under emergency conditions when a jam has formed and flooding has occurred.

a. Structural measures. Structural measures for ice jam control may incorporate features that can be used to alleviate open-water flooding, as well as those designed specifically for ice jam floods. The cost of such measures includes construction, operation, and land acquisition, as well as costs associated with recreation and environmental mitigation. Unfortunately, while they are often very successful, structural solutions tend to be expensive. Structural solutions remain appropriate on rivers where chronic or serious threats persist, and where the extent of potential damages justifies the cost. Although the majority of the structural mitigation techniques are, by their very nature, permanent, some are designed to be removable. These removable structures are usually installed at the beginning of winter and removed after spring breakup when the threat of ice jam flooding no longer exists. A few removable structures are designed to be deployed after an ice jam threat has been identified and, in this respect, can be considered advance mitigation measures.

b. Nonstructural measures. These measures are designed to modify vulnerability to the flood threat or to reduce the severity of the ice jam and of the resulting flood. They are generally less expensive than structural solutions. The majority of the nonstructural techniques are used for advance and emergency measures when serious ice jam flooding is imminent or under way. For example, if sufficient warning is provided, ice can be weakened (by cutting or dusting) before an ice jam takes place. Blasting and mechanical removal are often employed only as emergency mitigation measures once ice jams have happened. The creation of ice storage zones upstream from a known jam site to minimize the amount of ice reaching the jam site is a permanent measure, since these areas, once established and properly maintained, can be used year after year.

c. Freezeup jam mitigation. Freezeup ice jam control usually targets the production and transport of the frazil ice that causes jams. This may be accomplished by encouraging the growth of an ice cover that insulates the water beneath, decreasing the production of frazil ice. The ice cover collects and incorporates frazil ice that is transported from upstream. This reduces the amount of ice moving downstream.

d. Breakup jam mitigation. Breakup ice jam control focuses on affecting the timing of the ice cover breakup, thereby reducing the severity of the resulting jam to the point where there is little or no flooding. Breakup mitigation may also aim at controlling the location of the ice jam by forcing the jam to occur in an area where flooding damages will be inconsequential.

12-3. Selecting Mitigation Measures

Table 12-1 summarizes the currently available jam mitigation techniques and indicates whether they are applicable to freezeup or breakup jams and whether they are appropriate for permanent, advance, or emergency measures. In paragraph 12-4 and those following, the ice jam mitigation methods are described in detail: first, those that are primarily permanent measures; second, those appropriate for advance measures; and third, those applicable to emergency situations. Traditional flood-fighting methods, namely floodproofing, sandbagging, levee closing, or evacuation, are obviously applicable to ice jam floods. They are only briefly summarized under the pertinent subparagraphs.

a. Mitigation strategy. The best mitigation strategy often combines structural and nonstructural measures, such as an ice boom associated with temporary modifications in the operation of an upstream water control dam, as well as permanent, advance, or emergency measures. Table 12-2 lists common ice jam mitigation strategies and corresponding techniques.

b. Data collection. Following an ice jam flood, when an ice jam control program is developed to prevent similar events from recurring, it is first necessary to determine the type of jam, source of ice, local and remote causes of the jam, and meteorological and hydrological conditions that led to the jam formation. To address all of these points, an ice jam data collection program, as described by White and Zufelt (1994) or Elhadi and Lockhart (1989), should be an integral part of an ice jam mitigation effort. Data collection should not be limited to the immediate vicinity of the jam location. It is important to study upstream and downstream areas, since the source of ice and the actual causes of ice jamming at a particular site may be far removed from the actual jam location. This data-gathering phase of the program is critical to selecting the jam mitigation strategy and corresponding mitigation techniques best appropriate to the site under study.

c. Coordination. Successful ice jam mitigation often requires multi-jurisdictional cooperation and interagency coordination. For example, a catastrophic breakup ice jam on the Delaware River in February 1981 affected three states and caused $14.5 million in damages. After extensive collaboration among Federal and State agencies in New Jersey, Pennsylvania, and New York, a diversion channel was proposed to be built physically in New Jersey that also provided major flood loss reduction benefits to New York and Pennsylvania.

Table 12-1
Ice Jam Mitigation Methods

Technique	*Jam Type*	*Type of Mitigation*
Structural		
Dikes, levees, floodwalls	F,B	P
Dams and weirs	F, B	P
Ice booms	F, B	P, A
Retention structures	B	P
Channel modifications	F, B	P
Ice storage zones	B	P, A
Nonstructural		
Forecasting	F, B	A, P
Monitoring and detection	F, B	E, A, P
Thermal control	F, B	E, A, P
Land management	F, B	P
Ice cutting	B	A
Operational procedures	F, B	A, P
Dusting	F, B	E, A
Ice breaking	F, B	E, A
Mechanical removal	F, B	E, A
Blasting	F, B	E, A
Traditional Techniques		
Floodproofing	F, B	P
Sandbagging	F, B	A, E
Evacuation	F, B	A, E
Levee closing	F, B	A, E
Key:	B = Breakup jam F = Freezeup jam	P = Permanent measure A = Advance measure E = Emergency measure

12-4. Permanent Measures

In this paragraph, several measures are briefly discussed that can be considered for the permanent or long-term correction of ice jamming problems. See Part I, Chapter 3, *Ice Control*, for greater detail and description of certain of these measures.

a. Dikes, levees, and floodwalls. Dikes, levees, and floodwalls physically separate the river from property to be protected. These measures protect against open-water floods as well as ice jam floods. However, designs adequate for open-water protection may not be adequate to handle ice jam stages that cause physical damage.

Table 12-2
Ice Jam Mitigation Strategies and Applicable Techniques

Protect surrounding areas from flood damages
Dikes, levees, and floodwalls
Floodproofing
Floodplain land-use management
Sandbagging
Levee closing
Evacuation
Reduce ice supply
Thermal control
Revised operational procedures
Ice booms
Dams and weirs
Ice storage zones
Dusting
Ice retention
Increase river ice and water conveyance
Channel modifications
Revised operational procedures
Control ice breakup sequence
Detection and prediction
Ice booms
Ice cutting
Ice breaking
Revised operational procedures
Displace ice dam initiation location
Dams and weirs
Ice piers, boulders, and cribs
Ice booms
Ice breaking
Channel modifications
Remove ice
Thermal control
Ice breaking
Mechanical removal
Blasting

b. Dams and weirs. Dams are used to affect the thermal and flow regimes of a river. As breakup jam control structures, dams are designed to suppress or change the duration or timing of ice jam formation downstream by intercepting the solid ice pieces coming from upstream. For freezeup jam control, a dam promotes the formation of an upstream stable sheet-ice cover to minimize the generation of frazil ice that could result in the formation of a freezeup jam. For example, gates may be designed to allow run-of-river flow during most of the year, but in the winter be closed at freezeup so rapids are inundated (Figure 12-1). This eliminates local frazil ice production, reduces the supply of frazil moving downstream, and slows the freezeup jam progression.

(1) A dam designed to reduce ice jam flooding can be part of a multi-objective community project, where benefits for open-water flood control, navigation, recreation, water supply, irrigation, or hydro-power justify much of the construction costs.

(2) For smaller rivers, when financial or environmental constraints eliminate consideration of major structural works, relatively low-cost alternatives can still provide significant ice jam control. For freezeup control, a still experimental fabric tension weir (Figure 12-2), supported by cables anchored at the banks, may be an economically feasible alternative. For breakup control, a permeable,

Figure 12-1. Lancaster, New Hampshire, ice-control structure

Figure 12-2. Tension weir

cable-supported wire mesh, similar to submarine net (Figure 12-3), may be strung across the stream to temporarily hold ice from upstream while the downstream reaches of the stream are cleared of ice. These two types of structures are removable and can be seasonally deployed. However, they often require local bed and bank protection against scour for stability and effectiveness. Provisions to allow part of the flow to divert around the structures to limit the upstream flow depth may be required.

c. Ice booms. Ice booms are the most widely used type of ice-control structure (Figure 12-4). They are a series of timbers or pontoons tethered together and strung across a river to control the movement of ice. Booms are flexible and can be designed to release ice gradually and partially when overloaded. Ice booms are relatively inexpensive and can be placed seasonally to reduce negative environmental impacts.

(1) Booms commonly stabilize or retain an ice cover in areas where surface flow velocities are 0.69 m/s (2.25 ft/s) or less and relatively steady. In some cases, a weir or small structure can improve hydraulic conditions at the ice boom location, especially on small, steep streams. Some booms are located at the outlets of lakes or reservoirs to keep ice from entering downstream ice-jam-prone reaches.

(2) Conventional ice booms may be used in breakup situations to hold back the ice for a brief time, allowing the initiation of emergency response measures, such as evacuation or sandbagging. Booms can be placed to direct the movement of ice pieces away from an intake or navigation channel. Ice-control booms are also used to promote ice cover formation during freezeup as part of freezeup ice jam mitigation efforts.

d. Ice retention. Ice retention structures control breakup jams by promoting the initiation of an ice jam at a suitable location where flooding will cause little or no damage. Fragmented ice is captured and retained upstream from the retention structure to create the ice jam. Ice retention structures can range from suspended structures, such as a submarine net or vertically oriented ice booms, to streambed structures, such as concrete piers (Figure 12-5), large boulders, or rock-filled cribs placed at regular intervals across the width of the stream. Provision for a floodplain or diversion channel may also be required to limit the rise in upstream water levels and the corresponding loads on the structural elements, as well as to limit the upstream flooding potential.

(1) Suspended structures may be placed seasonally but require adequate permanent anchoring to withstand the ice forces. These structures are generally more suited to smaller rivers and streams. The size and anchoring of projecting structures, such as piers, boulders, or cribs, must be determined to withstand the anticipated ice forces, and their spacing is a function of the average ice floe size.

(2) Retention structures for ice jam control do not block the entire river width, and thus allow for recreational navigation and fish passage. Therefore, they can be installed permanently. The bed of the stream may need to be protected against scour around all elements of this type of structure to ensure that they remain stable.

e. Channel modification. Modifications to the river channel can improve the passage of ice through reaches where ice jams tend to form, such as changes in slope, river bends, slow moving pools, and constrictions. Dredging or excavation can widen, deepen, or straighten the natural channel. Old bridge piers and natural islands and gravel bars can be removed. Diversions (Figure 12-6) can bypass ice and water flow around the normal jamming sites, lowering the upstream stage. When diversion channels are used, they should be designed to remain dry except during floods, so that they will be available to function as open-water channels and not contribute to the downstream ice supply. A diversion channel can improve the performance of an ice-control structure. If an ice-control dam or weir is used to control a

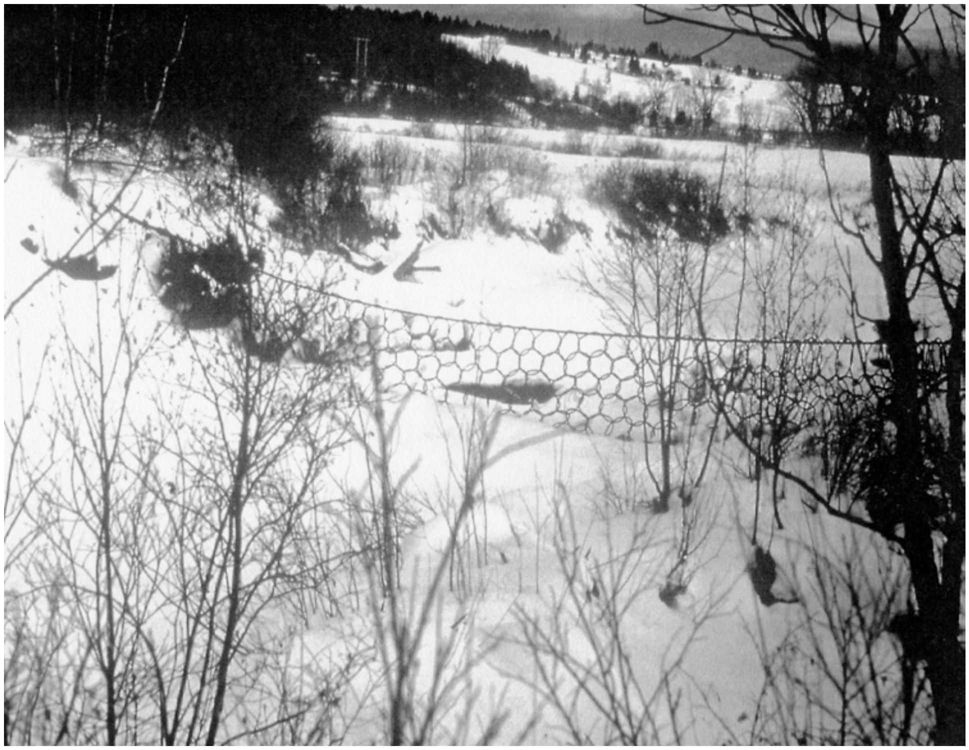


Figure 12-3. Submarine net

breakup ice run, an associated high-level diversion could be used to limit the discharge reaching the structure, reducing river stages to prevent local flooding, and ensuring the stability of the ice being retained.

f. Creation of ice storage zones. Breakup ice jam frequency and flood levels can be reduced through storage of ice upstream from damage-prone areas in ice storage zone sites (Figure 12-7). Ice storage zones reduce the volume or rate, or both, of ice moving to a downstream jam location. By developing low overbank areas, where ice can easily leave the channel during breakup, perhaps supplemented by dikes or booms to redirect ice movement, the volume of ice passing downstream can be substantially reduced. The ice left behind settles in side channels, the floodplain, or on the riverbanks. Another approach is designing and creating ice storage zones to *enhance* natural jamming. Measures such as minor channelization, tree removal, bank regrading, berm construction, and installation of booms, piers, or other in-stream structures can be employed to initiate an ice jam at a location where ice storage will be maximized, damage will be minimal, and potential for failure and release of the jammed ice is low.

g. Thermal control. Thermal control of ice jams uses an existing source of warm water to melt or thin a downstream ice cover. Water, even a fraction of a degree above freezing, can be quite effective in melting ice over a period of days or weeks (Wuebben and Gagnon 1995).

(1) External heat sources include cooling water discharges from thermal power plants, wastewater treatment plant effluent, and groundwater. The thermal reserve provided by water in nearby lakes and large reservoirs may also be a source of warm water for thermal control. Because water reaches its maximum density at a temperature of about 4°C (39°F), colder water in lakes tends to stratify above warmer water. An ice cover can form on the water surface, even though the water at depth is still well

a. Prior to freezeup

b. After freezup

Figure 12-4. Ice boom on Allegenhy River near Oil City, Pennsylvania

Figure 12-5. Ice piers for breakup control

above freezing. Warm water can be brought to the surface using air bubblers, pumps, or flow enhancers. In the case of a reservoir, a low-level outlet in a dam may be used to release warm water.

(2) Warm water inputs can thin an ice cover prior to breakup, so that it will not provide a jam initiation point. Warm water inputs can also reduce the volume of ice available to jam. Thermal control may be used to melt or thin an existing ice jam, thereby increasing the flow area within the jam and decreasing upstream water levels.

h. Floodplain land-use management and mapping. The best strategy for reducing flood losses is to keep people and property out of the floodplains. Appropriate land-use planning would dramatically reduce the flood damage potential. This is particularly applicable in areas that experience chronic flooding. Floodplain mapping is essential for careful land-use decision making. More than 20,000 communities have floodplain maps prepared by the National Flood Insurance Program. Since most flood insurance studies were prepared for open-water flood events, ice jam flooding may not conform exactly to the regulatory or mapped floodplains. However, these maps remain useful tools for determining general floodplain boundaries and elevations.

i. Floodproofing. There are four basic types of floodproofing to minimize damage to individual structures during floods (Figure 12-8). These are: 1) raising or relocating of a building, 2) barrier construction, 3) dry floodproofing, and 4) wet floodproofing. Specific techniques of floodproofing are presented in the Corps manual on floodproofing (U.S. Army 1991).

(1) Raising a building usually involves jacking it up and setting it on a new, higher foundation, so that the inhabited areas and utilities are above predicted flood levels. Care must be taken that the new foundation can withstand the expected forces from the water flow and ice and debris loading. Sometimes

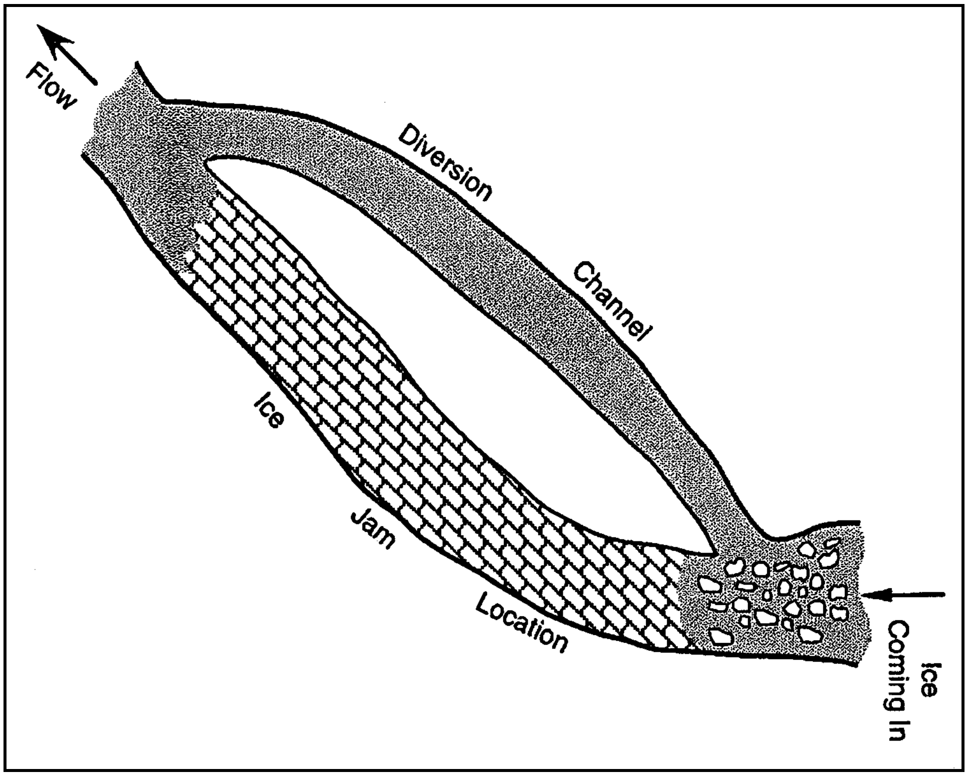


Figure 12-6. Schematic of diversion channel for ice jam flooding control

this requires openings to allow flow through the new foundation. Relocation of the building to higher ground is quite effective but not always possible or acceptable.

(2) While raising or relocating buildings are very effective methods of floodproofing, barrier construction can be equally effective in some cases. Barriers such as berms or floodwalls are constructed around a building to prevent floodwaters from reaching it. Openings in the barrier (for example, a driveway) should be avoided. Possible sources of flow through the barrier, such as seepage through the barrier and inflow from water or sewage lines, must be considered in barrier design.

(3) Dry floodproofing involves sealing the outside of the building to prevent floodwaters from entering. Dry floodproofing is usually only considered for cases where flood levels are less than a few feet above the base of the building, because at higher levels the pressure of the water (and ice) can collapse walls.

(4) Wet floodproofing allows the flood waters to enter a structure while at the same time minimizing damage by relocating utilities, such as furnaces or hot water heaters, above predicted high water levels. Wet floodproofing can be used where construction of barriers and dry floodproofing are not feasible.

12-5. Advance Measures

Mitigation measures deployed in anticipation of actual ice jam flooding are known as advance measures. These measures are used to reduce vulnerability to ice-jam-related flooding. Some emergency measures, such as ice removal, may also be initiated in advance of flooding.

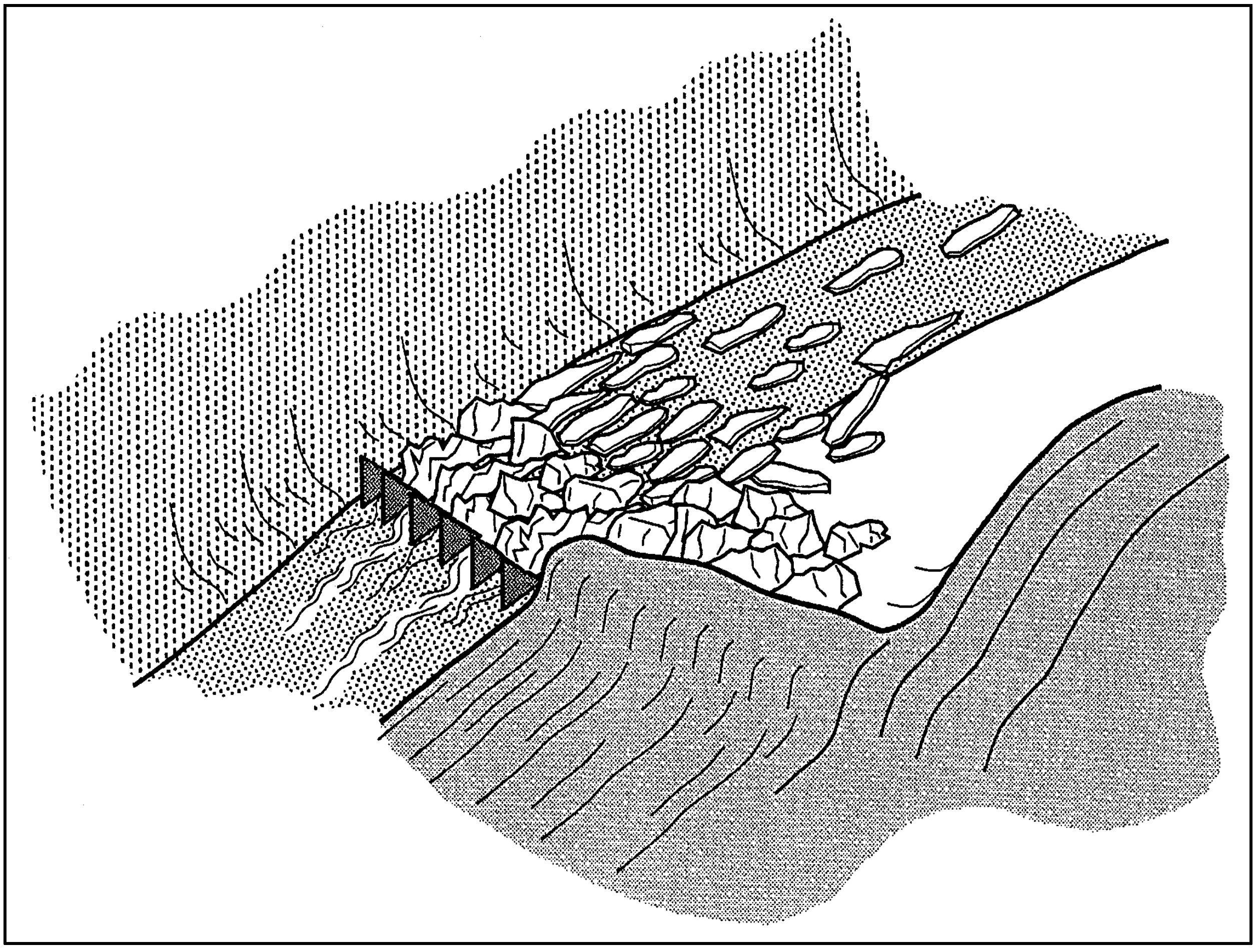


Figure 12-7. Ice storage zone combined with ice retention structure

a. Forecasting. Because of the highly site-specific nature of ice jams, limited available data on ice jams, and the complexity of the hydrological, meteorological, and hydraulic processes involved in the formation of ice jams, forecasting ice jam flooding on a general level is not yet feasible. However, it is possible to analyze various ice jam parameters and develop a range of values that can be used to estimate the likelihood of a particular ice jam occurring under certain conditions (Wuebben et al. 1992). As more communities adopt flood detection systems, forecasting potential to reduce losses improves. Refer to Chapter 11, paragraph 11-4, for additional discussion of ice jam forecasting.

b. Monitoring and detection. The effects of ice jam flooding are often more localized than those of open-water floods. Therefore, it is difficult to generalize ice jam data regionally. Since analytical techniques are less developed than those for open water floods, there is a stronger need for local historical data to serve as the basis for policy making. Simple remote gages to collect data on river ice movement and breakup are useful. Water level gages can detect any rapid increase in river stage, which often precedes ice breakup. Automated temperature sensors help to verify whether conditions are conducive to ice jam formation or breakup. Ice motion detectors (Zufelt 1993) can be imbedded in intact ice covers prior to breakup to give advance warning of the initiation of breakup upstream from a likely jam site (Figure 12-9). Existing gages can be augmented with telemetry transmitters that send data directly to a local monitoring center or State and Federal agencies (e.g., National Weather Service or U.S. Geological

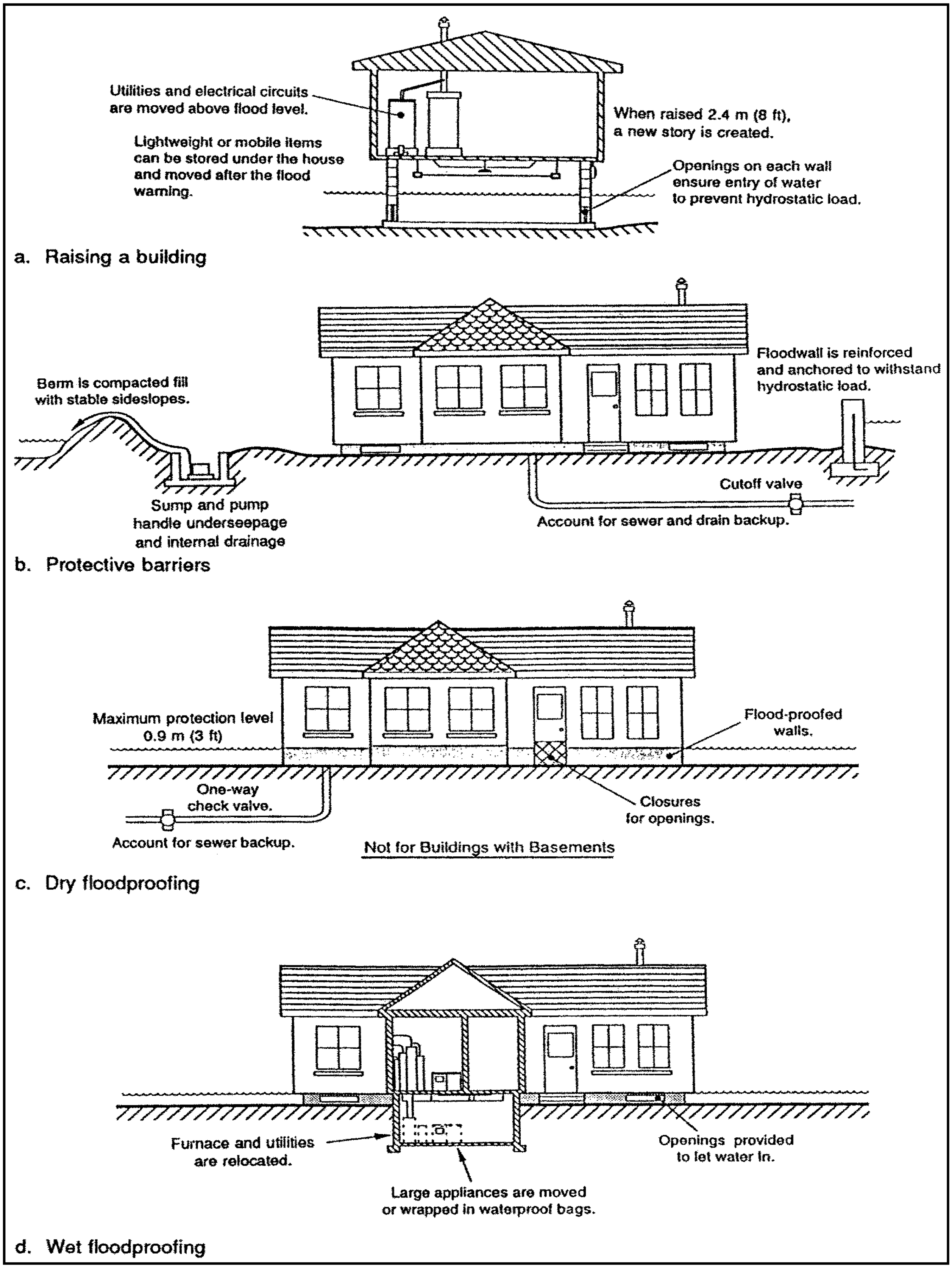


Figure 12-8. Floodproofing techniques (U.S. Army 1991)

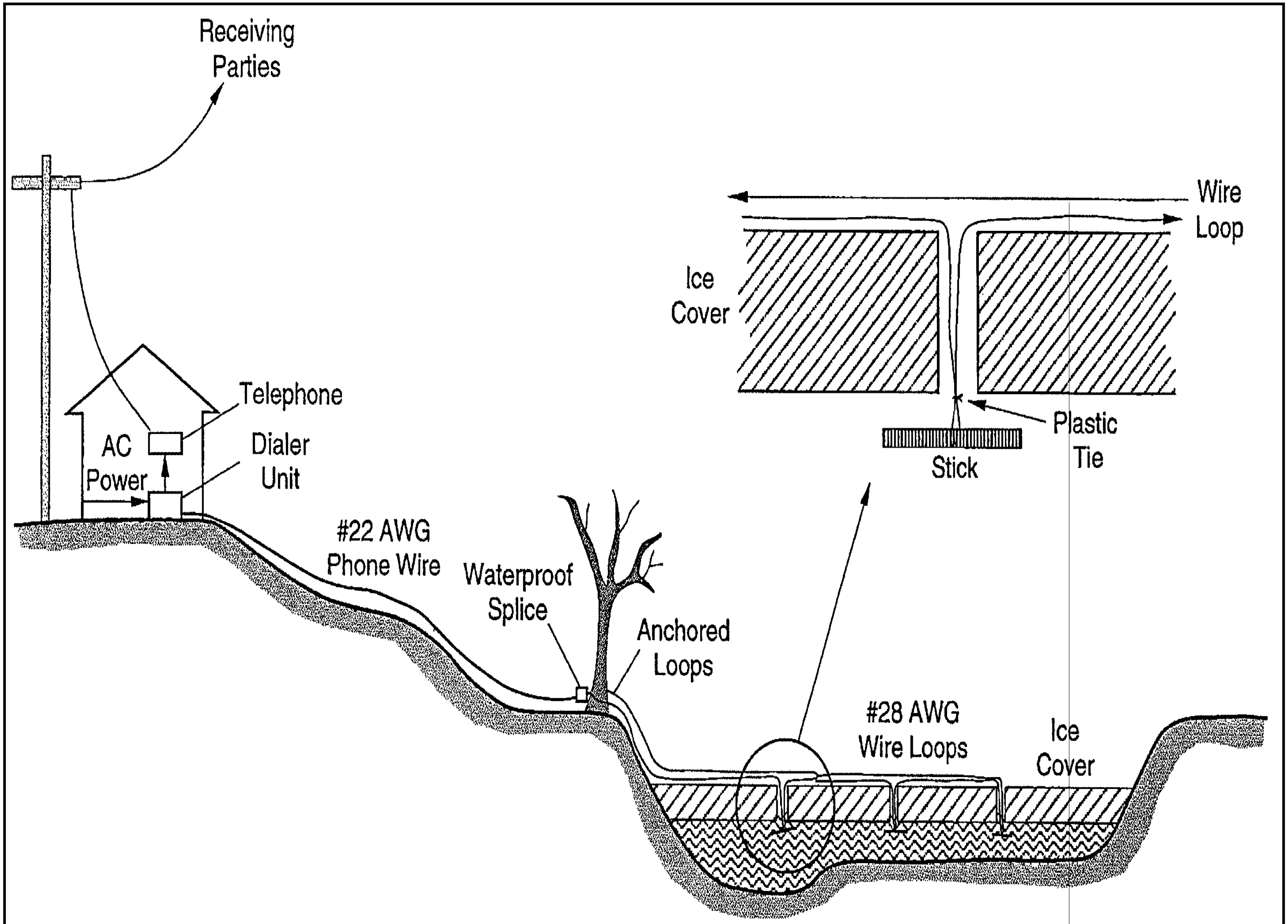


Figure 12-9. Schematic of ice motion detectors

Survey) by telephone, radio, or satellite. An effective warning system must include a fully developed response system, in addition to a detection system, to save lives and reduce property damages.

c. Ice cutting. Mechanical or thermal ice cutting creates areas of weakness in an ice cover. This technique may be used to cause a stable ice sheet to break up earlier than normal, preventing it from acting as an obstruction to movement of upstream ice. On the other hand, ice cutting in selected locations can create a flow path for ice and water at breakup, reducing the probability of jamming. Ice cutting (Figure 12-10) involves carving trenches in the ice, either mechanically (using a chainsaw, a trenching machine, a backhoe, or some other convenient device) or thermally (using a source of warm water or a substance that reacts chemically with the ice and melts it). The trenches can be partial or the full depth of the ice. They may follow the natural thalweg of the river channel, be cut along the edges of the channel to facilitate movement of the ice sheet, or be cut in a pattern designed to weaken the ice sheet. Ice cutting must be carefully timed to avoid refreezing the slots.

d. Revised operational procedures. Flow control may be available at dams or navigation structures located upstream or downstream from an ice jam problem site. The pool level can be raised or lowered to change the location of jamming in the river above the pool. Lowering the pool level early in the winter may expose some frazil ice production areas that would otherwise be covered. Lowering the pool after an ice cover has formed allows additional runoff storage before breakup. Discharge can be lowered at critical periods during ice formation to lower velocities and induce rapid and more extensive ice cover formation downstream. At breakup, lower discharge can decrease ice jam flooding or, in some cases, eliminate ice jam formation.

e. Dusting. By dust is meant any dark substance that can be spread on the ice in a thin layer to absorb solar radiation and thereby alleviate possible jam conditions before the fact. Covering ice surfaces with a thin layer of dark material induces more rapid melting and ice weakening (Figure 12-11). Conventional materials include coal dust, fly ash, top soil, sand, and riverbed material. Initial tests with biodegradable materials, such as leaves, mulch, and bark, show promising results (Haehnel et al. 1996). These types of materials are more easily spread than sand or coal dust by means of commercially available seeders and spreaders, but the materials must be dry enough to flow freely for even distribution and to avoid freezing. The rough surface of an actual jam creates so many shadows that dusting is generally not effective. Wind can be a problem, causing the finer dusting materials to drift or snow to drift over the dust (Moor and Watson 1971). Moor and Watson describe a reach of the Yukon River downstream of Galena, Alaska, which has regularly caused ice jams. Dusting this reach each spring, 2 to 3 weeks before breakup, weakens the ice sufficiently that the frequency of jams is much less there since the practice started. Ideally, the dust should be applied as early as possible but after the last snowfall.

(1) In general, the ice could be weakened by dusting in any reach where the cover regularly stops the ice run and causes a jam. The degree of melting depends on the quantity and material properties of the material deposited, solar radiation, and snowstorms. In areas where there are late snowstorms, several applications may be necessary. The melting period may be too short for significant reduction in ice volume or weakening if breakup takes place rapidly. The possible adverse environmental impacts of dusting materials must be considered before they are applied.

(2) The dusting operation should spread the material layer as evenly as possible. A surface concentration of about 50 percent should be the goal; too much dusting material insulates the ice rather than acting to promote deterioration. Important factors are time, the higher sun angles in the late spring, and good luck in avoiding snowstorms that would cover the dust. Agricultural aircraft generally apply

Figure 12-10. Ice cutting

the dust, which keeps costs fairly low. Moor and Watson (1971) give a cost of 34.9 cents (1970 dollars) per lineal foot (100 feet wide) ($1.14 per lineal meter [30.5 meters wide]) in a remote section of Alaska. White and Kay (1997) give 31.7 cents (1994 dollars) per lineal foot (30 feet wide) ($1.04 per lineal meter [9.1 meters wide]) for dusting on the Platte River, Nebraska.

(3) The particle size can vary, depending on what is available. Moor and Watson (1971) quote 0.5 pounds per square yard (0.27 kg/m^2) for sand and 0.35 pounds per square yard (0.19 kg/m^2) for fly ash. V.I. Sinotin (1973) gives similar rates: for 0.04-inch (10-millimeter) diameter dust he suggests 0.18 pounds per square yard (0.10 kg/m^2) and for 0.2-inch (51- millimeter) dust, 0.92 pounds per square yard (0.50 kg/m^2).

(4) A logical offshoot of dusting is to pump water and bottom materials onto the ice surface. This is limited to streams with silt or sand bottoms and, according to Moor and Watson (1971), is ten times more expensive than aerial dusting. However, the approach does have application where the stream is too narrow or sinuous for aerial work, or where environmental considerations preclude adding material to the stream.

12-6. Emergency Management for Ice Jam Flooding

Emergency measures are those taken after an ice jam has formed and flooding is imminent or already happening. The effectiveness of the emergency response may be reduced unless an emergency action plan exists that specifically refers to ice jams. Comprehensive emergency management includes four phases: preparedness, response, recovery, and mitigation. See *Natural Disaster Procedures*,

Figure 12-11. Ice dusting

ER 500-1-1, for additional information and guidance. Emergency planners should have a clear line of command for multi-governmental management of ice jam flooding events. Plans should be tested in advance to be sure that all phases can be carried out and that all necessary materials and equipment are available when needed. Before implementing emergency measures, it is necessary to monitor the river ice conditions upstream as well as downstream from the jam site so as to select the best measures and to eliminate those that may only displace the flooding problem to another location. Early ice monitoring can also provide lead time to allow other emergency measures to be taken. For example, the jam progression rate is important in freezeup ice jams, particularly when severe cold conditions conducive to rapid progression are forecast. For breakup jams, knowledge of the upstream ice thickness, extent, and relative strength is needed in estimating the remaining ice supply to the jam. The downstream ice conditions also need to be assessed, if only to determine whether or not there is sufficient open-water area to receive ice when the jam releases.

12-7. Emergency Measures

Ice jam emergency response measures include the specific measures of ice breaking, mechanical ice removal, and ice blasting, plus the traditional flood fighting efforts of evacuation, levee closing, and sandbagging, all of which qualify as advance measures.

a. Icebreaking. This technique is only usable in a few rivers. Ice covers can be broken prior to natural breakup using icebreaking vessels or construction equipment (Figure 12-12). Downstream movement of the broken ice should be enhanced to prevent localized breakup ice jams. Icebreaking is particularly useful to ease navigation in larger rivers and lakes. See Chapter 17 for a more comprehensive discussion of icebreaking.

Figure 12-12. Icebreaking vessel

(1) When the channel depth is sufficient and the ships are available, icebreakers are certainly the easiest, safest, and possibly the cheapest way to break up a jam. This operation is carried out by the captains, who are responsible for the safety of their ships, so little more needs to be said regarding safe operations. However, icebreaker operation can be expensive, and icebreakers cannot be used in small rivers of limited depth. The availability of an icebreaker on short notice and the difficulty of access to the ice in upstream reaches can also limit this method.

(2) Reinforced lake tugs and river icebreakers are used to clear harbors and rivers, primarily in the Great Lakes system. On large rivers open to commercial navigation, towboats are used to break a channel through level ice or localized ice accumulations. The most powerful towboats available are needed for this purpose. Ideally, two or more towboats work *en echelon* (staggered, one behind and to the side of the other), with the largest or more powerful towboat in the lead. The following ship has to be careful to ensure an equal width channel. If it crosses the path of the leader, the resulting narrow section will inevitably cause a jam and the downstream channel will no longer keep itself clear.

(3) Occasionally, if circumstances permit, an icebreaking vessel can work in conjunction with blasting (discussed below). The propeller wash and wave action of the ship will help to quickly clear the ice loosened by the blasting, and the ship will offer a factor of safety for the people on the ice. A combined operation like this will require extra cooperation as well as good communication.

(4) When a river ice jam is very thick, two towboats of essentially equal power have been used together. They mate-up bow to bow, and while the propeller wash of one boat loosens and erodes the ice, the second boat holds the first in position. This operation takes a great deal of skill and coordination between the pilots.

(5) Air cushion vehicles (ACVs) can break large extents of relatively smooth sheet ice covers, usually in areas where the sheet ice may stop the ice run and initiate a jam. The advantages of an ACV

are its speed and maneuverability and its ability to operate in shallow water areas. Disadvantages are that it breaks but does not move the ice, it cannot operate over rough ice accumulations because of potential damages to its flexible skirts, and operation in cold weather can lead to severe icing of the propulsion system.

(6) Construction equipment can be used to break up an ice cover or an existing jam, either from the shore or, if the ice is safe, from the river itself. It is generally best to begin at the downstream end of the ice cover and work upstream, so the broken ice will be carried away by the flow. A heavy weight or wrecking ball can be dropped repeatedly on the ice surface to break up the ice (Figure 12-13). Ice can be broken either to form a channel or weaken the ice in specific locations.

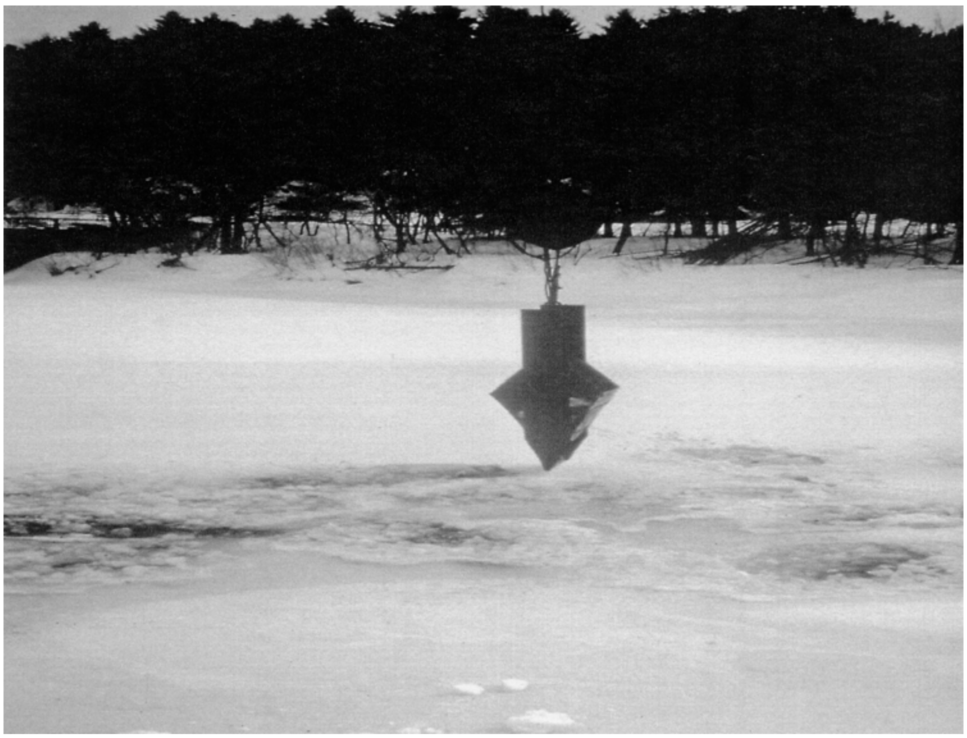


Figure 12-13. Icebreaking using a heavy wedge suspended from a crane

b. Mechanical removal. Mechanical removal involves taking the ice out of the river and placing it elsewhere using bulldozers, backhoes, excavators, or draglines, starting from the downstream end of the ice accumulation (Figure 12-14). This, of course, eliminates any downstream problems, but it is neither cheap nor fast. This approach is most effective on small streams, because the time required to excavate makes the technique prohibitive on larger rivers. Also, there are significant safety concerns associated with equipment operation on wide or deep rivers. The approach is limited to dry jams in relatively shallow streams. In other words, this approach is used generally for midwinter jams on small streams after the flooding has receded. The idea is to create a small channel within the jam. The lack of access for heavy equipment to an ice jam site frequently is an impediment to mechanical removal of ice.

(1) In February 1978 it cost approximately $11,500 (1978 dollars) to make a 790-meter (2600-foot) channel with one Caterpillar 235 backhoe. When the ice blocks are small and thin, mechanical clearing

a. Using a dragline

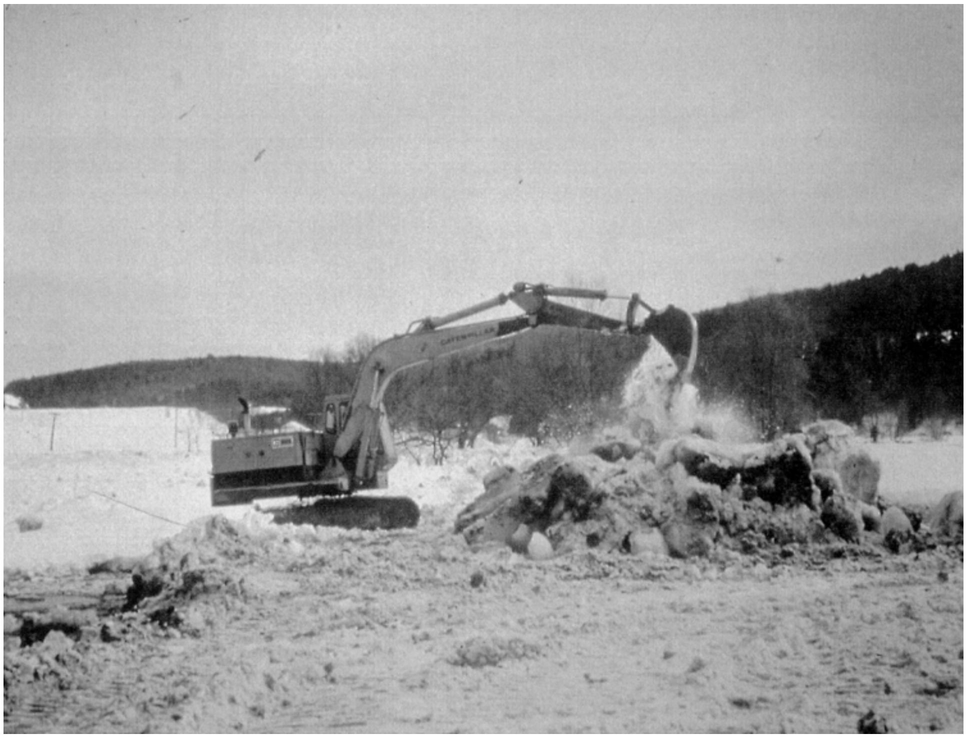
Figure 12-14. Ice removal

does not present too great a problem. When the blocks are around 3.0 × 3.0 × 0.6 meters (10 × 10 × 2 feet) or larger, small equipment is generally inadequate.

(2) Each site is different, so that equipment and methods used are up to the operator, who must be aware of the problems of power lines, poor bottom, and access. An immediate problem is disposing of the ice. Usually, it can be pushed to each side, leaving a channel about one-third the normal river width. In reaches where the channel has been severely restricted by man-made works, it may be necessary to remove all the ice.

c. Ice blasting. A popular solution to ice jam problems, blasting breaks up an ice cover or loosens an ice jam so that it is free to move. Successful blasting takes time and careful planning and execution.

(1) Absolute prerequisites to successful blasting are: 1) enough flow passing down the river to transport the ice away from the site, and 2) sufficient open-water area downstream to receive the ice. Otherwise, the ice will simply re-jam elsewhere and cause problems for another community. Blasting has been used to remove or weaken strong lake ice that initiated breakup jams at tributary–lake confluences, or to create a relief channel within a grounded jam to pass water and decrease upstream



b. With a backhoe

Figure 12-14. (Concluded)

water levels. As with icebreaking and mechanical removal, it is recommended that blasting proceed upstream from the toe of the jam.

(2) The ideal time to blast a jam is just after it has formed. In actuality, a jam is never blasted this quickly because a blasting crew and governmental approval cannot be mobilized until the jam is well formed and flooding has begun. If the flow has dropped because of cold weather or has moved into another channel so that after a blast there will not be enough water to carry the loosened ice downstream, the blasting should be canceled.

(3) While very dramatic, blasting is not a quick or easy solution. Blasting requires planning to locate and acquire the explosives, the equipment to drill holes, and the personnel. At all times when the crew is working on the jam, a lookout should be on duty upstream to sound the alarm if the jam lets go by itself. At least two people are required to drill holes, and depending on the roughness of the surface, at least four more to carry the charges to the holes. Add a blaster, a supervisor, and two people to load the charges and you have a crew of 11. With good luck this crew can blast two rows of charges along 0.8 kilometers (about a half mile) of river per day, possibly more when a routine has been established.

(4) To be effective, the charge should be placed below the surface of the ice, which may be dangerous or impossible during an ice jam event. If the sheet ice or jam is stable, holes can be drilled at regular intervals from the surface to receive the charges. If not, the charges need to be dropped from a helicopter into existing openings (if any) in the ice cover.

(5) To blast from the top of the ice, certain procedures should be followed to maximize the degree of success. It is important that each charge be placed in the water immediately below the ice so that the large gas bubble resulting from the blast will be most effective in breaking the ice. The charges should be

weighted to sink, but also roped to the ice surface so that they remain as close as possible to the ice underside and are prevented from being carried downstream by the current. As shown in Figure 12-15 (adapted from Mellor 1982), the diameter of the hole of the crater in the ice is primarily a function of charge weight, and is relatively independent of ice thickness. For example, a charge size of 18 kilograms (about 40 pounds) will create a hole of 12 to 14 meters (40 to 45 feet) in diameter for ice thicknesses ranging from 0.3 to 1.8 meters (1 to 6 feet). Two more or less parallel rows of charges, set close enough so that the craters intersect, usually give the best results by creating a wide enough channel to preclude most secondary jamming. The thalweg of the river should be located and the blasting line placed along it as much as possible.

(6) Although any kind of explosive can be used, experience has shown that ANFO works well. ANFO is a mixture of fuel oil with ammonium nitrate fertilizer. The mixture must be detonated with a strong booster such as a stick of dynamite, TNT, or other special booster charges sold by powder companies. The ANFO charge must be kept dry, and it is recommended that it be placed in a plastic bag that can also hold the weight (such as a brick or sandbag) necessary to sink the charge. ANFO will dissolve with time if a misfire takes place. This will avoid leaving live charges on the river bottom. As a guide, it is preferable to use Primacord for all downhole and hookup lines. The charge is then set off with one electric cap that is taped to the Primacord at the last moment after the blasting party is off the ice (see Figure 12-16).

(7) Safety and environmental concerns must be addressed before implementation. A formal safety plan covering all operations is necessary. It should comply with both local and Federal regulations. Such matters as person in charge, communication, transportation, warning personnel, etc., should be fully covered. In particular, blasting in populated or developed areas may lead to damages to surrounding buildings from falling ice chunks. In general, blasting should be a last resort.

d. Evacuation. The principle behind evacuation is to move people at risk from a place of relative danger to a place of safety via a route that does not pose significant danger. Local law enforcement departments usually serve as lead organizations employing standard operating procedures. Winter weather conditions should be taken into consideration when planning evacuation timing, equipment, and routes.

e. Levee closing. If ice jam flooding has been predicted, levees should be closed immediately and interior drainage pumps prepared for possible activation. Again, winter weather conditions that can hinder levee closing, such as snow drifts or frozen valves, should be identified. Monitoring water levels at levees may aid in the identification of possible overflow sites before there is serious damage.

f. Sandbagging. Although ice can cause significant damage to sandbags used as protective barriers, the use of sandbagging as an emergency response measure can be very effective in reducing damages at particular facilities or locations. For example, sandbagging around sewage treatment plants or low points on roads or river banks can significantly reduce flood losses (see Figure 12-17).

12-8. Case Studies

In Appendix B, seven case studies are presented that describe the solutions chosen to mitigate ice jamming problems in a wide variety of locations. The methods employed include thermal control, improved natural storage, ice retention, mechanical removal, floating ice booms, revised operational procedures, a

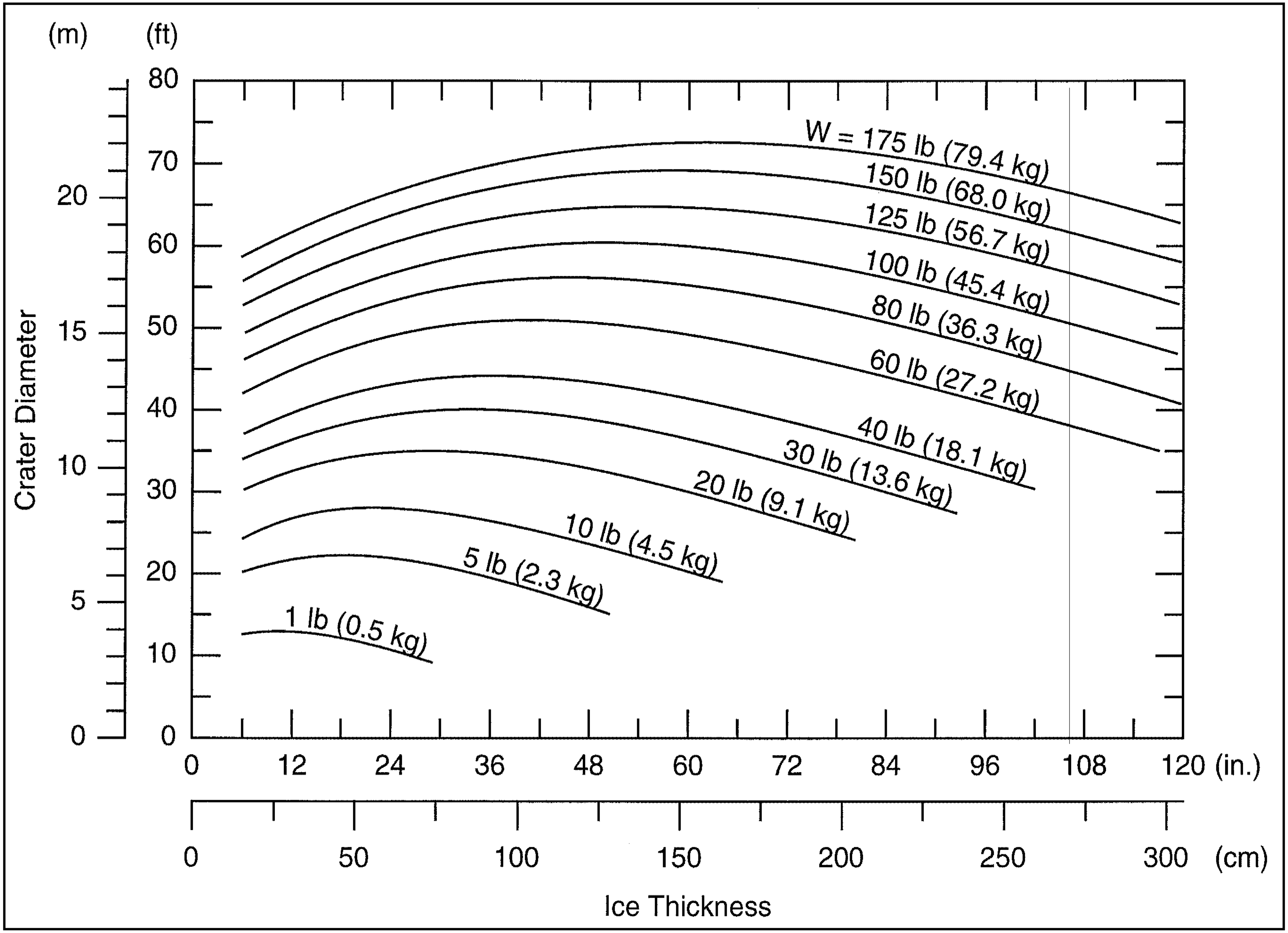


Figure 12-15. Crater hole diameter as a function of ice thickness and charge weight

Figure 12-16. Ice blasting

permanent ice control dam, an ice control weir, land acquisition, aerial dusting, floodproofing, and relocation. Review of these case studies will provide the opportunity to connect ice jam problems with successfully implemented solutions.

12-9. Conclusion

Each measure for dealing with ice jams described in this chapter has its own advantages and disadvantages. The decision as to which method to use may be easy. The difficult problem, particularly in the case of emergency measures, is to decide if any work is necessary. Will the jam go out by itself? How great a hazard really exists? Experience is helpful for this decision, but ice jams are not that common and few people have the opportunity to observe many jams for logical comparison. Thus, advice from local people familiar with the particular stream and its history is invaluable.

12-10. References

a. Required publications.
None.

b. Related publications.

ER 500-1-1
Natural Disaster Procedures

a. To protect sewage treatment plant

Figure 12-17. Use of sandbags in Oil City, Pennsylvania, in anticipation of ice jam flooding

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b. To protect downtown buildings

Figure 12-17. (Concluded)

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Part III: Winter Navigation on Inland Waterways

Chapter 13
River Ice Management Study

Section I
Study Concept

13-1. General

Operational or structural solutions to ice problems on rivers can be applied in several ways. They can be employed individually, case by case, to overcome the ice problems that are regarded as most important on a given waterway or portion thereof. This approach will solve ice problems, and in so doing, it will improve winter navigation. However, a shift of emphasis, from solving individual ice problems to maximizing the overall efficiency of winter navigation on an entire waterway, is a better technique; this results in the need for a comprehensive, system-wide approach. This system approach is essentially a planning process, culminating in the development of a River Ice Management (RIM) Plan that is unique for the waterway in question.

13-2. Objectives

The planning process works toward three objectives. First, winter navigation is to be conducted with the highest possible efficiency, approaching that of the other seasons of the year. Second, ice interruptions to navigation are to be kept as infrequent and as short as possible. Third, if a specific ice emergency does happen, all reasonable and possible ice-problem solutions will have been identified and implemented where appropriate, with the assurance that no further action could be taken to alleviate the emergency.

13-3. Elements

In the remainder of this chapter, the elements of a study leading to a River Ice Management Plan are identified and discussed briefly. Appendix C summarizes the elements in outline form. In the remaining chapters of the manual, these several elements, which include the various operational and structural solutions to river ice problems affecting navigation, are addressed in much greater detail and, in several instances, illustrated by examples.

Section II
Study Elements

13-4. River System Definition

Managing river ice is almost a basin-wide effort; so, knowing the exact configuration of the river system is very important. The primary concern is the main, navigable stem of the river. However, non-navigable reaches of the main stem that are bypassed by locks and canals are also of major interest. It is necessary to know what percentage of the flow goes through each section and what the water velocities are. The tributaries are of interest because they add ice to the system. Also to be identified are any features that affect ice passage or accumulation, e.g., channel geometry, confluences, and man-made or natural channel restrictions.

13-5. Ice Problem Identification

Proper implementation of a winter navigation plan requires that problems be identified, along with their locations and sources (see Chapter 14).

a. Certain problems are natural phenomena and are inherent to navigation during winter months. Ice jams may limit passage through a section of river. Ice accumulation in the upstream approaches at many locks causes shipping delays as vessels must wait for ice to be locked through.

b. Other problems are more directly induced by winter navigation. Ice builds up on the undersides of barges, sometimes resulting in scraping and damage to the riverbed or miter gate sills. Barges having underside ice buildup have grounded and blocked channels on the Upper Mississippi River, and the normal dredging response to a grounding is very difficult under ice conditions. Moored barges may be broken away by moving ice, resulting in damage to downstream structures. Increased traffic during periods of ice may increase bank erosion significantly.

c. The source of the ice that creates the problem needs to be identified. Possible ice sources include tributaries, upstream locks and dams passing ice, and vessels traveling out of established tracks. Once these ice problems and their ice sources are identified, an appropriate solution, whether operational or structural, can be considered. Not to be overlooked are possible future changes in the river system that may have an influence on ice formation (e.g., changes in water quality affecting freezing temperature).

d. All possible scenarios are to be considered in implementing a winter navigation plan. Past ice emergencies on the river system in question should be thoroughly examined. Emergencies have been avoided by varying operational schemes. Solutions to ice emergencies on other river systems should also be examined, so that nothing is overlooked. Once a winter navigation plan is developed, it should be analyzed with all possible ice emergencies in mind and revised as necessary.

13-6. Ice Forecasting

Forecasting river ice conditions means predicting when and where ice will form, how thick it will be, the extent of the ice cover, and how long it will last. Practically, there are two types of river ice forecasts. The first is a *Long-Term Water Temperature Forecast.* This is made (starting in the fall) to predict river water temperatures to determine when the water will reach the freezing point, making ice formation possible. The present water temperature at the time the Long-Term Water Temperature Forecast is made must be known, and a forecast of air temperatures must be made or be available. The water temperature response to changes in the air temperature can be determined by examining records of water and air temperature of previous years. This type of forecast can be made for periods of several days to several months. The second type of forecast is a *Mid-Winter Ice Forecast.* Typically, these are made for periods of a week or less, predicting the water temperature, the volume of ice that will be formed or melted, where the ice will form or melt, the extent of the river that will be covered with ice, and the ice thickness. To make a Mid-Winter Ice Forecast, the existing stages, discharges, water temperatures, and ice conditions along a river must be known. Forecasts of the air temperature, tributary discharge, and tributary water temperature must also be made or be available. Locations and amounts of possible artificial heat inputs into the river must be known. A heat balance can be determined for the river system that will indicate the volume of ice that will be formed or melted. The extent of the ice cover and its thickness are calculated using the river velocity, flow depth, and type of ice. The Mid-Winter Ice Forecast will produce forecasts of the discharge, stage, ice thickness, and water temperature at each point specified along the river. Under the RIM Program, forecasting methodologies to produce both types of forecasts were developed, and are described in greater detail in Chapter 15. Each has the ability to include real-time data provided by Corps data systems, to incorporate short-term and long-term forecasts of air temperature, and to provide the specified outputs.

13-7. Structural Solutions

Structural solutions are covered in detail in Chapter 3 and additionally in Chapter 18. In brief, they involve controlling ice by installing some type of structure or device where it will have a desired effect on either an ice cover, ice floes, brash ice, frazil ice, or ice adhering to navigation structure surfaces. The desired effect may be to divert ice away from the main channel, to prevent ice from moving out into the channel, to keep an ice cover from being broken up by wind and wave action or by ship activities, to reduce the quantities of ice passing a particular point, or to reduce the amount of frazil ice forming in a reach. In the vicinity of a navigation structure, the objective may be to block or divert moving ice from a lock entrance, to pass ice from the pool through the dam to the channel below, or to reduce or eliminate adfreezing on walls, gates, and other surfaces.

a. A common structural solution is an ice boom, which is a line of floating logs or pontoons across a waterway used to collect ice and stop ice movement (a navigable pass can be provided in the boom). The boom is held in place by a wire rope structure and buried anchors. Other solutions may use weirs or groins supplemented by booms. Artificial islands and navigation piers can also be helpful in stabilizing ice covers. The various methods for inducing a stable ice cover to form are used in locations where ice covers need to have additional stability to compensate for the disruptive forces of winter navigation or short-term weather changes.

b. Structural solutions in and around navigation projects include devices that are installed to help mitigate particular ice problems that pose a direct interference to project operation. High-flow air systems are effective in deflecting and moving brash ice away from critical locations in a great variety of circumstances. Flow inducers have also been installed in lock chambers to assist in keeping areas ice-free. Ice passage at navigation dams is made more practical by certain structural features, such as submergible dam gates, or bulkheads, which can be raised from lock chamber floors to serve as skimming weirs for passing ice. Ice accumulation on critical surfaces such as gate recess walls, strut arm roller rails, and seals can be effectively controlled by installing electrical heating devices of several specialized designs. Other proven measures for controlling ice accumulation on structure surfaces are coatings and claddings. Coatings, such as epoxies and copolymers, reduce ice adhesion forces between ice and concrete or steel surfaces. Claddings, such as high-density polyethylene, are replaceable surfaces from which ice can be chipped more easily than from concrete or steel.

c. Each of the possible structural approaches is effective for a particular ice problem. Many ice problems require a combination of structural solutions, often teamed with operational solutions, to fully mitigate the difficulties imposed by ice.

13-8. Operational Solutions

There are various operational techniques to control or mitigate ice problems at navigation projects. Thermal methods are presented in Chapter 3, Section II, with additional discussion specific to navigation projects in Chapter 18, Section III, and Chapter 19, Section III. Additionally, when lock and dam personnel apply the structural solutions as mentioned above or described in Chapters 3 and 18, these applications actually become operational techniques in themselves.

a. Moving tows in convoy, i.e., scheduling vessels to move together in large groups during periods of heavy ice conditions, has been shown to hold some promise for the navigation industry. The appeal of this to the Corps is that it can cause less ice to be produced in a winter season, and thus reduce the amount of ice that has to be locked through, diverted, or passed at a navigation project.

b. At locks and dams, the operational techniques vary from physical ice removal using various tools, to flushing ice from critical areas with towboat propwash and passing ice through the dam spillway gates. Separate lockages of ice are sometimes required to accommodate tow traffic. Maintaining high lock chamber pool levels can keep lock walls at a higher temperature than if they were exposed to cold air. As a result, ice buildup on the wall surfaces may be lessened. Careful operation of seal heaters aids substantially in reducing ice buildups at dam gates, helping to keep the gates operational.

c. Warm water discharges offer opportunities for ice suppression at certain locations. The warm water may originate from power plant cooling systems, industrial plants, or reservoir discharges. The distributions of these warm inflows influence their effectiveness in melting or weakening ice, or in maintaining open-water areas.

d. Energy from unconventional sources, such as heat from groundwater, solar heating, or wind energy, has been thought to offer promise for ice control at navigation projects. However, analyses have shown that this would be likely only in a very few restricted cases. Nonetheless, electrical heating appears to be the most efficient way to accomplish many ice control tasks at navigation projects. The key is to select the most practical source for electrical energy.

13-9. Recommended Plan

The objective of the study or system analysis, composed of the foregoing study elements, is to develop a River Ice Management Plan. In practice, it may be more reasonable to develop several alternative plans, each of which may have attractive features. While it may not be possible to apply a strict benefit–cost analysis to most ice management plans, such criteria should at least guide the choices of the feasible alternative plans from among the many variations and versions examined. Generally, it will be possible to select one of the alternative plans as the most desirable, in that it provides the highest net benefit or is most likely to eliminate chances for ice emergencies. This is then designated the Recommended Plan. The Recommended Plan may include, among other things, structural measures for improving the winter capabilities of navigation projects. For reasons of financial, personnel, and time resources, a realistic time span must be assumed to accomplish these structural improvements. Therefore, it would be most reasonable to express the Recommended Plan in terms of phases, with the individual phases chosen and ordered according to their anticipated individual benefit–cost ratios. In simple terms, as outlined in Appendix C, a system approach covering many study elements leads to a Recommended River Ice Management Plan for a given waterway or part thereof. The Recommended Plan then serves as a goal toward which subsequent operational and structural decisions lead, resulting in increased efficiency of winter navigation and the supporting operation of navigation projects.

Chapter 14
River Ice Problem Identification

14-1. Surveys Needed

To fully understand the ice processes involved and their effects on winter navigation, the entire river system needs to be fully defined. A general survey of the river system should be made, defining its hydraulic characteristics under open-water conditions, as well as how these characteristics change in times of ice. This survey should indicate how extensive the ice problems are and where they are most concentrated. Areas of ice generation, growth, and deposition, as well as ice-cover initiation points, should be identified. All tributaries must be considered to determine their ice inputs during freezeup, throughout the winter, and during breakup periods. Existing hydraulic structures, such as navigation dams, locks, or hydropower installations, should be examined to see how they influence the river system under present operating procedures. Can these structures control flow? Do they retard velocities, thereby causing ice deposition? Which dams pass ice and how do they pass ice? What influence does ice passed through a dam have on ice problems downstream? What facilities exist for ice passage at locks and dams? Some dams may only be able to pass ice during high flows, while other structures use the auxiliary lock chamber for routinely passing ice. Questionnaire-type surveys can be employed to gain the information outlined above (Haynes et al. 1993, Zufelt and Calkins 1985). These surveys should poll river users as well as the operators of any structures. These and subsequent interviews with specific users will yield information about things such as areas of ice cover, areas of ice generation, ice thicknesses, types of ice, and restrictions to flow and ice passage. Ice problem locations can be identified, as well as other areas of concern, i.e., high traffic areas, temporary fleeting areas, etc.

14-2. Hydrology and Hydraulic Studies

Records should be examined to determine if there have been any previous hydrological or hydraulic studies of portions of the river system. Flood insurance studies, working numerical hydraulic models, navigation models, and backwater studies may offer data on flow velocities, discharges, stages, operational procedures, etc. Some existing mathematical models (such as HEC-2) have been adapted to incorporate an ice cover into the system. Rainfall and snowmelt runoff models for tributaries may give insight into when and with what magnitude the ice cover will break up. Past physical model studies of navigation structures or hydropower installations can give insight into ice movement, accumulation, and passage, as well as ice effects on tows. Ice retention in tributaries and non-navigable main stem reaches must be studied. Existing and planned physical models can incorporate ice studies into their modeling sequence. In conducting any hydraulic or hydrological studies, it is important to obtain as much information on the ice characteristics of the river system as possible. Winter field observations are an invaluable source of information on ice thicknesses and areas of ice cover. Operational logs of lock and dam facilities usually contain information on weather and waterway conditions. Hydropower and other power plants, as well as water supply or treatment plants, often keep records of water and air temperatures, along with ice conditions at their intake or outfall structures. Towing companies sometimes keep records of ice conditions, especially when they affect shipping schedules. River users and structure operators generally have a good knowledge of average winter ice conditions and these people should be interviewed.

14-3. Identification of Ice Problems

Ice problems should be identified by type, location, and severity. On-site observations of the problem areas are also useful. A survey questionnaire to poll river users and structure operators is quite valuable. A sample questionnaire is shown in Figure 14-1.

1. Location: River ____________
   Mile ____________
2. Hydraulic structure: No ______ Yes ____________
   Name ____________
3. Problem area: Bend ____________
   Island(s) ____________
   Spillway Gates ____________
   Lock Gates and/or Approaches ______
4. Description of problem: (use reverse side if necessary)
   ____
   ____
   ____
5. Documentation available: Reports* ____________
   Memos* ____________
   Individuals ____________
   (*copies appreciated if available)
6. Have there been any attempts to alleviate the problem?
   No ______ Yes ______
   If yes, Re-design ____________
   Operational changes ____________
   Reports ____________
7. How does this problem rank with other ice problems in your jurisdiction in its impact on the operation of the structure/river system?
   High ____________
   Medium ____________
   Low ____________
8. Identify any structures that have been specifically designed, modified, or retrofitted to alleviate this ice problem:
   Site   Point of Contact   Address & Telephone Number

Figure 14-1. Questionnaire for collecting information on ice problems affecting navigation projects and navigational activities

a. Information sources. Aerial photos and video coverage of the river system during winter can provide data on problem type and location, although problem severity is best estimated by those with firsthand knowledge of the area. Lockmasters, towboat operators, and homeowners adjacent to the area in question are an excellent source of data and should be polled or interviewed as necessary. Operations personnel are usually well informed of problem areas, including emergency conditions.

b. Problem categories. There are two general problem categories: those occurring at or near navigation structures, and those occurring in the river pools between navigation structures. Navigation dams may experience limited ability to pass ice moving downstream because of gate-setting limitations. Spillway gates may ice up because of leaking seals or normal operations, resulting in restrictions in movement, overstressing of structural components, or even inoperability. Lock facilities may experience ice accumulations in the upper and lower approaches or behind miter gates, slowing operations significantly. Ice may adhere to the lock miter gates, lock walls, line hooks, vertical checkpins, or floating mooring bitts, resulting in increased winter maintenance. Problems generally associated with areas away from navigation structures include severe ice accumulations or jams near islands and bends, tributary ice inflows, and problems encountered near docks and fleeting areas. Following are detailed descriptions of typical ice problems that have been reported in the past. This list, however, is not all-inclusive.

14-4. Ice Problems Around Navigation Projects

a. Ice in upper lock approach. Broken ice, carried downstream by the river current and wind, or pushed ahead of tows, often accumulates in the upper lock approach, causing delays (Figure 14-2). Separate ice lockages often must precede the locking of downbound tows, and flushing ice during these ice lockages is difficult. Occasionally, a tow must back out of the lock after entry because the ice doesn't compact in the chamber as much as expected, preventing the tow from fully entering the lock chamber and thus causing further delays. Upbound tows may have to limit their size to be assured of enough power to push through the accumulations of ice. Tow haulage units usually have too little power to pull the first cuts of double lockages out of the chamber against heavy accumulations of ice. So, double trips or smaller tows are called for. During periods of low traffic, ice accumulations sometimes freeze in place, causing further delays and difficulty in operating the upper gates.

Figure 14-2. Ice accumulation in the upper lock approach area

b. Lock miter gates. Ice accumulations in the upper lock approach can cause pieces of ice to become wedged between the miter gates and the wall recesses (Figure 14-3). Ice pushed into the lock chamber ahead of downbound tows causes the same difficulties for the lower gates. The gates must be fanned or the ice pieces prodded with pike poles to make them move out of the way. Sometimes, compressed air lances or steam jets are used to disperse the trapped ice.

c. Ice buildup on lock walls and miter gates. During extremely cold weather, and with fluctuating water levels in lock chambers, ice will build up on the lock walls and miter gates, forming a collar (Figure 14-4). This collar is thickest at the upper pool level. Enough ice can build up on the walls to keep the gates from being fully opened, thus limiting the width of tows and leaving the gates exposed to

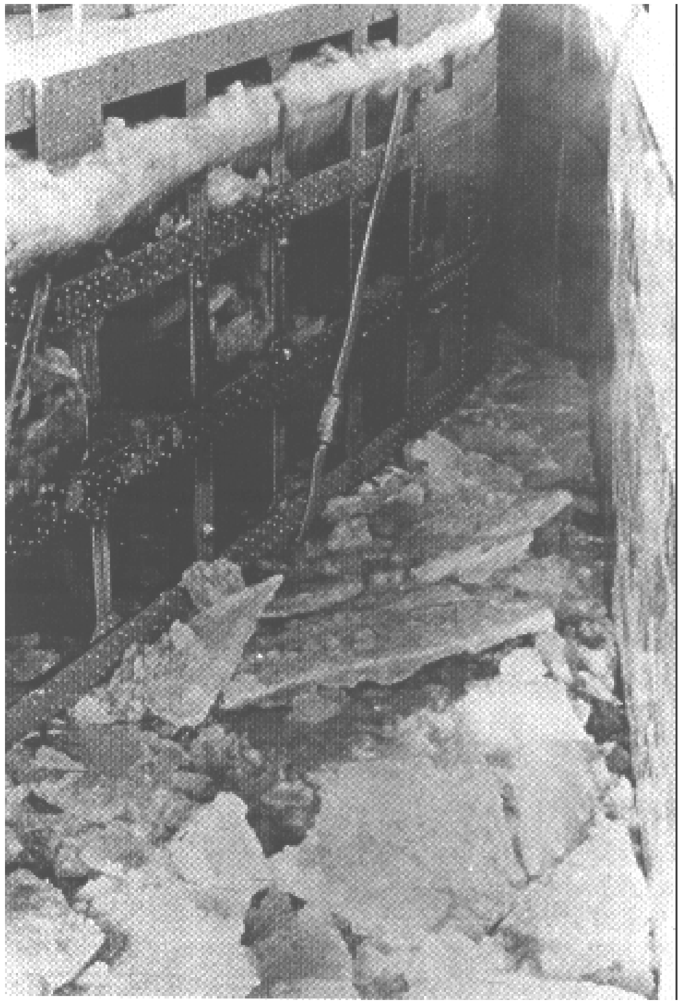

Figure 14-3. Broken ice accumulation between the lower miter gate and the gate recess wall, which hinders full recessing of the gate

damage. Even where the buildup is minimized or controlled in the gate recesses, ice on the chamber walls can be thick enough to restrict tow widths. Most of the inland waterways that have barge traffic can place width restrictions on the lock chambers. This is not desirable, but at least it allows navigation to continue with narrower tows. (On river systems such as the St. Marys or the St. Lawrence, however, the usable width of the locks is critically important, because the vessel widths can't be reduced.)

d. Floating mooring bitts. Ice pieces may jam between the floating mooring bitts and the lock wall, rendering the bitts inoperative. Ice layers may build up on the wheels, track, or flotation tank of a bitt (Figure 14-5), causing the bitt to freeze in place; the bitt can then dangerously and unexpectedly jump upward from its submerged position. Usually, bitts must be tied off at the top of the lock wall and remain unavailable for winter use.

e. Vertical checkpins or line hooks. The vertical checkpins or line hooks in the lock walls may accumulate layers of ice because of fluctuating water levels. This causes difficulties when check lines slip and jump off the pins or hooks.

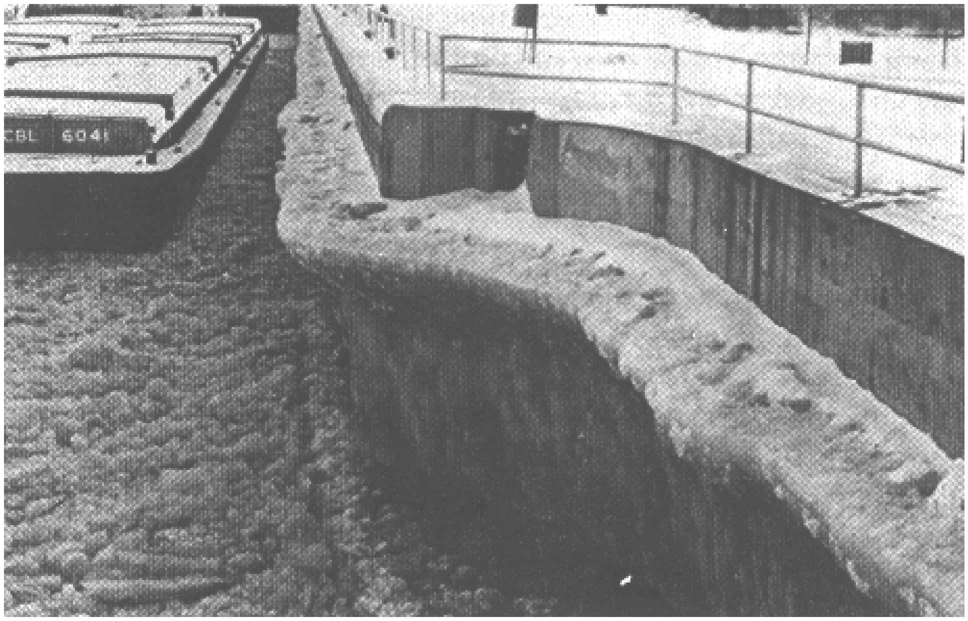

Figure 14-4. Ice collar formation on the gate recess and chamber walls, restricting the full opening of the miter gates and limiting the usable width of the lock

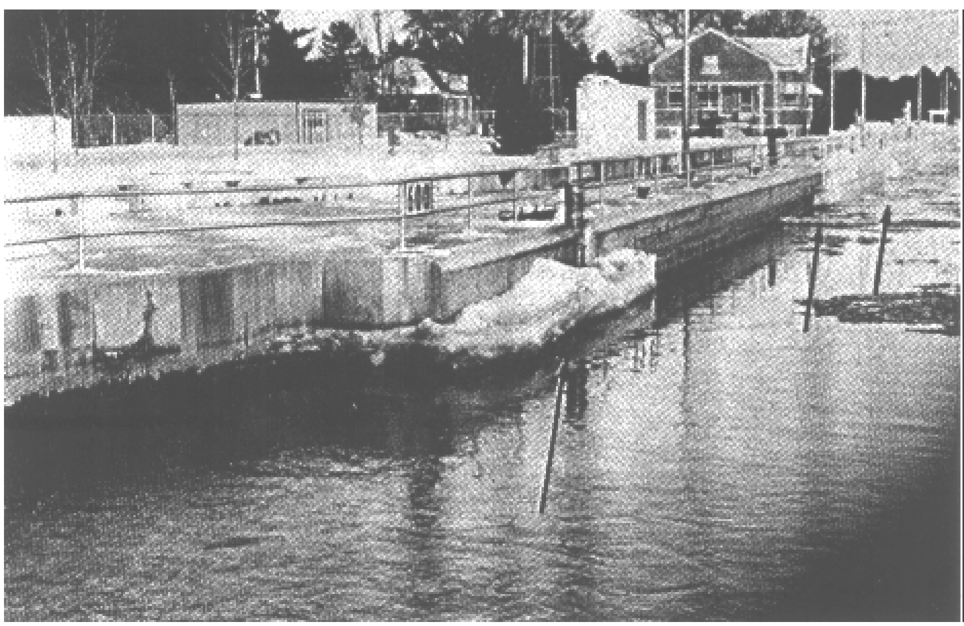

Figure 14-5. Ice interference with floating mooring bitts (arrows) in a lock chamber wall

f. Ice in lower lock approach. Ice may accumulate downstream of a lock because of upstream wind, or an island, bend, or other constriction. Ice passing through the lock or over the spillway adds to this accumulation. The continual buildup of ice may block the entrance to the lock for upbound tows.

g. Dam spillway gates. Broken ice carried downstream usually accumulates at the dam (Figure 14-6). During periods of low flow, normal gate openings are small and will not pass this ice. Low tailwater presents a problem of excessive scour if gates are raised high enough to pass the ice. In colder weather, these accumulations will freeze in place, making it necessary to break up the ice to start it or keep it moving (usually done by towboats). Some lock and dam facilities have been equipped with submergible tainter gates specifically designed for passing ice and drift. At a few installations, the gates are rarely used in the submerged settings, owing to excessive vibrations that could cause damage to the gate and supporting structure of the dam. Some of these submergible gates have been retrofitted to prevent them from being used in the submerged position. Other lock and dam facilities report no problems with operating these gates in the submerged position. A feature of all submergible gates is that they leak more than nonsubmergible gates. In winter, freezing of this leakage adds to the problems described in the following two paragraphs. Three installations on the Monongahela River are equipped with split-leaf (movable crest) tainter gates, designed for passing ice and debris. The gates seem to work well, but during periods of low flow, towboat assistance is required to break up the ice behind the dam and start it moving. Lock and Dam No. 16 on the Mississippi has reported that an emergency bulkhead placed in the entrance to a roller gate bay passes ice well.

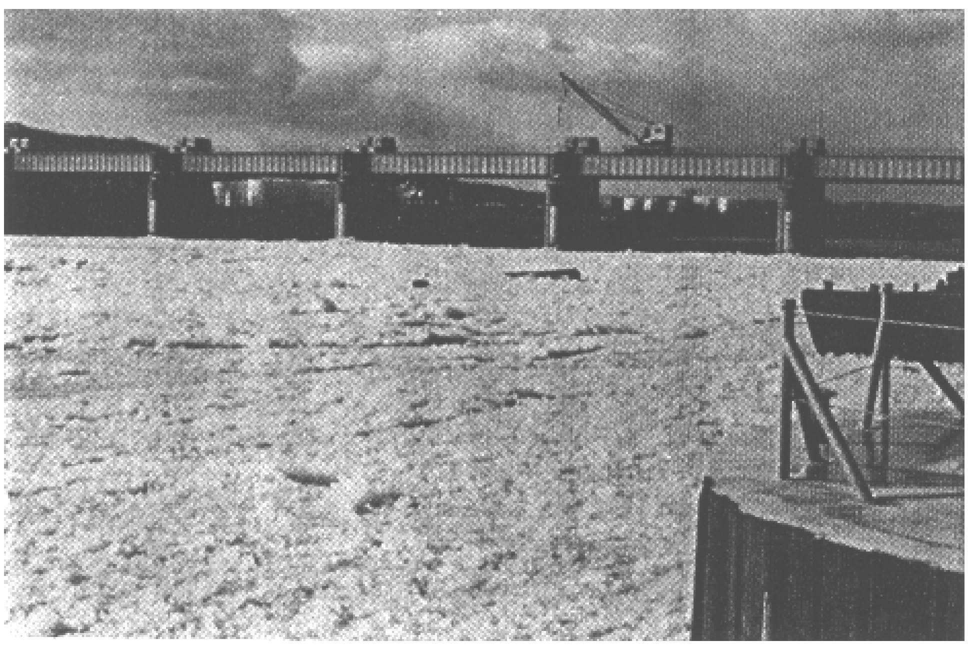

Figure 14-6. Ice accumulation upstream of the gates of a navigation dam

h. Spray icing of spillway gates. Spray from the operation of spillway gates can cause ice to form on the pier walls or under the arms of tainter gates (Figure 14-7). This may cause jamming or stop the gates from fully closing. In some cases, the weight of ice formed on the gate structure is so great that the operating machinery cannot raise the gate.

i. Tainter gate seals. The side and bottom seals of tainter spillway gates may leak, causing spray. This spray results in ice buildup on the pier walls or the gates themselves, causing operational difficulty

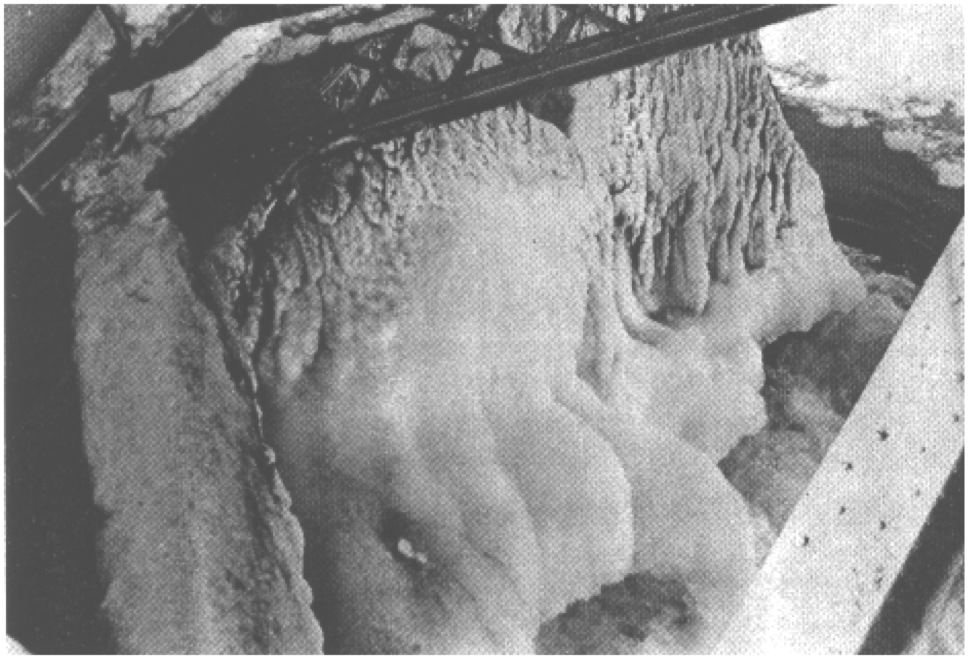

Figure 14-7. Tainter gate structure and gate pier wall with icing that has accumulated through spray and splashing in the course of winter operation

(Figure 14-8). It is possible for this ice to bridge across from the pier to the gate, rendering the gate seal heaters ineffective. During severe cold, the gates must be moved frequently or they will freeze in place. Attempts to operate gates when frozen in place can result in damage to the operating machinery, hoisting mechanisms, and chains or cables.

j. Ice formation on intake trash racks. Broken ice and frazil ice can accumulate on trash racks, causing a reduction in flow. This results in loss of water supply and possible shutdown if flows are substantially blocked. In the case of hydropower intakes, power production may be interrupted.

14-5. Ice Problems Occurring Between Navigation Projects

The channels around islands, bends, and other constrictions tend to accumulate thick deposits of ice (Figure 14-9). During periods of significant ice, these accumulations may form jams, which can cause scouring and eroding of bed and banks. Navigation can be interrupted or delayed and structural damage is possible, especially during breakup of the jam. Minor jams may raise the water level upstream, while major jams can cause severe flooding. Tows must limit their size in some problem areas.

a. River bends. River bends are often the cause of ice accumulation. The nonuniformity of depth and velocity over a bend cross section, coupled with secondary flow circulation, results in a nonuniform ice cover. Under open-water conditions, multiple cells of secondary currents are set up that, in general, push surface water toward the outside of bends and bed material toward the inside of bends (Figure 14-10). If these same circulations exist under ice conditions, one would expect thick accumulations on the outside of bends, while the relatively tranquil flow on the inside of the bend would allow shore ice to form easily, reducing the open surface width. Limited laboratory experiments (with a fixed bed) have shown that these secondary currents may be modified by the presence of an ice cover, further compounding the nonuniformity of the ice cover. In addition to this nonuniformity, vessels often have

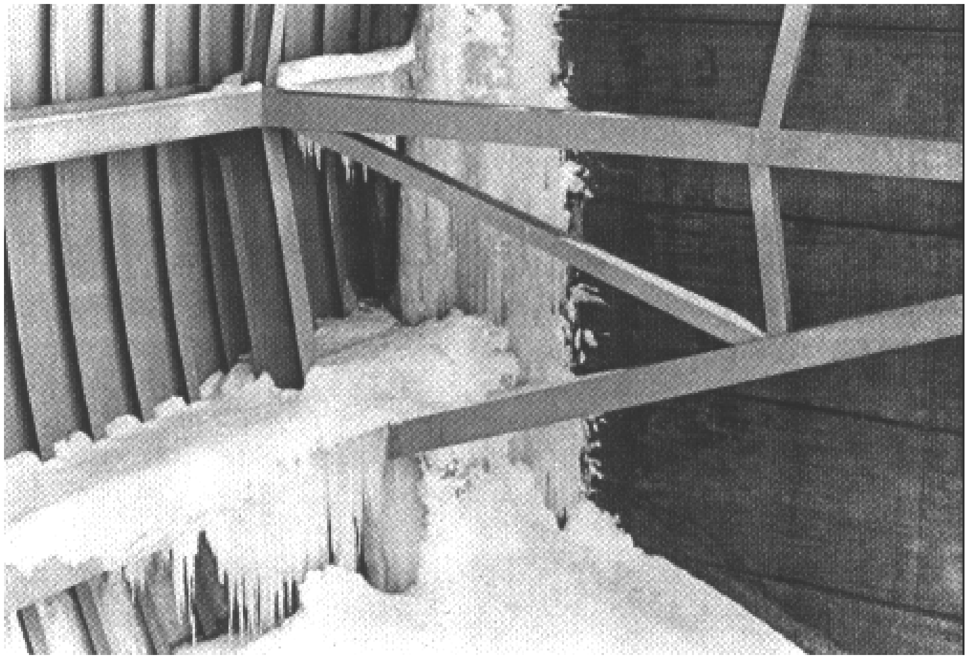

Figure 14-8. Tainter gate frozen in place by ice formed by leakage past the gate's side seals

Figure 14-9. Heavy accumulations of ice floes and brash ice

trouble tracking around bends under ice conditions, particularly severe bends as on the upper Monongahela River. Figure 14-11 shows a vessel track around a severe bend. Note the wide, irregular appearance of the track caused by transiting problems. Experience in the Pittsburgh District indicates that river bends having 110 degrees or more of curvature will cause transiting difficulties when ice is present.

b. Reduced open width of river surface. Laboratory experiments with plastic "ice" have shown that there is a relationship between the characteristic size of ice floes and the open width of a channel for the occurrence of arching and channel blockage. Once blockage has taken place, an accumulation of surface

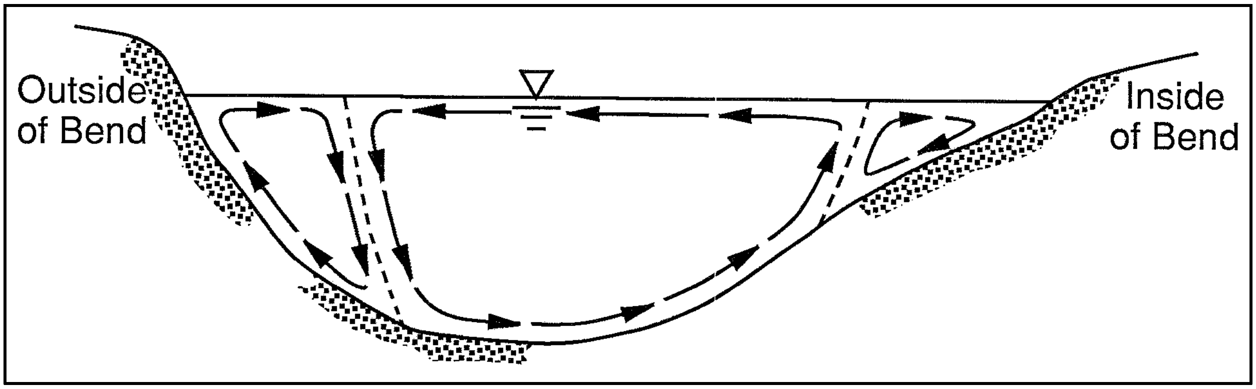

Figure 14-10. Transverse velocities forming secondary circulation cells in river bends

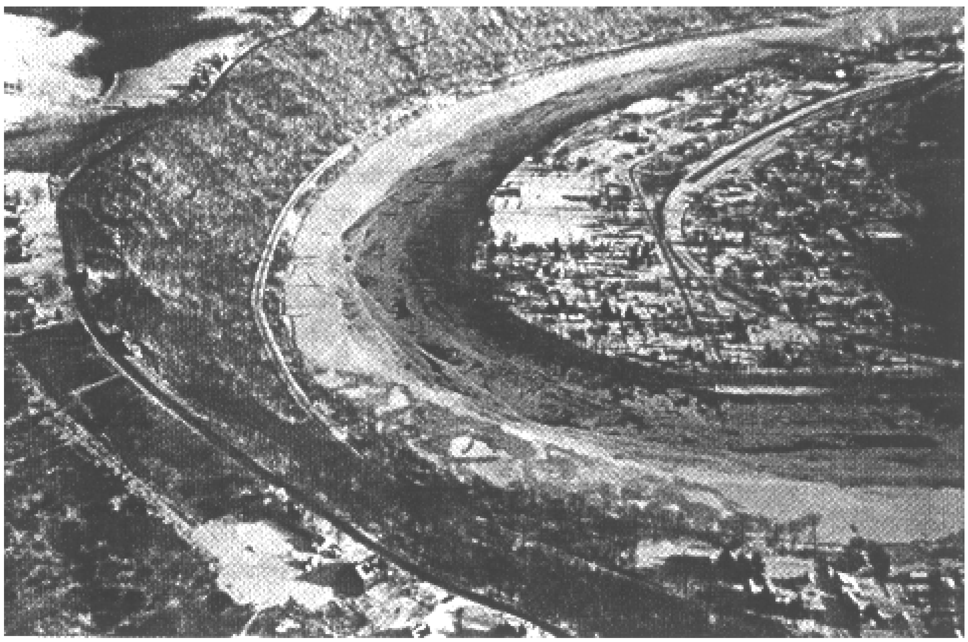

Figure 14-11. Broken, irregular vessel track around a sharp river bend, indicating difficulties in navigating through the ice

floes may progress upstream. One mechanism that accelerates the blockage process is the growth of shore ice, which reduces the open width of the river surface. The shore spans of bridges often freeze over quickly during periods of low flow, and this width reduction may be enough to cause blockage when ice discharge in the river is high. Figure 14-12 shows the Allegheny River at Pittsburgh, Pennsylvania, where the open surface width has been reduced significantly by the freeze-over of the shore spans of several bridges. Islands may also cause a reduction in open surface width. Typically, one channel around an island carries the major portion of flow while the other freezes over. Again, this surface-width reduction may be enough to initiate blockage. Figure 14-13 shows an island with one of the channels frozen over.

c. Tributaries. During breakup, tributaries may discharge large quantities of ice into the main river. If the main river is still frozen or partially ice-covered, an accumulation may result. On a large scale, this is what happens when the Monongahela River breaks up, discharging ice into the Ohio River. Typically, only the larger tributaries are significant and the duration of this type of problem is small. Very steep

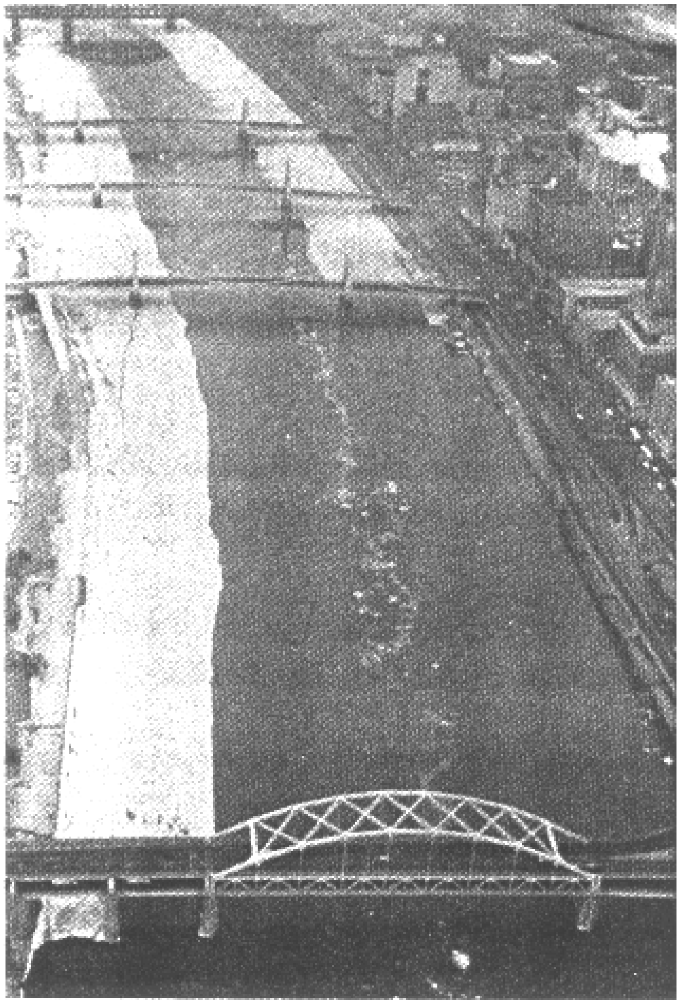

Figure 14-12. Shore ice formation, with bridge piers providing added stability to the shore ice

tributaries may remain open all winter long, generating large quantities of frazil ice. The upper reaches of the Allegheny River (above Lock and Dam No. 9) supply frazil to downstream areas through the winter. Tributaries, whether large or small, may also have fans or bars extending into the main river. These shallower areas tend to freeze over quickly, extending shore ice into the river and reducing the open surface width. A special case exists on the Illinois Waterway in the vicinity of Marseilles Lock and Dam. The river is split by a long island, with the dam at the upstream end of one channel (the north channel) and the lock at the downstream end of the other (the south channel). The north channel is fairly steep and generates frazil ice all winter long. The south or navigation channel is flat and generally freezes as a lake. A short distance downstream of the lock, the two channels rejoin with a flat slope. The frazil moving down the steep north channel suddenly loses velocity and tends to accumulate downstream of the junction. Accumulations in this area can reach thicknesses of 1.8 meters (6 feet) and lengths of 0.8 kilometer (1/2 mile). It is not unusual for towboats to spend 10 to 18 hours to navigate through this section.

d. Fleeting and mooring areas. Under midwinter conditions, there is often a narrow shipping track that remains open following the channel line in an otherwise frozen river. This is characteristic of the

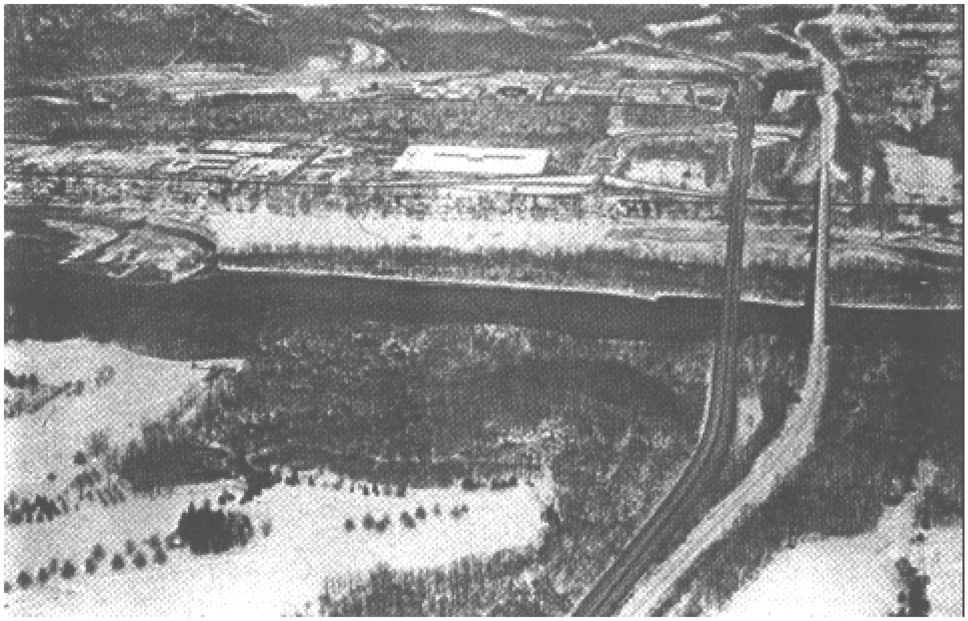

Figure 14-13. River divided into two channels by an island; the main channel is open while the secondary or back channel is ice covered

upper Monongahela River. Tows travel in these established tracks, leaving them only to move to mooring cells, fleeting areas, or docks. If care is not taken to move to these areas by additional established tracks, large ice pieces can be broken away from the cover and become lodged in the main shipping track. Figure 14-14 shows a fleeting area near shore and an established navigation track following the shipping channel.

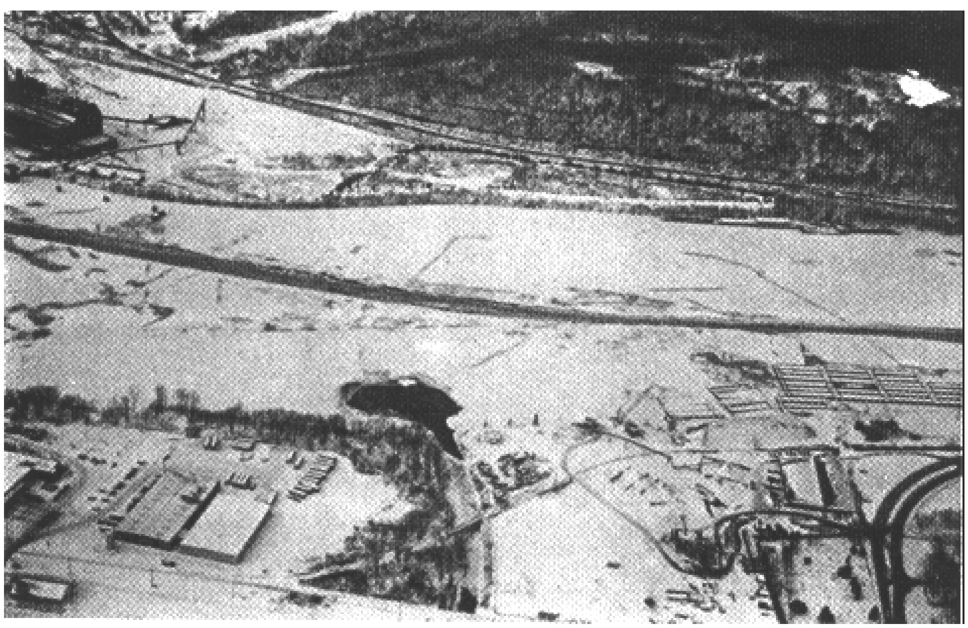

Figure 14-14. Navigation track in the middle of the channel, with a fleeting area at the near bank; traffic using the fleeting area can break free large floes that can move out to block the track

14-6. References

a. Required publications.
None.

b. Related publications.

Haynes et al. 1993
Haynes, F.D., R. Haehnel, and L. Zabilansky. 1993. *Icing Problems at Corps Projects*, Technical Report REMR-HY-10, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Zufelt and Calkins 1985
Zufelt, J., and D. Calkins. 1985. *Survey of Ice Problem Areas in Navigable Waterways*, Special Report 85-2, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Chapter 15
Ice Forecasting

15-1. General

Forecasting of ice conditions on inland waterways is based on the premise that, given forecasts of future meteorological conditions and forecasts of future hydraulic conditions, it is possible, through knowledge of thermodynamics, open channel hydraulics, ice physics, and an understanding of the behavior of the various forms of river ice, to develop forecasts of the future ice conditions. The methodology described in this chapter produces ice forecasts that are unique to a specific river or basin for which an Ice Forecasting System is developed.

a. The first goal of an Ice Forecasting System is to anticipate the period when ice formation is possible and, if possible, assign probabilities to the likelihood of formation. This type of forecast is known as a Long-Term Water Temperature Forecast. Such forecasts are made by a computer model of the overall heat balance of the river watershed, which indicates the long-term water temperature response to changes in air temperature.

b. A second type of forecast is much more detailed in its results. The goals of this type of forecast are to predict the reaches of a river where ice will form, when that ice will form, the areal extent of stationary ice, the ice thickness, the time of breakup, and ice jams and other extreme ice conditions. This Mid-Winter Ice Forecast is very sensitive to day-to-day changes in meteorological conditions and flow conditions, making it apply to a much shorter time, generally 5 to 7 days. This short-term forecast requires the development of three closely interrelated models: first, a dynamic flow model to simulate the channel hydraulics, including the influence of ice; second, a thermodynamic model to simulate the heat transfer between the waterway and the atmosphere; and third, an ice formation model to distribute the ice along the waterway and to calculate the ice thickness.

c. In this chapter, general overviews of the Ice Forecasting System, including the Long-Term Water Temperature Forecasts and the Mid-Winter Ice Forecasts, are presented. For each type of forecast, its objective, the basic theory, the model operation, the data required for model calibration, the data required for model operation, and the results are discussed.

Section I
Long-Term Water Temperature Forecasts

15-2. Objective

Predictions of water temperature are made primarily to estimate when the water temperature will be at or near the freezing temperature, 0ºC (32ºF). It is at this time that ice can be expected to form. Advance knowledge of the date that freezing temperatures will be reached allows efficient management of resources necessary to deal with the problems that can be caused by ice at locks and dams and other Corps facilities, and may assist operational planning for other navigation interests.

15-3. Model Description

River water temperatures reflect the balance of heat flow into and out of the volume of water that makes up the river discharge. This principle forms the basis of river water temperature forecasting. At any point along a river, the water temperature at that point reflects the heat balance upstream of that point. Mathematically, this temperature can be represented by a convection–diffusion equation. However, this equation can require a great deal of information to solve, and much of the information may not be known for future times. An efficient alternative is a total watershed approach. This approach assumes the following:

- The temperature of the river is well-mixed vertically; that is, the temperature of the river is uniform from the surface to the bottom. (This will be true of almost all rivers with any velocity. This may not be true of reservoirs, lakes, or other large bodies of water without appreciable flow velocity.)

- The heat flow into and out of the river water is dominated by exchanges with the atmosphere. (This allows the prediction of the river water temperatures to be based on forecasts of future meteorological conditions. Other heat sources, such as industrial or municipal effluents, can be factored into the forecast by studying past response of the river water temperature. However, if the water temperature of the river upstream of the point for which the forecast is to be made is dominated by such sources, this approach may lead to large inaccuracies.)

- The river is essentially free-flowing, having only a relatively small portion of its drainage area covered by reservoirs or lakes, the temperatures of which are not dominated by artificial heat sources.

a. Heat transfer components. There are many components of the heat balance that affect and determine the actual resulting river water temperature. These include heat transfer to the atmosphere, heat transfer to the ground, the influx of groundwater, and artificial heat sources. As stated previously, the heat transfer is dominated by the exchange with the atmosphere. This exchange has many modes, including long-wave radiation, short-wave radiation, evaporation, condensation, and precipitation. However, many of these modes are difficult to forecast, and forecasts of them are not generally made. Therefore, a simple but generally accurate means of approximating the heat transfer rate ϕ is made based on the equation

$$\phi = h_{wa}(T_w - T_a) + q \tag{15-1}$$

where

T_a = temperature of the air

T_w = temperature of the water

h_{wa} = effective heat transfer coefficient from the water to air

q = heat inflow that is independent of the air temperature, such as solar radiation.

b. Convection–diffusion equation. In this watershed approach, the one-dimensional convection–diffusion equation can be simplified to the form

$$\frac{DT_\mathrm{w}}{Dt} = -\frac{\phi}{\rho C_\mathrm{p} D} \qquad (15\text{-}2)$$

where

D/Dt = total derivative

ρ = density of water

C_p = specific heat of water

D = mean channel depth.

c. Air Temperature Representation. In principle, the average daily air temperature over the entire period of a year can be represented by a Fourier series. However, in practice, it is efficient to represent the actual mean air temperature on any day by

$$T_\mathrm{a} = \overline{T} + \alpha \sin\left(\frac{2\pi t}{T} + \theta\right) + T_{\delta_\mathrm{j}} \qquad (15\text{-}3)$$

where

t = Julian date

T = number of days in year (365 or 366)

θ = phase angle

$\overline{T}$ = mean annual air temperature

a = amplitude

T_{δ_j} = deviation in air temperature.

The deviation in air temperature represents the difference between the actual daily average air temperature and the sum of the yearly mean temperature and the first harmonic representation of the daily average air temperature. The values of T, a, and θ can be found by analyzing air temperature records from previous years that have been collected in the region where the water temperature forecasts are to be made. Examples are shown in Table 15-1. The deviations of daily average temperature from the first harmonic representation for all past data can be calculated. The deviations for future times are, of course, unknown.

Table 15-1
Mean Annual Air Temperatures and First Harmonic Coefficients Determined for Selected First-Order National Weather Service Stations, for Application to the Air Temperature Representation in the Long-Term Water Temperature Forecast Model

Station	*Mean Annual Air Temperature T, °C (°F)*	*Amplitude a,°C (°F)*	*Phase Angle q*	*Period of Record*
Pittsburgh, Pennsylvania	10.16 (50.29)	12.64 (22.75)	–1.9085	1965–1982
Huntington, West Virginia	12.63 (54.73)	11.66 (20.99)	–1.8734	1965–1982
Covington, Kentucky	11.80 (53.24)	12.84 (23.11)	–1.8866	1965–1982
Louisville, Kentucky	13.39 (56.10)	12.43 (22.37)	–1.8769	1965–1982

d. Model parameters. By substituting Equations 15-1 and 15-3 into Equation 15-2 and integrating to solve for T_w, an equation describing water temperature is derived:

$$T_{w_j} = \overline{T} + a\cos\alpha\sin\left(\frac{2\pi t}{T} + \theta - \alpha\right)$$

$$= \left[T_{w_{j\text{-}1}} - \overline{T} - a\cos\alpha\sin\left(\frac{2\pi t}{T} + \theta - \alpha\right)\right]e^{-K_r}$$

$$= T_{s_j}\left(1 - e^{-K_r}\right) + T_q\left(1 - e^{-K_r}\right)$$

where $\alpha = \tan^{-1}\left(2\pi / K_r T\right)$.This equation is the basis of the water temperature forecast model. There are two coefficients in this equation, the response coefficient K_r , and the equivalent temperature T_q. The forecast of the water temperature on day $j(T_{wj})$ is based on information known from the previous day, j–1. The forecast is made in 1-day increments, starting from the date of the forecast. In principle, the forecast can extend indefinitely into the future. However, in practice, the forecasts are limited by the lack of knowledge of future air temperature deviations.

e. Data required for model calibration. The unknown coefficients in the model equation, K_r and T_q, must be determined by analyzing past air temperature records and water temperature records. This suggests the importance of complete and accurate temperature records for forecasting. Generally, the water temperature records are the most difficult to obtain. The unknown coefficients are estimated by a least-squares approach, by minimizing a function Φ:

$$\Phi = \sum_{j=1}^{n}\left(T_{w_a} - T_{w_j}\right)^2$$

where T_{w_a} is the actual water temperature on day j, and T_{w_j} is the water temperature forecast for that day using known values of a, θ, $T_{\delta j}$, and T. The results of calculating the response coefficient and equivalent temperature for six stations on the Ohio River are shown in Table 15-2. In this case separate coefficients have been calculated for two 3-month periods: October through December, and January through March. These two periods cover the entire winter season.

Table 15-2
Sample Model Coefficients for Six Stations on the Upper Ohio River, for Application to Long-Term Water Temperature Forecasts

	Response Coefficient K_r		*Equivalent Temperature Tq, C° (F°)*	
Location	*Oct-Dec*	*Jan-Mar*	*Oct-Dec*	*Jan-Mar*
Emsworth L&D*	0.1737	0.0725	1.35 (2.43)	3.45 (6.21)
South Heights, Pennsylvania (ORSANCO)	0.0637	0.0697	1.35 (2.43)	3.45 (6.21)
Montgomery L&D	0.1087	0.0706	1.27 (2.29)	3.52 (6.34)
Hannibal L&D	0.0998	0.0700	0.20 (0.36)	2.95 (5.31)
Racine L&D	0.1000	0.0633	0.20 (0.36)	1.80 (3.24)
Meldahl L&D	0.0596	0.0594	0.20 (0.36)	1.79 (3.22)

* Lock and Dam.

15-4. Model Operation

From the analysis of previous data, the following information is known—air temperature characteristics (mean annual air temperature, first harmonic amplitude, and phase angle), and the water temperature response coefficient and equivalent temperature. From real-time water temperature measurement stations at each location where forecasts are to be made, the actual river water temperatures at the time of the forecast are obtained. The forecasts of air temperature are obtained from the National Weather Service (NWS). Generally, these are represented as deviations from the normal air temperature as described by Equation 15-3. A diagram of the model is shown in Figure 15-1. Generally, the model is run to estimate the period when ice formation is possible, that is, when the water temperature is 0ºC (32ºF). However, this would not be a conservative estimate because unforecasted deviations in air temperature may cause the water to reach 0ºC (32ºF) sometime before the actual forecasted date, and often, for a given winter season, 0ºC (32ºF) may never be reached. Therefore, the following nomenclature has been developed. The term *most-likely ice period* is used to describe the time when the water temperature is forecasted to be 1.5ºC (34.7ºF) or less. The term *ice watch* is used to describe the time when the water temperature is forecasted to be 0.5ºC (32.9ºF) or less.

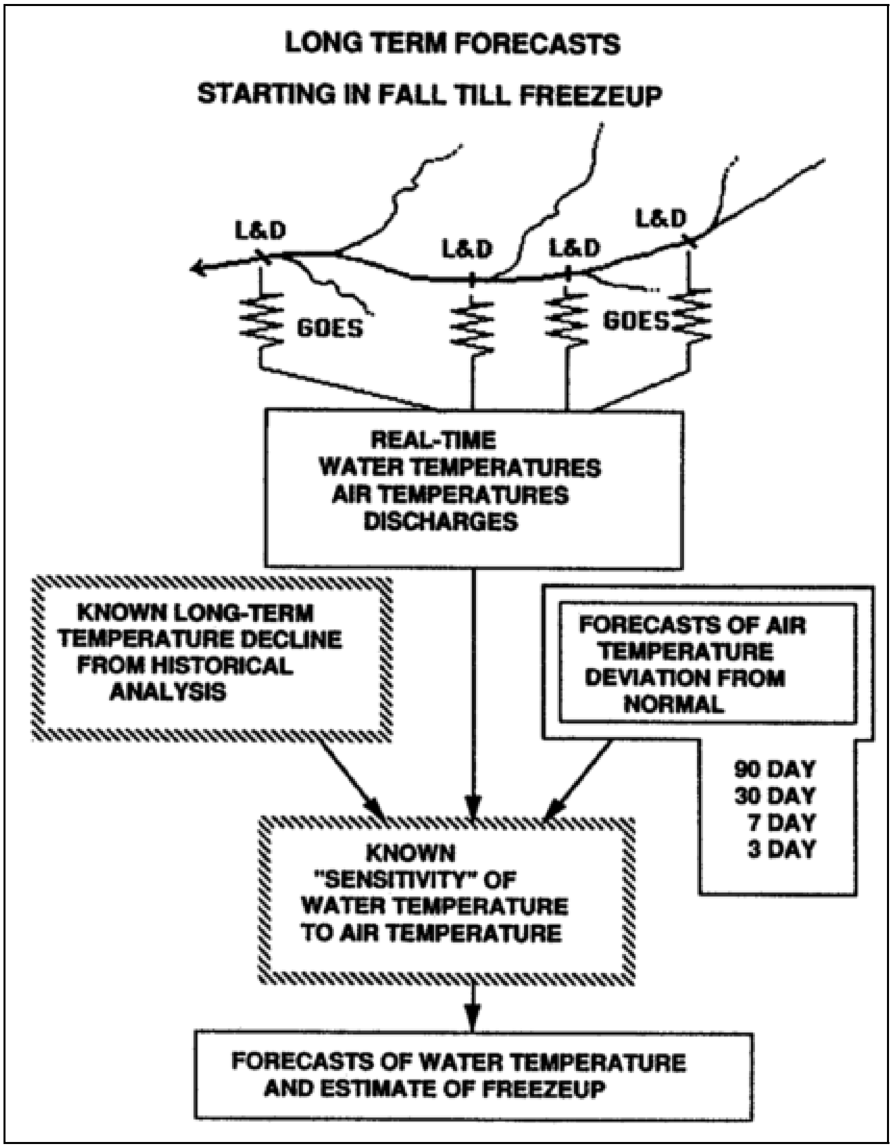

Figure 15-1. Flowchart of long-term water temperature forecast model

15-5. Model Results

An example of a sample water temperature forecast is shown in Figure 15-2. This example indicates the location of the forecast, the date of the forecast, the water temperature on the date of the forecast, and the air temperature forecasts provided by the NWS. In this case the NWS forecasts are for normal temperature, that is, the temperature deviations from the temperatures described by Equation 15-3 have been set to zero. Then the example provides the actual forecasted water temperature and a description of the *most-likely ice period* and the *ice watch* period.

RIM WATER TEMPERATURE FORECAST

SITE: Emsworth Locks and Dam
Ohio River Mile: 6.2

Date of Forecast: 4 October 1987

Water Temperature: 15.0°C (59.0°F)

Air Temperature Forecasts: 3 Day: NORMAL
7 Day: NORMAL
30 Day: NORMAL

DATE	FORECASTED WATER TEMPERATURE °C	°F
01 Nov 87	10.2	50.4
01 Dec 87	4.2	39.6
15 Dec 87	1.9	35.4
01 Jan 88	0.2	32.4
15 Jan 88	0.8	33.4
01 Feb 88	1.0	33.8
15 Feb 88	1.5	34.7

MOST LIKELY ICE PERIOD: 19 Dec 87—15 Feb 87

ICE WATCH: 27 Dec 87—5 Jan 88

Figure 15-2. Typical output information of the long-term water temperature forecast model. *Successive model runs (updates) would yield more precise estimates of the* most-likely ice period *and the* ice watch period

15-6. Model Accuracy

To assess the accuracy of the Long-Term Water Temperature Forecast model, the Ohio River Valley Sanitation Commission (ORSANCO) station at South Heights, Pennsylvania, has been used because of its long period of record. There are several ways of assessing the accuracy of the forecast. The first is to determine the mean error of the forecast, that is, the average absolute value of the difference between the forecasted water temperature and the actual. Results of forecasts done on 14 years of records are shown in Figure 15-3. The error is calculated based on the forecast that could be made by assuming that a perfect air temperature forecast is available, that is, by using the actual recorded daily average air temperature. It can be seen that, for the 25-day period following the date of the forecast, the forecasted water temperatures are more accurate than those determined by simply using the long-term mean water temperature as an estimate.

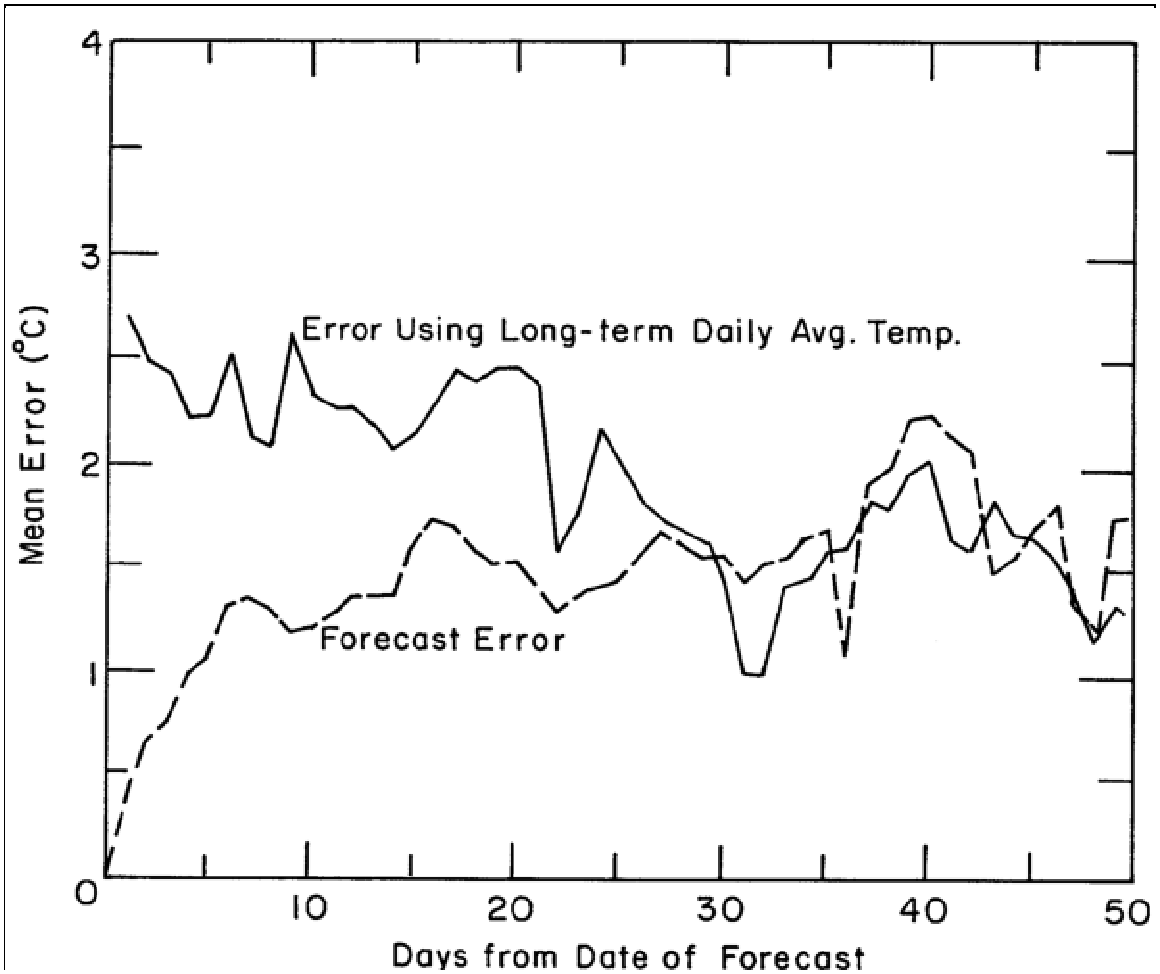

Figure 15-3. Forecast-model accuracy illustrated by plot of error as a function of days since forecast was made. *Forecast naturally has its greatest accuracy immediately following the date of forecast, after which error generally increases with time. For comparison, error resulting from simple long-term daily average water temperatures is also shown and seen to decrease slightly with time. For the period up to about 25 days after a forecast is made, the error in forecasted water temperatures is more acceptable than that associated with reliance on long-term averages.*

Section II
Mid-Winter Ice Forecasts

15-7. Objectives

The objectives of the Mid-Winter Ice Forecasts are to provide accurate predictions of the reaches of a river system where ice will be formed, the reaches of a river system where there will be stationary icecover, the thickness of the stationary ice cover, the thickness of frazil ice deposited under the ice cover, the water temperature in every reach, and the breakup date of the stationary ice cover. These predictions are to be made as far into the future as possible. However, owing to limitations of weather forecasts, the ice forecasts have a realistic limitation of 5 to 7 days.

15-8. Forecast Model Description

The Mid-Winter Ice Forecast model (Shen 1991)is composed of three submodels and several supporting models. The Mid-Winter Ice Forecast model also has several items that must be specified; these are known as System Parameters. The three submodels are the Hydraulic Model, the Thermal Model, and the Ice Model. Each of these submodels is based on physical principles that will be discussed below. Moreover, each of these submodels has several items that must be entered as input; these are the Physical Parameters and the Initial Conditions. The Initial Conditions define the river system at the time the forecast is made. Each submodel must also be supplied with parameters known as Boundary Conditions; these are not determined by the ice forecast model, but rather are independently forecasted parameters (such as air temperature and tributary discharge) that drive the ice forecast model. The ice forecast model uses the Boundary Conditions to predict new values of the parameters supplied as Initial Conditions at each time step. These new values are the output of the model, and can serve as the Initial Conditions for the following time step. The output of the model is the forecast of future ice conditions. This is outlined in Figure 15-4. This section consists of a description of the Mid-Winter Ice Forecast model and the required System Parameters, Physical Parameters, Initial Conditions, and Boundary Conditions. This is followed by a discussion of the Model Output of the ice forecast model and a description of the application of the ice forecast model to a river system. The application discussion includes the role of supporting programs to interface the data collection program and generate the Initial Conditions and the Boundary Conditions and also to interpret the Model Output.

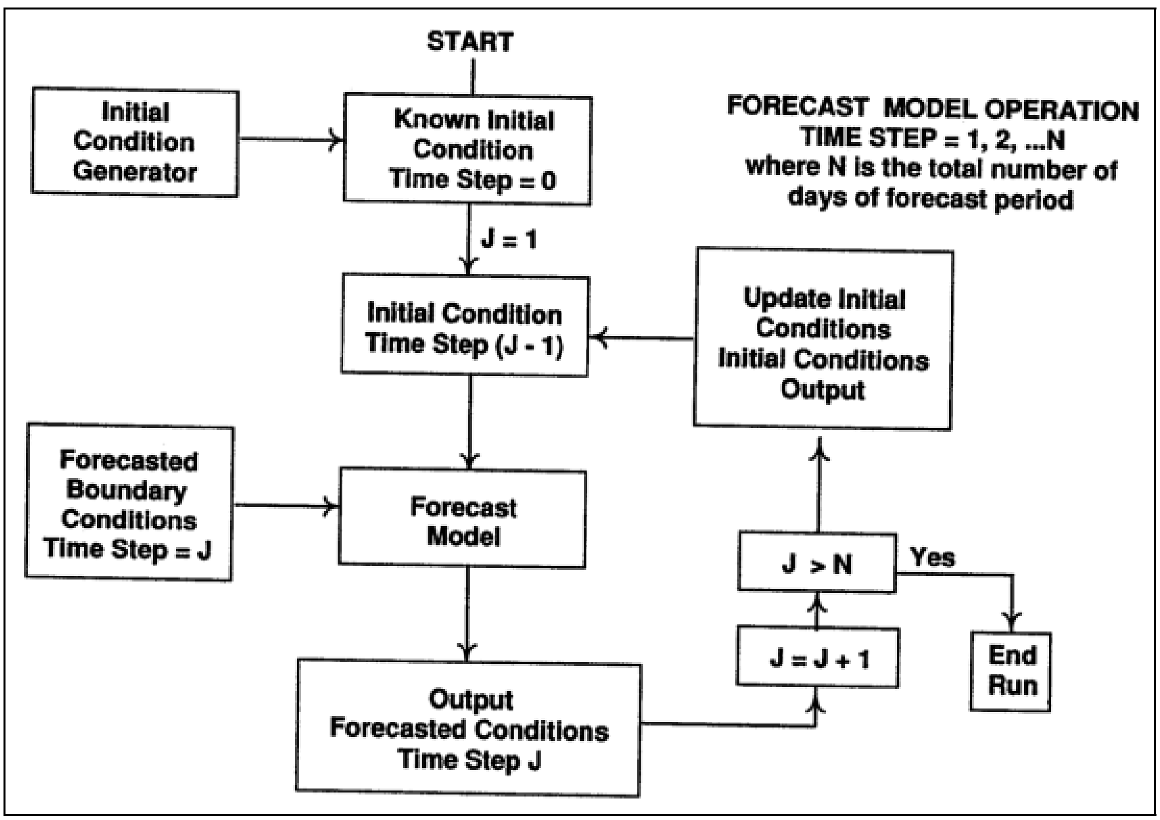

Figure 15-4. Flowchart of mid-winter ice forecast model

15-9. Hydraulic Model Description

The Hydraulic Model used is a one-dimensional, unsteady-flow model. This submodel solves two equations. The first equation is the conservation equation. It assures that the flow entering, leaving, and stored in a reach is balanced. This equation can also consider tributary inflow and other lateral inflow. It may also consider storage of flow in a floodplain. The second equation is termed the momentum equation. This equation assures that the momentum entering and leaving a reach is balanced by the forces acting on that reach. The momentum equation considers the forces of gravity, the channel friction, the hydrostatic pressure, and the possible acceleration of the flow. Both the conservation equation and the momentum equation are one-dimensional, that is, all properties are averaged over any cross section, and the only dimension considered is longitudinal or along the channel.

a. Model equation solutions. Taken together, the conservation and momentum equations are nonlinear, partial differential equations. Therefore, they cannot be solved directly, and they cannot be represented directly in a computer. Generally, they are represented in their finite-difference form and solved at discrete points, termed nodes. The system of nodes is used to represent the river system under consideration. Generally, a node is a point at which information about the channel geometry is known, or for which information is required, such as a lock and dam project. Each node is separated from the next by a distance (the reach length) that can have different values from one node-pair to another. The closer the spacing of nodes is (i.e., the shorter the reach length), the more accurately a river can be represented and the more data that are then required. A river system (a main stem with tributaries) can be represented by such a system of nodes. It is then necessary to indicate the starting and ending node of each tributary, and the node where the tributary and main stem join. An example of such a system is shown in Figure 15-5.

b. Influence of locks and dams. The Hydraulic Model must also be able to include the effects of locks and dams on the conservation and momentum equations. Generally, for a dam with control gates, this will mean fixing an upper pool or upper gage elevation at a lock and dam if the discharge is below a certain known value. If the discharge exceeds this value, then a rating curve is supplied to determine the upper pool stage. A lock and dam with a fixed crest spillway, for example, has a rating curve to describe its upper pool elevation.

c. Ice effects. The influence of ice must also be taken into account by the Hydraulic Model. The influence of ice will act to reduce the hydraulic radius of a cross section by increasing the wetted perimeter, reduce the cross-sectional area available for flow, and introduce a roughness that will cause an additional friction force that acts on the flow.

d. Hydraulic model output. The principal outputs of the Hydraulic Model are the discharge and the cross-sectional area (from which the depth, velocity, and water-surface top-width are derived) for each node for every time step.

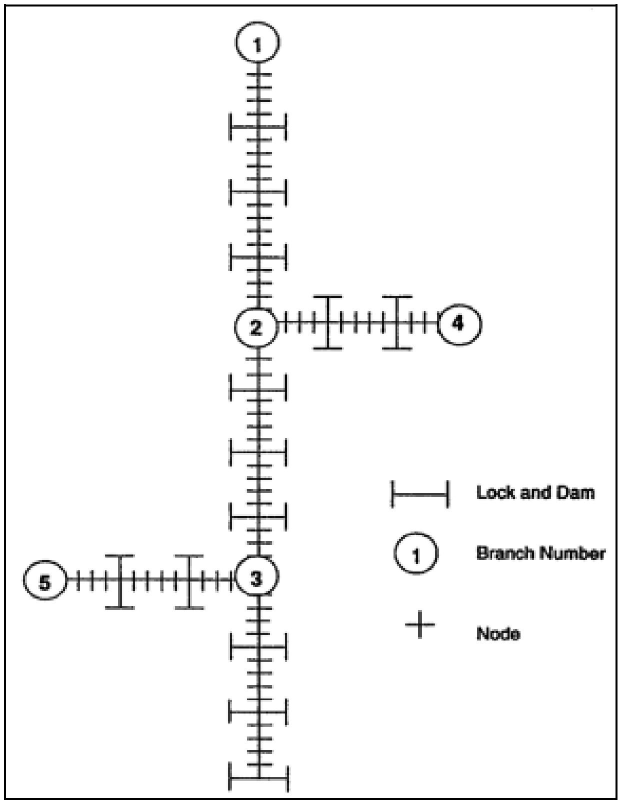

Figure 15-5. River system represented by nodes and branches, for use in the hydraulic model. *Note that nodes exist not only at lock and dam projects and at tributary junctions, but also wherever hydraulic and channel information is known or desired*

15-10. Thermal Model Description

The Thermal Model computes a heat balance over each river reach. This submodel accounts for heat gained or lost in the reach, and assures that this is reflected in the water temperature response of that reach. However, because of the physical properties of water, it is not possible for the water temperature to decline in any appreciable way below 0ºC (32ºF). At this point, further heat loss from the water will result in the production of ice, and heat gain will result in the melting of ice. Once all ice in a reach has melted, further heat gain will result in a rise in the water temperature.

a. Heat balance. Generally, the heat transfer to or from river water is dominated by the heat exchange from the open-water surface to the atmosphere. Heat exchange with the channel bed and banks is minor, as is heat gain from friction. Artificial heat sources, such as cooling water discharged from power plants, can be significant and must be included. The presence of an ice cover can greatly reduce the heat exchange with the atmosphere. In this case, the heat transferred through the ice by conduction must be calculated. The presence of an ice cover will allow heat to leave the river water, but not to be gained by the water from the atmosphere. When the ice is greater than about 5 centimeters (2 inches) thick, the heat transfer rate from the water is primarily controlled by the rate at which heat can be conducted through ice.

b. Heat transfer from open water. The heat transfer from an open-water surface to the atmosphere comprises several different modes. These modes include long-wave radiation, short-wave radiation, evaporation, and conduction. It has been found that the daily average heat transfer rate per unit area of open water is represented very well by an equation of the type

$$\phi = h(T_w - T_a)$$

where

ϕ = heat transfer rate per unit area

T_w = temperature of the water

T_a = temperature of the air

h = heat transfer coefficient.

The value of the heat transfer coefficient is influenced by the atmospheric stability and wind velocity, but in general can be considered to be a constant for a given region. This equation is of the same form as Equation 15-1. The difference is that here we are considering a specific area or reach of the river, while Equation 15-1 addresses the basin as a whole.

c. Heat transfer through an ice cover. Heat transfer through an ice cover is a balance of the heat lost to the atmosphere, the heat conducted through the ice, and the heat transferred from the water to the bottom of the ice cover. If more heat is transferred to the atmosphere than is transferred from the water to the ice, the ice cover will grow in thickness. If less heat is transferred, the ice cover will melt. The rate of thickening or melting is determined by the product of the latent heat of fusion of water and the heat transfer rate.

d. Temperature response. The temperature response of a reach of river water is determined by the overall heat loss or gain from the reach, the volume of water contained in that reach, and the heat capacity of the water. The overall heat loss or gain is the product of the heat transfer rate per unit area and the surface area. Both the surface area and volume of a reach are determined by the Hydraulic Model.

e. Initial ice formation. The initial formation of ice in a reach can be quite complex, and the type of ice formed is dependent on the hydraulic conditions in that reach. Generally, the initial ice is in the form of very small disks that are well distributed through the depth of flow; this ice is termed frazil ice. Frazil will tend to collect at the water surface and to move with the general flow velocity. The Thermal Model can calculate the heat loss and calculate the amount of ice formed. However, the formation of a stationary cover ice is determined by the Ice Model (see paragraph 15-11). The presence of open water implies the formation of frazil, and the presence of a stationary ice cover will imply the thickening or melting of that cover.

f. Thermal model output. The output of the Thermal Model is the water temperature at each node for every time step. If the water temperature is at 0ºC (32ºF), the volume of ice formed or melted will also be calculated. If the reach is open water, the volume of frazil formed will be determined. If the reach is ice covered, the change in thickness will be determined.

15-11. Ice Model Description

Given the hydraulic conditions of stage and velocity (determined by the Hydraulic Model), and the water temperature and volumes of ice formed or melted (determined by the Thermal Model), the Ice Model will then determine where the stationary ice covers are initiated, the manner in which they are formed, their length, their initial thicknesses, and the volume of frazil that is eroded or deposited under them. It is important to note that while the other submodels (the Hydraulic Model and the Thermal Model) are based on general physical principles (that is, the conservation of matter, momentum, and energy), the Ice Model largely reflects principles gleaned through actual observation of the behavior of river ice and the development of empirical relationships.

a. Ice bridging. It is assumed that the initial ice formed on the river is frazil. The frazil particles will rise buoyantly and collect at the water surface to form a slush, which will then flocculate to form pans of ice. It is not possible at this time to calculate what the initial thickness of these pans will be, but a thickness for the initial pans must be entered as a Physical Parameter into the program. Therefore, the initial formation of ice will be in the form of pans whose thickness is a preset parameter. These pans will move with the flow velocity until they reach an obstacle in the flow, or until the concentration of floating ice increases to the point where the ice "bridges" naturally across the stream channel and forms a stationary cover. It is not possible at this time to calculate where these natural bridging points will occur, or under what conditions of flow and ice concentration they will occur. Therefore, the initial bridging locations must be determined through judgment and entered into the program as Physical Parameters. For example, it can be assumed that ice will initially bridge at the locations of locks and dams. Most often, ice bridges at the same locations each winter season. These locations may be at sharp bends, low velocity reaches, etc.

b. Progression by juxtaposition. The initial formation of a stationary ice cover in a reach where an obstacle exists at the downstream end will follow the logic shown in Figure 15-6. This obstacle may be an input ice-bridging location, or the edge of the ice cover that has progressed upstream in the previous time step. The first condition to be addressed is this: Will the ice pans that arrive at the stationary cover remain floating or underturn? If they remain floating, the cover is said to progress by juxtaposition. It is assumed that, if the Froude Number of the flow, defined as

$$F_{\mathrm{D}} = \frac{V}{\sqrt{gD}}$$

where

V = mean velocity

g = acceleration of gravity

D = channel depth

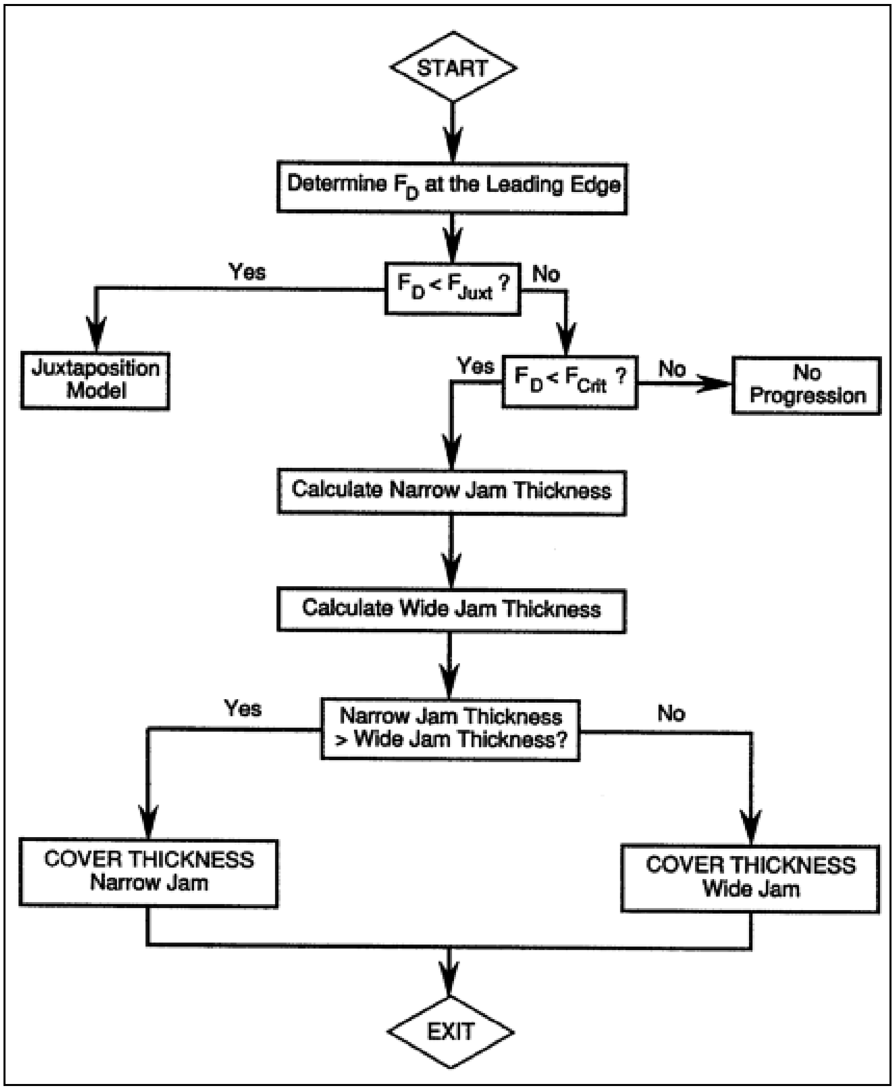

Figure 15-6. Flowchart of the logic used in the ice model. *This flow-chart is for determining whether the upstream ice cover progression is by juxtaposition or by jamming (with the associated narrow-jam or wide-jam thickness), or whether there is no progression of the ice cover*

is less than the Juxtaposition Froude Number, then the pans will not underturn and the cover will progress upstream by juxtaposition. The Juxtaposition Froude Number must be entered as a Physical Parameter. It is one of the empirical parameters used in the Ice Model.[‡] The rate of

[‡] Suggested values of the Juxtaposition Froude Number are available, or estimates can be made using semi-empirical formulas described by Ashton (1986), where the parameter is termed the "block stability criterion for underturning."

ice-cover progression upstream will be determined by the concentration of arriving ice, the velocity of the arriving ice, the thickness of the cover, the porosity of the cover, and the fraction of the total ice flow going into the cover formation. (The porosity of the cover and the fraction of the total ice flow going into the cover are also entered as Physical Parameters.) If, on the other hand, the Froude Number of the flow is greater than the Juxtaposition Froude Number, then the pans will underturn, and may or may not progress upstream. If the pans do progress upstream under this condition, they do so by jamming rather than by juxtaposition.

c. Limit of ice-cover progression. If the Froude Number of the flow exceeds the Juxtaposition Froude Number, it is necessary to check and see if the Froude Number of the flow is greater than a limiting value of the Froude Number for progression. If this is true, no ice-cover progression is possible. All the arriving ice will be swept under the existing ice cover and carried downstream. This means that, until the hydraulic conditions change, the river will remain as ice-free, open-water upstream of this point. This limiting value of the Froude Number for progression is also an empirical value, entered as a Physical Parameter; suggested values are available.

d. Wide and narrow ice jams. If the Froude Number of the flow exceeds the Juxtaposition Froude Number, but is less than the limiting value of the Froude Number for ice-cover progression, then the ice cover can progress in one of two modes. These modes are termed the narrow-jam and wide-jam modes. These modes reflect the balance of forces acting on the ice cover.

(1) In the wide-jam mode, the ice cover must thicken to transfer the forces acting on the cover to the channel banks. The forces acting on the cover are the bottom friction ascribable to the flow and the component of the weight of the cover parallel to the water surface caused by the slope of the water surface. These forces are resisted by the friction of the ice against the channel banks and by any cohesion with the channel banks. It is assumed that the forces acting on the cover are in equilibrium with the resisting force of the channel banks at every point along the channel. The thickness of ice required to provide this equilibrium is termed the equilibrium ice jam thickness, and is calculated assuming that the ice acts as a passive granular material. The Physical Parameters that are required are the underside roughness of the ice cover, the coefficient of friction of the ice with the banks, the coefficient of passive stress for granular ice, the bank cohesion, and the porosity of the ice cover. Once the equilibrium ice jam thickness has been calculated, the progression rate is determined with the same procedure as before.

(2) In the narrow-jam mode, it is assumed that the thickness of the ice cover is determined by the hydraulic conditions at the leading edge of the ice cover. Forces acting on the cover are not a consideration. Specifically, it is necessary that the ice cover be thick enough so that a "no-spill" condition is satisfied. That is, the cover is thick enough to resist the sinkage caused by the acceleration of flow beneath the leading edge of the cover.

(3) Generally, it is not possible to determine beforehand whether an ice cover will progress in the wide-jam or narrow-jam modes. The thickness that will result from each mode is calculated and the mode that results in a greater thickness is used.

e. Conservation of moving ice. The Ice Model balances the concentration of moving ice for each time step. Ice that reaches a stationary ice cover, and does not go into the formation of the ice cover via one of the modes described above, is assumed to be transported under the ice cover. This ice can be deposited under the ice cover, and is considered to be deposited frazil. The deposited ice can then be eroded if the velocity of the water increases sufficiently. The rate of deposition to the underside of the ice cover is determined by a mass balance calculation on the transported ice. The Physical Parameters required are the probability of deposition of an ice particle that reaches the ice/water interface, the buoyant velocity of the frazil particle, and the critical velocity for deposition. If the flow velocity is above the critical velocity for deposition, the frazil will not be deposited. Erosion of the deposited frazil takes place when the local flow velocity under a frazil deposit increases beyond the critical velocity for erosion. The Physical Parameter that is required here is the critical velocity for erosion.

f. Ice-cover stability. After an ice cover has been formed, it can be lost when the forces acting on the cover exceed its ability to transfer these forces to the channel bank. This will happen if the hydraulic conditions change, or if the ice-cover thickness is reduced by melting. Therefore, at each time step, a force balance must be determined on the ice cover in each reach. The friction on the ice cover from the flow and the component of the weight of the cover parallel to the water surface caused by the slope of the water surface are balanced against the ice cover's ability to resist the applied forces. The ice-cover strength is determined by the ice thickness, the coefficient of friction of the ice with the banks, and the bank cohesion. If the force acting on the ice cover exceeds the ability of the ice cover to resist that force, the ice cover is then considered to collapse and become floating and mobile ice.

15-12. System Parameters

System Parameters are data that describe the physical river system that is to be modeled and the manner in which the model is to operate. Generally, these System Parameters do not change their values as the model is run. The following are required System Parameters:

- Number of tributary branches.
- Number and location of nodes.
- Number and location of locks and dams.
- Number of lateral inflows.
- Time step length.
- Total time of model run.

15-13. Physical Parameters

Physical Parameters are data that describe the physical processes that are being modeled. Generally, these are physical constants and do not change their value while the program is being run. These constants are either measured in the field, determined during model calibration, estimated from observation and laboratory experiment, or known from physical principles.

a. Hydraulic Model physical parameters.

(1) Measured in the field:

- Channel geometry of each node.
- Floodplain areas.

(2) Determined from model calibration:

- Channel roughness.
- Contraction and expansion coefficients.

(3) Physical principle: Density of water.

b. Thermal Model physical parameters.

(1) Determined from model calibration:

- Air–water heat transfer coefficient.
- Ice–water heat transfer coefficient.

(2) Physical principles:

- Density of water.
- Heat capacity of water.
- Thermal conductivity of ice.
- Heat capacity of ice.
- Latent heat of fusion of ice.
- Density of ice.

c. Ice Model physical parameters.

(1) Estimated from observation and laboratory experiment:

- Buoyant velocity of frazil particles.
- Probability of ice particle depositing on cover.
- Critical velocity of frazil deposition.
- Critical velocity of frazil erosion.
- Coefficient of passive stress.
- Ratio of longitudinal stress to bank friction.
- Ice–bank cohesion.
- Bridging flag at each node.
- Underside roughness coefficient of ice cover.
- Juxtaposition Froude Number.
- Limiting value of the Froude Number for progression.

- Ice-cover porosity.
- Deposited frazil porosity.
- Initial ice pan thickness.
- Fraction of total ice flow going into the ice-cover formation.

(2) As noted in paragraph 15-11, the Ice Model does not have Physical Parameters based on physical principles nor determined by means of model calibration.

15-14. Initial Conditions

The Initial Conditions are those that describe the physical conditions of the river system at the time that the forecast is made. The following Initial Conditions must be known at each node.

a. Hydraulic Model initial conditions.

- Water surface elevation.
- Discharge.

b. Thermal Model initial condition: Water temperature.

c. Ice model initial conditions.

- Floating ice concentration.
- Ice-cover length.
- Ice-cover thickness.
- Deposited frazil thickness.

15-15. Boundary Conditions

The Boundary Conditions cannot be determined by the Mid-Winter Ice Forecast model. They are the parameters (forecasted by other means) that drive the model. The Boundary Conditions can change with each time step.

a. Hydraulic Model boundary conditions.

- Tributary discharge.
- Lateral inflows.
- Downstream stage.

b. Thermal Model boundary conditions.

- Tributary water temperature.
- Lateral inflow water temperature.
- Air temperature at every node.

c. Ice Model boundary conditions. There are currently no Boundary Conditions to be entered in the Ice Model. However, if known, the ice concentration of the tributaries and lateral inflows could be entered.

15-16. Model Output

The output of the Mid-Winter Ice Forecast model, in general, consists of updated values of the Initial Conditions based on the input Boundary Conditions. Each of the three submodels produces its own output. The output can be specified at each node and at each time step.

a. Hydraulic Model output. The output of the Hydraulic Model consists of the stage and discharge at each node at each time step. The mean velocity can also be calculated since the cross-section geometry is known.

b. Thermal Model output. The output of the Thermal Model consists of the water temperature at each node at each time step.

c. Ice Model output. The output of the Ice Model consists of the following for each node at each time step:

- Concentration of moving ice.
- Presence or absence of an ice cover, and if an ice cover is present, the length and thickness of that ice cover.
- Thickness of deposited frazil.

15-17. Model Calibration

The initial calibration setup of the Mid-Winter Ice Forecast model is not described in detail. However, in general, calibration of the model consists of adjusting the values of the Physical Parameters in each of the submodels so that the Model Output accurately reproduces the observed conditions. This procedure is necessary because in many cases there is no means of actually measuring the required Physical Parameters.

a. Hydraulic Model calibration. Calibration of the Hydraulic Model consists of adjusting the roughness coefficients that determine the resistance of the channel to flow. Generally, the roughness coefficients are adjusted so that, at observed discharges, the corresponding observed water elevations are matched.

b. Thermal Model calibration. Calibration of the Thermal Model consists of adjusting the heat transfer coefficients that determine the heat transfer rates from the water to the air, and from the water to the underside of the ice cover.

c. Ice Model calibration. A telling indication of the uncertain knowledge of river ice is the large number of parameters that could be adjusted during the calibration of an Ice Model. Generally, every Physical Parameter listed under the Ice Model (paragraph 15-13*c*) can be adjusted, as a definite value for each parameter cannot yet be calculated from our understanding of ice physics. Unfortunately, this is not a very satisfactory state of affairs. It is recommended that suggested values of the Physical Parameters be used and not adjusted, unless direct evidence of the need for adjustment is produced.

15-18. Model Operation

A general overview of the operational setup of the Ice Forecasting System is shown in Figure 15-7. The system may be divided into four general components: Data Collection and Transmission, Data Reduction and Data Base Management, Initial Conditions and Boundary Conditions Generators, and the Mid-Winter Ice Forecast model itself.

a. Field data collection and transmission. Data collected and transmitted for the model at present are water temperature, air temperature, and water-surface stage. This information is collected by Data Collection Platforms (DCPs) and transmitted via Geostationary Observational Environmental Satellite (GOES) to a down-link at a central location. The equipment and setup of a DCP with the appropriate sensors are addressed in Chapter 16. Thermistors, which change resistance in response to temperature change, are used to measure temperature. As DCPs can generally only measure voltages, a voltage divider circuit must be used to convert the thermistor resistance to a voltage that can be measured by the DCP. Generally, the following data must be transmitted to accurately determine temperature—the measured voltage across the voltage divider circuit, the measured voltage across the thermistor, and a measurement of the voltage across a reference resistor. The last measurement is necessary to correct for any impedance mismatch.

b. Data reduction and data base management. The transmissions from the DCPs are coded, and these coded transmissions must be decoded and converted to the proper engineering units. To determine temperature accurately from thermistor measurements, the actual thermistor resistance must be determined (based on the transmitted voltages), the resistance must be corrected for any impedance mismatch, and then the thermistor matched up with the proper calibration constants to convert the thermistor resistance to a temperature. A program (DCP.FOR) was developed for this purpose. DCP.FOR has a highly flexible structure for describing a particular DCP site, and this description can easily be modified or updated. This is particularly important during the setup of large data collection networks, when sensors may often be moved, recalibrated, or replaced. DCP.FOR can also decode the messages from any other meteorological sensor that has a linear output. DCP.FOR creates an output file whose format is fixed, but allows any arrangement of sensors as input to the DCP. A single file is created for each station for each month. The measured value of each sensor, in engineering units, is stored in a fixed format in the file. This allows a flexibility in the sensor configuration at the DCP, while maintaining a data base whose format is fixed. The output file of DCP.FOR has been interfaced with the Corps DSS data base system.

c. Initial Conditions and Boundary Conditions Generators. These are programs that take the actual field data and the forecasted values of air temperature and tributary discharge to create the proper Initial Conditions file and Boundary Conditions file for the Mid-Winter Ice Forecast model. These are discussed in more detail in paragraphs 15-20 and 15-21.

d. Mid-Winter Ice Forecast Model. The Mid-Winter Ice Forecast model was discussed previously. The model (using the Initial Conditions and the Boundary Conditions created by the Initial Condition and Boundary Condition Generators) prepares the forecast of the ice conditions. Two different modes of operation will be described: the Update Mode and the Forecast Mode (see Paragraph 15-22).

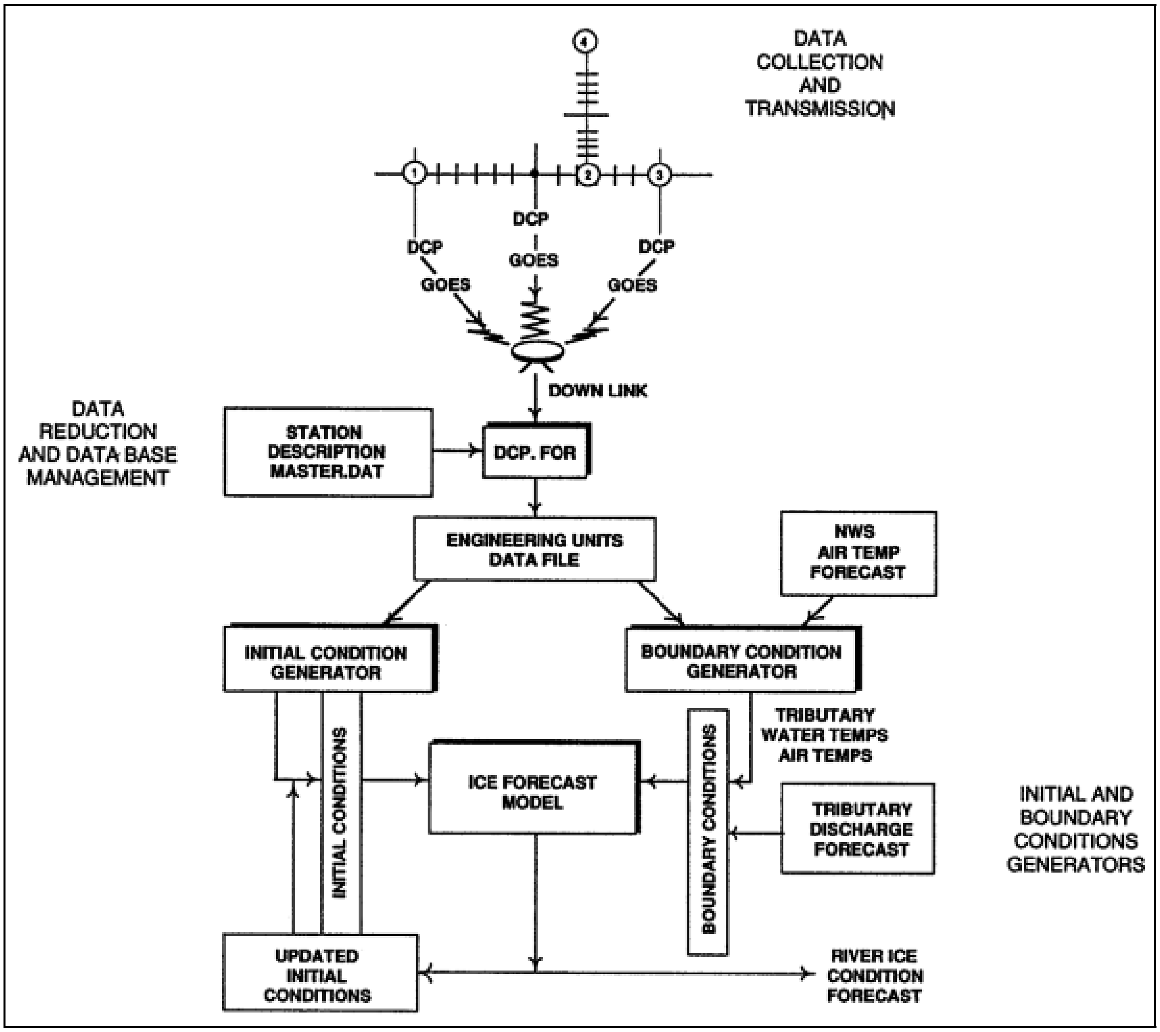

Figure 15-7. Overall flowchart of the ice forecasting system. *Within the Ice Forecasting System, the Mid-Winter Ice Forecast model operates under the support of Data Collection and Transmission, Data Reduction and Data Base Management, and Initial Conditions and Boundary Conditions Generators (DCP.FOR and MASTER.DAT are computer program names)*

15-19. Location of Field Measurement Sites

Ideally, a field measurement site could be located at each node of the model. The site would provide information on the water stage, discharge, air temperature, and water temperature. However, this would be prohibitively expensive, and the amount of data generated would quickly bury any practical data management scheme. In fact, field measurement sites should be kept to a minimum and located where they will provide the optimum information to allow the most accurate creation of the Initial Conditions and Boundary Conditions as input to the Mid-Winter Ice Forecast model. In general, the following guidelines apply:

- Field sites to measure water temperature should be located at the upstream end of the main stem and at the upstream end of each tributary to be modeled.

- Field sites to measure air and water temperature should be located throughout the river system to be modeled, and in sufficient density to provide a representative "picture" of the actual conditions. To determine this, some background study will be required to understand the meteorological and climatological conditions of the river system to be modeled. For example, on the Ohio River, field sites were located at an average spacing of about 130 kilometers (about 80 miles) along the river. However, in the upstream reaches of the Ohio River, where the winter climate varied over rather short distances, the stations were much closer. A good indication of climatic variation can be seen on a map indicating average freezing degree-days for a given winter month; January is the best month to represent this variation.

- A field site should be located at the downstream end of the river system that is modeled.

15-20. Initial Conditions Generator

The Initial Conditions required in the model are listed in paragraph 15-14.

a. Hydraulic Model. The generation of Initial Conditions for the Hydraulic Model is not discussed in detail here. It can be assumed that the Initial Conditions of stage and discharge are available from a previous model run (Update Mode), from a steady-state backwater measurement, or from physical measurement with interpolation.

b. Thermal Model. The Initial Condition of water temperature for the Thermal Model at each node can be determined from a previous model run (Update Mode) or from the reported measurements from the field sites. To determine the water temperature at each node from the field sites, the procedure is to first determine the average water temperature at each site for the previous 24 hours. Then, for the main stem, linearly interpolate the water temperature at each node between the field sites. For the tributaries, linearly interpolate the water temperature between the site at the upstream end of the modeled tributary section and the temperature calculated in the previous step for the main stem at the confluence of the tributary and the main stem. If no upstream site is available, a reasonable approximation is to use the temperature of the main stem at the confluence as the temperature for the entire reach of the modeled tributary.

c. Ice Model. The Initial Conditions for the Ice Model are the floating ice concentration, ice-cover length and thickness, and thickness of deposited frazil. It is not possible to physically measure the concentration of floating ice, although it can be visually estimated by experienced personnel during overflights. The ice-cover length can also be estimated from visual observation, preferably by aerial videotaping of the entire reach to be modeled, as described in Chapter 16. Generally, the solid ice cover and frazil thicknesses are not available, except at a very few locations. With the Ice Model data so scarce and incomplete, the realistic alternative is to generate the initial ice conditions from previous model runs (Update Mode).

15-21. Boundary Conditions Generator

The Boundary Conditions required are listed in paragraph 15-15. The Boundary Conditions are independently forecasted parameters that drive the model. Generally, the Boundary Conditions can change with every time step. Inaccurate forecasts of future Boundary Conditions will produce inaccurate model results.

a. Hydraulic Model. The generation of Boundary Conditions for the Hydraulic Model is not discussed in detail here. The forecasts of tributary and lateral discharges and downstream stage can be determined by a variety of means.

b. Thermal Model. The principal Boundary Condition of the Mid-Winter Ice Forecast model is the air temperature Boundary Condition of the Thermal Model. Generally, the daily average air temperature is used as the Boundary Condition. Forecasts of maximum and minimum air temperature are available from the NWS. A good estimate of the daily average is the mean of the maximum and minimum. Forecasts of the air temperature will undoubtedly be available at several locations throughout the river system where the Mid-Winter Ice Forecast model is to be used. A linear interpolation between the air temperature forecast locations is used to determine the air temperature Boundary Condition at each node.

(1) The forecasts of the tributary water temperature are made using the total watershed approach that is employed in making the Long-Term Water Temperature Forecasts, described in Section I. Information that is required includes the response coefficient and the equivalent water temperature, the actual water temperature on the day the forecast is made, and the forecasted air temperatures. With this information, based on the total watershed approach, a forecast of the tributary water temperature Boundary Condition can be made.

(2) The forecasts of the lateral inflow water temperature can be used to include the influence of artificially heated discharge from power plants, etc. Generally, the lateral inflow water temperatures will not be a factor, as these will be very near or at the main stem water temperature. For locations where heated discharges may be important, the lateral inflow water temperature can be put at a set value above the nearest forecasted tributary water temperature, representing the heat added by a power plant or industrial facility.

c. Ice Model. There are generally no forecasts of ice conditions suitable for use as forecasted Boundary Conditions of the Ice Model. If an ice run is expected on a tributary, this could be used as a Boundary Condition as long as the ice concentration can be estimated.

15-22. Modes of Operation

The Mid-Winter Ice Forecast model can be operated in two modes, a Forecast Mode and an Update Mode. The Forecast Mode starts with the existing Initial Conditions and uses forecasted values of the Boundary Conditions to produce the Model Output. The Update Mode starts with the Initial Conditions that existed the last time the model was run. If the model is operated daily, for example, the Initial Conditions are those existing on the previous day. The actual values of the Boundary Conditions, measured at the field sites, are then used to produce the Model Output. In this way the previous existing conditions are updated to reflect the present existing conditions. Generally, the model is run twice on any day a forecast is made, once to update the Initial Conditions and once to forecast the future ice conditions.

15-23. Model Results

A sample of the Model Output over an entire winter season is shown graphically in Figure 15-8. In this simulation, actual recorded air temperatures and tributary discharges were used. The ice bridging locations were chosen to be at each lock and dam, consistent with observation. The simulation is for the Upper Ohio River, and the location of each lock and dam is indicated. The period covered by the simulation in Figure 15-8 is from 22 December 1985 through 12 February 1986, and the presence of ice is shown as determined by the model. In Figure 15-9, a sample 5-day forecast is shown, also for the Upper Ohio River. This forecast was prepared based on forecasted air temperatures and the actual Initial Conditions on the day that the forecast was made.

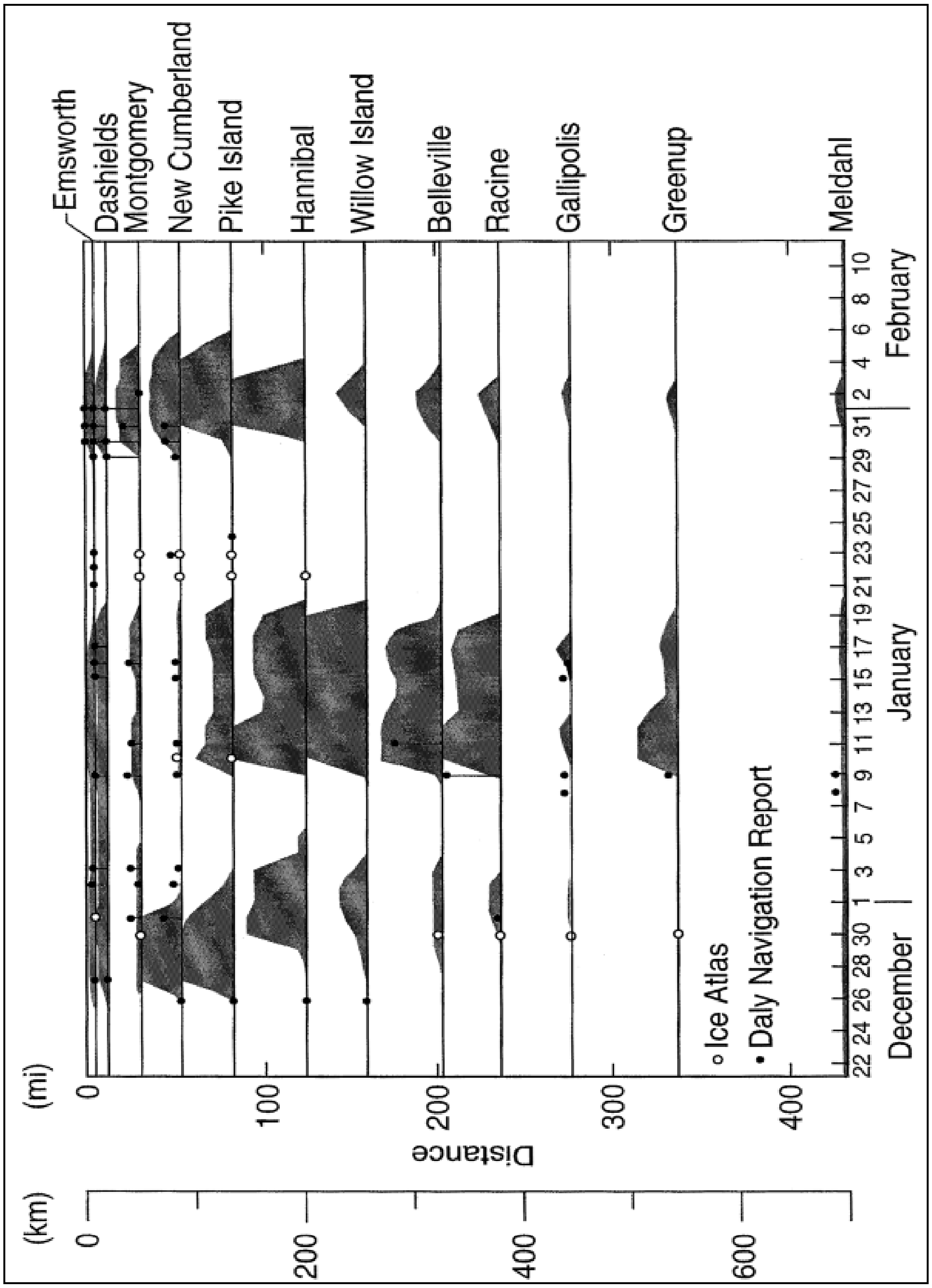

Figure 15-8. Portrayal of the output of the Ice Forecasting System for the Upper Ohio River during the 1985-86 winter. *The shaded areas indicate forecasted ice cover on the river; elsewhere the river was forecasted to be open. Choosing a river location on the diagram and moving across the diagram horizontally gives a time-based summary of the sequence of forecasted ice cover throughout the winter for that location. Similarly, choosing a date during the winter and moving vertically up or down the diagram gives a location-based summary of forecasted ice cover for the Upper Ohio on that particular date. Shown for comparison is ice coverage information based on daily navigation reports issued by the Pittsburgh and Huntington Districts, and an ice atlas (Gatto et al. 1987) based on aerial videotapes*

ICE COVER CONDITIONS ON 12-20-89

DAM	LENGTH MILES	ICE THICKNESS FEET	PER CENT OF POOL WITH ICE	WATER TEMP DEG F	AIR TEMP DEG F
EMSWORTH	0.00	0.00	0	32.70	14.00
DASHIELD	2.96	0.18	44	32.00	14.00
M-GOMERY	0.00	0.00	0	33.37	14.00
NEW CUM	15.20	0.24	79	32.00	14.07
PIKE IS	29.70	0.16	100	32.00	14.18
HANNIBAL	0.30	0.00	5	32.00	14.32
WILL IS	0.47	0.00	10	32.00	14.43
BELVILLE	0.00	0.00	0	32.23	14.56
RACINE	0.00	0.00	0	32.18	14.67
GLPOLLIS	0.00	0.00	0	32.70	14.74
GREENUP	0.00	0.00	0	33.26	14.85
MELDAHL	0.00	0.00	0	35.20	15.01

ICE COVER CONDITIONS ON 12-21-89

DAM	LENGTH MILES	ICE THICKNESS FEET	PER CENT OF POOL WITH ICE	WATER TEMP DEG F	AIR TEMP DEG F
EMSWORTH	0.00	0.00	0	32.88	8.01
DASHIELD	2.96	0.36	44	32.05	8.01
M-GOMERY	0.00	0.00	0	33.37	8.01
NEW CUM	15.20	0.34	79	32.07	8.40
PIKE IS	29.70	0.43	100	32.00	8.91
HANNIBAL	42.30	0.17	100	32.00	9.64
WILL IS	35.30	0.22	100	32.00	10.18
BELVILLE	41.20	0.12	100	32.00	10.83
RACINE	33.60	0.09	100	32.00	11.35
GLPOLLIS	1.89	0.00	22	32.00	11.70
GREENUP	3.64	0.00	74	32.00	12.20
MELDAHL	0.00	0.00	0	34.07	12.99

ICE COVER CONDITIONS ON 12-22-89

DAM	LENGTH MILES	ICE THICKNESS FEET	PER CENT OF POOL WITH ICE	WATER TEMP DEG F	AIR TEMP DEG F
EMSWORTH	1.73	0.00	43	32.00	1.00
DASHIELD	3.56	0.44	53	32.00	1.00
M-GOMERY	0.00	0.00	0	32.05	1.00
NEW CUM	15.20	0.42	79	32.31	1.40
PIKE IS	29.70	0.61	100	32.00	1.90
HANNIBAL	42.30	0.50	100	32.00	2.64
WILL IS	35.30	0.51	100	32.00	3.18
BELVILLE	41.20	0.44	100	32.00	3.83
RACINE	33.60	0.39	100	32.00	4.35
GLPOLLIS	40.70	0.30	100	32.00	4.69
GREENUP	60.80	0.31	100	32.00	5.22
MELDAHL	0.00	0.00	0	32.76	6.01

Figure 15-9. Typical output information from the Mid-Winter Ice Forecast model. *This output covers a 5-day period on the Upper Ohio River*

ICE COVER CONDITIONS ON 12-23-89

DAM	LENGTH MILES	ICE THICKNESS FEET	PER CENT OF POOL WITH ICE	WATER TEMP DEG F	AIR TEMP DEG F
EMSWORTH	6.00	0.48	100	32.00	-0.99
DASHIELD	7.10	0.55	100	32.00	-0.99
M-GOMERY	18.40	0.41	100	32.00	-0.99
NEW CUM	22.70	0.46	100	32.00	-0.44
PIKE IS	29.70	0.72	100	32.00	0.28
HANNIBAL	42.30	0.80	100	32.00	1.31
WILL IS	35.30	0.77	100	32.00	2.07
BELVILLE	41.20	0.74	100	32.00	2.97
RACINE	33.60	0.70	100	32.00	3.69
GLPOLLIS	40.70	0.64	100	32.00	4.17
GREENUP	60.80	0.64	100	32.00	4.89
MELDAHL	94.20	0.12	100	32.00	6.01

ICE COVER CONDITIONS ON 12-24-89

DAM	LENGTH MILES	ICE THICKNESS FEET	PER CENT OF POOL WITH ICE	WATER TEMP DEG F	AIR TEMP DEG F
EMSWORTH	6.00	0.81	100	32.00	0.00
DASHIELD	7.10	0.87	100	32.00	0.00
M-GOMERY	18.40	0.76	100	32.00	0.00
NEW CUM	22.70	0.80	100	32.00	0.46
PIKE IS	29.70	0.83	100	32.04	1.09
HANNIBAL	42.30	0.98	100	32.00	1.98
WILL IS	35.30	0.98	100	32.00	2.62
BELVILLE	41.20	0.98	100	32.00	3.42
RACINE	33.60	0.94	100	32.00	4.03
GLPOLLIS	40.70	0.89	100	32.00	4.44
GREENUP	60.80	0.88	100	32.00	5.05
MELDAHL	94.20	0.50	100	32.00	6.01

Figure 15-9. (Concluded)

15-24. References

a. Required publications.

None.

b. Related publications.

Ashton 1986
Ashton, G.D., ed. 1986. *River and Lake Ice Engineering*, Water Resources Publications, Littleton, Colorado.

Gatto et al. 1987
Gatto, L.W., S.F. Daly, and K.L. Carey 1987. *Ice Atlas, 1985-1986: Monongahela River, Allegheny River, Ohio River, Illinois River, Kankakee River*, Special Report 87-20, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Shen et al. 1991
Shen, H.T., G. Bjedov, S.F. Daly, and A.M. Wasantha Lal. 1991. *Numerical Model for Forecasting Ice Conditions on the Ohio River*, CRREL Report 91-16, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Chapter 16
Ice-Related Hydrometeorological Data Collection and Monitoring

16-1. Introduction

The Corps of Engineers must deal with ice problems affecting operations at Corps projects and at other locations for which the Corps has primary responsibility for responding to emergencies. In addition, effective regulation of Corps water control and navigation projects requires the collection of a wide variety of real-time hydrometeorological data from field sites, but monitoring procedures and resources are not uniform among, or even within, Corps Divisions affected by ice problems. Each District has established its own methods and priorities for collecting information or making observations to meet their needs. A number of instruments are available for both manual and automated ice observations. Manually collected ice observations use a great deal of manpower, and are costly and hazardous. They also provide only spot measurements of a process that is generally dynamic. Automatic data collection can be done around the clock, providing a continuous source of data while at the same time decreasing budgeted manpower and freeing personnel for other work. In remote sites, automated data collection is often the only option. Some Districts have independently developed their own methods of field data collection (e.g., Pomerleau 1992). However, little direct coordination has taken place among Districts in identifying instrumentation that could automate or simplify ice data collection, storage, and retrieval.

a. Survey of Existing Data Collection Methods Employed by the Corps of Engineers. A survey designed to identify existing and desired ice data collection instrumentation, methods, and storage, and types of ice effects, was sent to all Corps of Engineers Districts and Divisions affected by ice (Kay and White 1997). Ninety-nine survey responses were received. The three areas of Corps responsibility most often affected by ice are flood-control structures, navigation traffic, and locks. Freezeup problems predominate over breakup problems for all operations and structures included in the survey, except flood-control structures. The number of projects affected by both freezeup and breakup is equal to the number affected by freezeup alone. The physical properties rated highest by survey respondents for importance are stage and discharge, followed by air and water temperature, ice thickness, and condition of ice. Corps personnel are currently making the vast majority of ice observations from the shore or a nearby structure, such as a bridge, dam, lock, or levee, using still and video cameras. Some instruments or methods to collect data from the ice surface (e.g., the CRREL ice thickness kit, see Paragraph 16-6a) are used by a number of Districts, but they require intensive human effort. The use of DCPs is fairly common, but they are typically used to measure stage, discharge, and a few meteorological conditions. The survey results indicate that there is much potential for automating the storage and retrieval of ice data, but the willingness of observers to convert to computer storage was not gauged. Currently, ice data are predominantly stored in paper form. The information that is being stored digitally is in several different formats, including word processing programs and HECDSS, the time series data storage system developed by the Hydrologic Engineering Center (HEC 1990). A centralized data storage system is important, so Districts should strive for software uniformity as much as possible to avoid data translation problems. In the future, a fairly robust database should be set up, with the capability for GIS querying of those data included. The survey also showed that there is potential for increased use of existing instrumentation and that some new types of instrumentation, particularly remote sensing, are desired.

b. Sources of Information on Ice Conditions. Adequate information on ice conditions is a necessary part of an ice management program at Corps facilities. Corps Districts generally have one or both of the following objectives when documenting ice conditions as part of their river ice management activities.

(1) To analyze past ice conditions as an aid in forecasting future conditions during a given winter.

(2) To monitor current conditions during a winter in sufficient detail to allow planning of waterway operations and anticipating navigation problems.

(3) The first objective can be met using historical ground observations, aerial photographs, and satellite images. However, the most common District need is for monitoring current ice conditions along all their navigable waterways. At most navigation projects, Corps personnel already make ice observations and report them to District offices nearly every day during the winter season. The data are then available to users via computer modem. However, these ground observations are pertinent only for that portion of a waterway within sight of the observers. Ice conditions beyond that are uncertain, and yet such data for the entire waterway are required. Satellite images from current civilian satellites, which do show entire waterways, do not have sufficient spatial resolution nor can they routinely be in the hands of District personnel quickly enough to help decision-makers cope with waterway operations or ice emergencies (Gatto et al. 1987, Gatto 1988). As satellite sensors and image processing systems improve, however, future images may be provided rapidly enough and may be of sufficient resolution to be useful.

16-2. Existing Instrumentation and Observation Methods

All Corps Districts maintain some level of instrumentation to observe various hydraulic and hydrologic properties, but the quantity and types of ice observations vary greatly among them. This may be a reflection of either the severity of ice problems experienced or knowledge of the importance of ice data collection. The end use of the measurement data appears to affect how "high-tech" or "low-tech" the measurement devices are. For example, stage may be visually inspected and recorded once a day in a logbook by personnel at one project location, while another individual may be interested in continuously monitoring the rise and fall of stage at multiple locations during the freezeup and breakup periods. The survey indicated that various hydraulic and ice properties are being visually observed on-site, and that the observers seem to be generally satisfied with current practices. The respondents did not indicate a desire to measure additional properties, but, unfortunately, the survey did not gauge how willing personnel would be to automate those observations already being made. The more commonly used instruments and observation methods employed by responding Districts are listed in the following paragraphs, along with some of their advantages and disadvantages. A good reference for ice data collection is the report by White and Zufelt (1994).

16-3. Stage Measurements

According to the survey, the hydraulic properties most commonly measured by Corps of Engineers Districts are stage and discharge. For open water conditions, discharge is usually determined from a rating curve that relates a specific discharge to a specific stage. The stage–discharge relationship for ice-affected flows is often far more complex and depends greatly upon ice conditions (Rantz et al. 1982a, 1982b).

a. Manual Measurement of Stage.

(1) *Staff Gage.* One of the easiest ways of measuring stage is to use a staff gage that is installed either permanently or temporarily, depending on needs of the users. Staff gages vary from the standard USGS porcelain-enameled iron gage with markings every 0.6 centimeters (0.02 feet) (Rantz et al. 1982a) to a wooden building stud with markings every 15 centimeters (6 inches). Permanent gages should be attached to (or painted on) permanent structures, such as bridges or drainage structures, or located in sheltered areas, such as an area of heavy vegetation, to protect them from ice and debris. Permanent gages can be installed along a river bank, but they may be heavily damaged by ice. Temporary gages can be installed during flood emergencies to measure stages in areas not otherwise monitored. These gages can be subsequently reclaimed and reused, but must be installed in the water, or an area expected to be underwater, to be effective. This could pose a very serious threat to installation personnel during an ice jam flood. The greatest advantages to the use of a staff gage are that virtually anyone can make a reading with very little training, and they can be installed almost anywhere for relatively little cost and usually require little maintenance. However, there are several disadvantages to the use of a staff gage. Stage can only be measured at the time of observation, which often means that the peak stage at a location is not measured. Measurements are limited to daylight hours, unless the gage is in a well-lit area. Flooding or poor weather conditions may make access to the gage impossible or make the gage difficult to read accurately, even with binoculars. Often, personnel requirements make frequent gage readings impossible, especially if gages are spread over a wide area.

(2) *Wire Weight Gage.* Wire weight gages (Rantz et al. 1982a) consist of a weight attached to a cable wound in a single layer around a drum (Figure 16-1). The gage is contained in an aluminum box that is mounted on a bridge. The box contains a calibrated disk that the cable passes over when it is lowered to the water surface, and a counter that records the distance that the calibrated disk moves. Stage is calculated from the counter value when the box is placed a known height above the streambed. A chain gage is similar to a wire weight gage, except that the weight is attached to a chain that passes over a pulley. As the weight is lowered to the stream surface, the chain moves along a marked horizontal gage from which the distance moved is calculated (Bureau of Reclamation 1984). Wire weight gages and chain gages have the same disadvantages as do staff gages, with the additional disadvantages that relatively few people have the training or access required to make such measurements, and that the wind can blow the weights, causing the reading to be larger than actual (Bureau of Reclamation 1984).

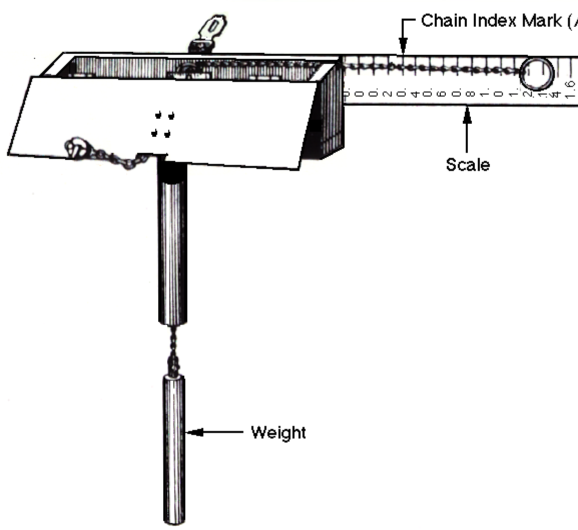

Figure 16-1. Chain gage used to measure stage (after Rantz et al. 1982a).

(3) *High Water Marks.* High water marks can be determined following a flood event, either by examination of vertical or near-vertical surfaces for evidence of the waterline, or by looking for ice scars on trees (White and Zufelt 1994). Ice scars are areas of damage to a tree trunk, usually caused by moving ice. The disadvantages of high water marks are that funding may not always be available to do the required surveys, rainfall or warm weather following an ice-related high water event can obliterate high water marks before they can be set, and additional flooding can obliterate high water marks before they can be surveyed.

(4) *Crest Stage Gage.* There are occasions when only the peak stage associated with an ice jam event is desired at a remote location. The USGS frequently uses crest-stage gages (Rantz et al. 1982a) in flood flow frequency studies to record maximum peak stages in known jam locations. These gages (Figure 16-2) are made of a galvanized pipe, with holes drilled near the bottom, that is installed in the streambed. A graduated rod or staff is placed within the pipe at a known datum. A perforated cup or cone filled with regranulated cork or similar substance is attached to the lower end of the staff. As the water level rises within the pipe, the cork is floated out of the cup, and it will adhere to the walls of the pipe and the staff at the highest level that the water reaches. The staff is removed from the gage and read as soon as the water drops to safe levels. These gages have low-cost, and reportedly good reliability and low maintenance. Keeping the water within the pipe liquid is important during winter operation, perhaps by heating the pipe or installing a solar cell at the top of the pipe to power heating coils or a small bulb.

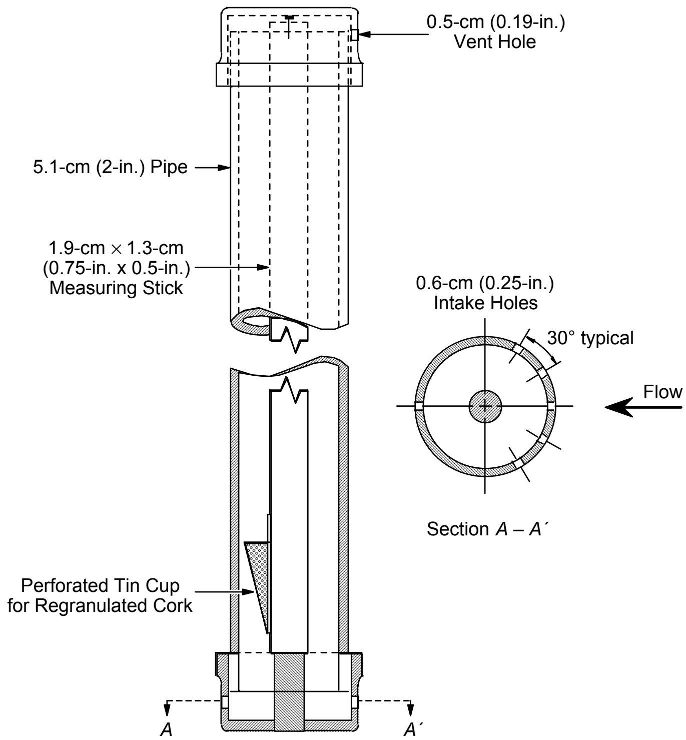

Figure 16-2. USGS crest stage device used to measure peak stage (after Rantz et al. 1982a).

(5) *Maximum-Minimum Stage Gage.* Another possible maximum stage recorder would be an adaptation of a maximum–minimum stage gage described by Zabilansky et al. (1992), in which a float of some type is fitted between two washers over a 19-millimeter (3/4-inch) pipe that is installed in the streambed. During the winter, ice attaches to the float and, as the float is moved up and down by ice action or waves, the washers are pushed up and down on the pipe, recording wave maxima and minima. A similar device could be used to record maximum stage during an ice (or open-water) event. A conceptual drawing of such a device is shown in Figure 16-3. The greatest challenges to installing such a device are to design the rod to withstand the lateral and uplift forces exerted by ice and to keep the float from freezing to the rod. The use of a dark material for the float and rod would help avoid freezing. The float would require some type of spring mechanism to prevent it from sliding down the rod when stage recedes, but to also allow it to be reset every year (or after every flood, if desired). A solar collector panel could be mounted to the top of the rod, and heating coils could be put inside to help stop ice from forming. With either the gage discussed in this paragraph or the one discussed in Paragraph 16-3a(4), the stage could be read at a later date as time and weather conditions permit, so long as a flow with higher stages does not occur in the interim. One drawback is that the date and time of the peak must be estimated. Several such devices could be put into place along a relatively short stretch of river to obtain jam profiles, or a network of such devices could be used to supplement USGS gaging locations for recording the peak stages at known jam locations, since USGS gages are not always located near a jam.

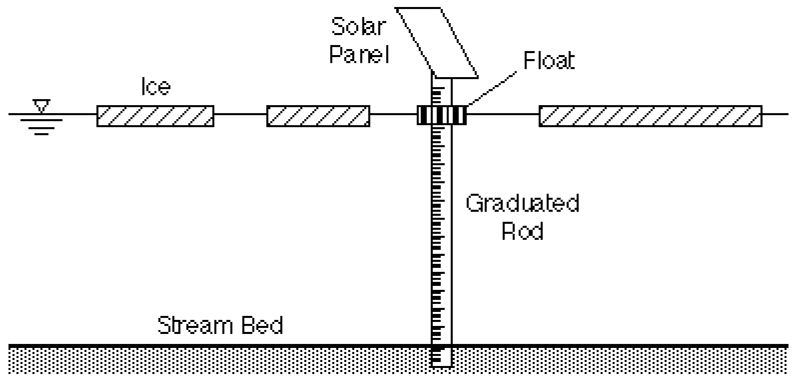

Figure 16-3. Conceptual view of maximum stage gage.

b. Remote Measurement of Stage.

(1) *Water-Stage Recorders.* Stage information has been remotely collected via water analog or digital stage recorders. Various types of stage recorders have been used for a number of years (Rantz et al. 1982a). One of the most common is a pen recorder with rotating drum. These instruments are reliable and accurate for recording stage and are relatively inexpensive to install and operate. However, they can suffer a number of mechanical problems that require relatively frequent checks. For example, the clock mechanism for driving the drum may not operate at the proper speed, the pen may run out of ink, or the float system may freeze in place during cold weather. The strip charts require regular visits to replace, and storage requirements for several years' worth of strip charts may become cumbersome. Stage must be read directly from the strip chart and can be read incorrectly, especially from charts with reversing pen mechanisms. The use of digital recorders is quite common in the Corps, especially at sites with DCPs, and they are often connected to a pen recorder. Automated digital recording is becoming more popular, as it avoids many of the disadvantages associated with strip charts

(2) *Pressure Transducers.* Pressure transducers are quite versatile, as they can be installed in a variety of situations. The pressure transducers now routinely used are capable of measuring stage to within 0.01 feet (3 millimeters). They have no mechanical parts, so they do not suffer from many breakdowns. One disadvantage is that the orifice lines can clog, particularly on streams with a high silt and clay load, causing readings to be in error until the lines can be back-flushed to clear the obstruction. Telemark systems are still used at some remote sites, but the advent of DCPs has reduced the use of this remote monitoring querying method.

(3) *Ultrasonic Measurement.* Ultrasonic instruments have been used for a number of years with varying levels of success. They have the advantage over traditional water level recorders that direct contact with the water is avoided, thus decreasing the incidences of freezing and damage by water-borne debris. Ultrasonic instruments are susceptible to rapid changes in air temperature, and wind can disturb the water surface enough to disrupt the return signal (Abraham and Hall 1994). The absolute accuracy of the ultrasonic sensor is relative to its range, although resolution may be to 0.01 feet (3 millimeters). In other words, two sensors with the same range may not have the same accuracy if their relative accuracy varies, or two sensors with the same relative accuracy will not have the same absolute accuracy if their ranges differ. The capabilities

of individual sensors will vary with manufacturer and cost. It is not known how an ultrasonic sensor would perform over an ice surface. To be truly portable, the sensor, its recorder, and the power source must be self-contained in a small, lightweight package, such as that shown in Figure 16-4. The unit would need to be enclosed in a weather-tight box that could either be permanently mounted on a surface, such as the side of a bridge, or it could be temporarily hung over the side of a bridge. If the housing were permanently installed, the components within could be removed and used among various locations. A data logger and ultrasonic sensor must be selected with the expected operating climate, data requirements, and operating properties in mind.

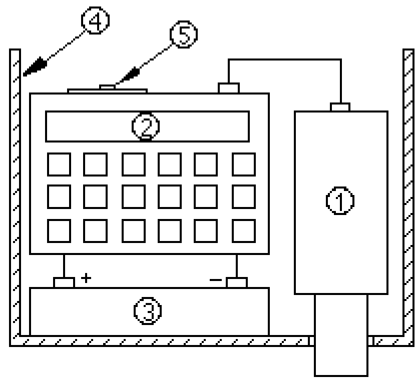

Figure 16-4. Section view of ultrasonic stage recorder: 1 is the ultrasonic sensor, 2 is the datalogger, 3 is the power source, 4 is the weatherproof enclosure, and 5 is the output port for downloading data to a laptop or telephone.

(4) *Radar Measurements.* Recently, the measurement of stage with a millimeter-wave (MMW) frequency modulated–continuous wave (FM–CW) radar has been explored. The system deployed by Yankielun and Ferrick (1993) could be mounted from a bridge and used to acquire, process, store, and display river stage data at time intervals ranging from 1 to 60 seconds around the clock. Their system had a maximum range of 11.46 meters (37.6 feet). With the proper siting, this system could also measure ice thickness (see Paragraph 16-6). The greatest drawback to the use of either ultrasonic or radar systems is that they measure distance to the first surface encountered, so that when a stream is ice covered, the distance to the ice surface would be measured, rather than the distance to true water surface. If true stage were desired, it would be necessary to maintain an area of open water below the instrument. The system described by Yankielun and Ferrick includes a radar front end, a function generator, a dynamic signal analyzer, and a 12-bit analog-to-digital converter internal to a laptop computer. The radar front end consists of a voltage-controlled oscillator (VCO), waveguide components, transmit and receive antennas, a mixer, and an audio amplifier. A schematic of the system is shown in Figure 16-5. Signal processing is probably the biggest obstacle to fielding this device. If measured stage for only one event is desired, processing could be done after the entire event has been recorded, but random or regular querying of stage is more complicated. An instantaneous value of stage could be substantially in error if waves, ice, or debris happen to be passing through the radar scan at the time of measurement. A typical procedure would be to sample stage for the period of time necessary for adequate accuracy, processing the data, time-averaging the stage values, and transmitting the

computed value. This may be difficult if the DCP is in a random report mode. Another option would be to sample stage continuously between DCP queries, process the stage data, and continuously update the time-averaged stage. The average stage and maximum and minimum stage could then be transmitted (provided the DCP has enough free channels) and the whole cycle would start over again. Signal processing requires a fairly robust system to process and continuously update values, and a fairly decent signal-processing algorithm needs to be developed to account for false values (e.g., if a bird or large debris passed through the radar beam).

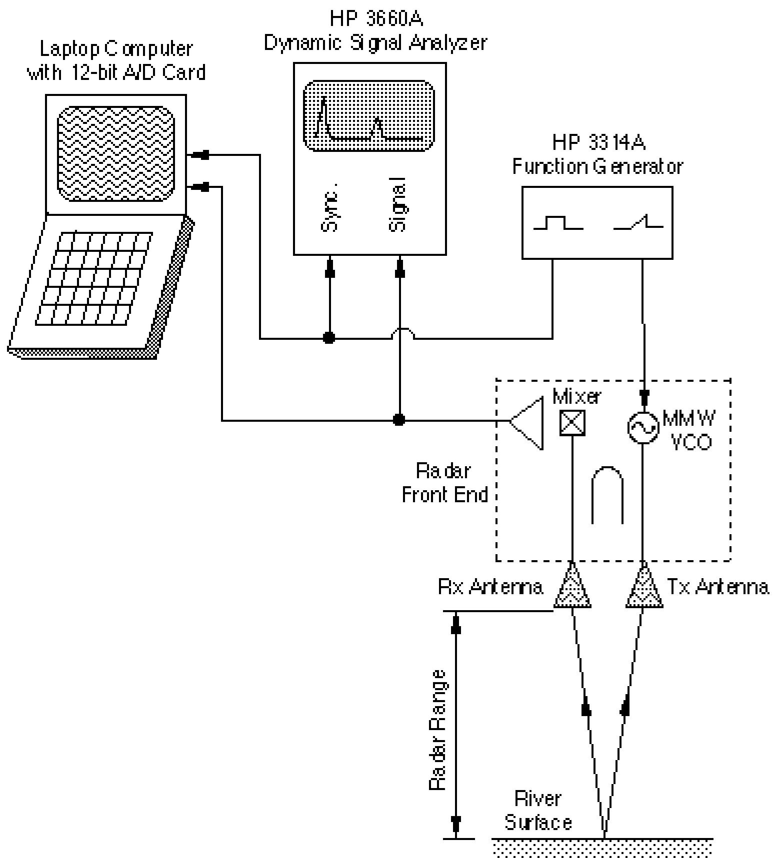

Figure 16-5. Schematic of MMW FM-CW used for velocity determination.

16-4. Discharge

Direct discharge measurements are generally made by the USGS (Rantz et al. 1982a), although some Districts maintain the capability to make discharge measurements at selected locations. Discharge measurements collected under an ice cover are generally thought to have greater uncertainty than discharge measurements made in open water at the same location (Cobb and Latkovich 1986). Ice does not even have to be present to affect the stage–discharge relationship; decreases in water temperature apparently affect bed roughness (Colby and Scott 1965).

a. Standard Discharge Measurements. The USGS uses Price-type vertical shaft meters to measure discharge. Because the accuracy of Price meters can be affected by ice or cold water

(Rantz et al. 1982a), the USGS has used the modified yoke Price-type winter meter as the standard for discharge measurement through an ice cover since 1988. The use of solid plastic rotors reduce rotor plugging during frazil ice conditions (Wagner 1994). The current USGS standard method of discharge measurement in ice-covered streams (Rantz et al. 1982a) requires the drilling of holes in the ice through which the current meter is immersed (unless open water exists relatively near the gaging station). The use of the ice surface as a working platform can lead to concerns for personnel safety.

b. Estimating Discharge from Stage-Discharge Curve. Guidance is available for preparing discharge-frequency curves for open-water conditions at gaged sites (e.g., Hydrologic Engineering Center [HEC] 1992, Water Resources Council 1982). Unfortunately, less attention has been given to the case where ice effects are important. In ice jams, gages may be badly damaged and made useless. In addition, because ice jams often cause high stages at relatively low discharges, the traditional discharge-frequency curve is not appropriate and a stage-frequency curve must be constructed. Developing an ice-affected stage-frequency curve brings additional difficulties. For example, ice jams are unstable at high discharges, so they may only affect a portion of the stage-frequency curve and some stages reported to be ice-affected may actually be open-water stages. Length of record, the major obstacle encountered in open-water flood frequency analyses at gaged sites (Greis 1983), is exacerbated for ice-related events, which are generally much less frequent than open-water events. They have even smaller sample sizes. When a mixed-population analysis is required, a search of USGS archived records is the best source of ice information needed to develop peak stages during ice-covered periods.

c. Near-Real-Time Discharge Estimates. Some USGS offices maintain separate rating curves for open-water and ice-covered flow, but, typically, the USGS has not corrected the daily discharges for ice effects until after ice out, using the hydrographic and climatic comparison (Walker 1991). Walker (1991) concluded that analytical methods could be better than the subjective hydrographic and climatic comparison, but recommended further refinement and investigation. Additionally Walker (1994) suggests that a method he calls the “first-visit complete-profile” be used nationwide to improve the accuracy of discharge measurements under ice-covered conditions. Wagner (1994) notes that, during the work of Melcher and Walker (1992) in Iowa in the 1987–88 season, a computer program was developed that allowed for daily discharge adjustments via computer monitor, based on other nearby weather data and discharge hydrographs. Holtschlag et al. (1997) developed a method for predicting real-time ice-affected discharge through application of an extended Kalman filter to measurements of stage and air temperature. This model was developed using data for two ice-affected gages (St. John River at Dickey, Maine, and Platte River at North Bend, Nebraska), but has not yet been implemented.

d. Potential Radar System for Discharge Measurement. It may be possible to combine a short-pulse radar and MMW FM–CW radar to make a discharge measurement device. The MMW FM–CW radar is capable of measuring ice velocity, while the short-pulse radar can profile the channel bed if it is operated at a low enough frequency. If ice velocity could be correlated to the average stream velocity below it, discharge could be determined by taking the point measurements of depth, multiplied by ice velocity, corrected to an average velocity. This instrument could be mounted on a vehicle and driven over bridges, or it could be mounted on an aircraft flying sections across the river. Some type of GPS unit could be used to determine cumulative distance across the stream as the radars collect data. Two constraints on this idea are operating within the range of the radar units and determining whether the FM–CW system can accurately determine ice velocity while in motion itself. Data processing would be another constraint on such a system. Several years of work will probably be required to make such a system workable.

e. Potential Discharge Measurement Using Acoustic Velocity Meters. Wagner (1994) states that the USGS and Environment Canada have both demonstrated that acoustic velocity meters (AVM) have potential for collection of stream flow data. AVMs have been successfully used to collect line velocity between transducers, and both agencies plan to continue to evaluate AVMs. Acoustic flow meters are already in fairly widespread use; one example of their use by the Corps would be for discharge measurement in a power plant penstock to detect decreases in flow caused by frazil buildup on trash racks. However, to use an AVM in the field for stream flow measurement will require a great deal more work, especially in adjusting line velocity to average channel velocity. Another problem is that the acoustic signal used by an AVM for stream flow measurements can be disrupted of during periods of slush-ice flow. If the problems with this instrument can be worked out, and it can be permanently installed at a site, it holds great potential for continuously measuring stream flow in real-time.

16-5. Air and Water Temperature

a. General. Air and water temperature are relatively easy to measure remotely, but some difficulties are still encountered. Air temperature is almost always collected at project sites using a mercury thermometer or some type of digital thermometer, or temperatures are obtained from the nearest National Weather Service site. As with any other type of instrument, a thermometer must be placed correctly to obtain a good reading. Accuracy to the nearest degree is often all that is needed for air temperature. Such is not always the case with water temperature measurements. Frazil ice forms when water supercools below the freezing point by only a few hundredths of a degree (Ashton 1986). However, if the temperature measurement device is only accurate to the nearest degree, water temperatures of nearly 0.5°C (warm enough to melt ice) and –0.01°C (supercooled) will both register as 0°C. When estimates of frazil ice production are needed (e.g., estimating when heavy frazil ice production may begin to affect navigation traffic, or when river intake structures might be affected), an instrument capable of reading to the nearest 0.01°C may be needed.

b. Thermistors. Typically, a glass-bead thermistor is used when very precise temperature measurements are needed. Generally, thermistors are used in conjunction with a digital multimeter. They can be permanently installed and connected to a data logger or DCP for recording temperature data. When connected to a DCP, a voltage divider circuit that converts resistance to voltage is needed. A good reference for permanent thermistor installation guidelines can be found in EM 1110-8-1(FR). A typical installation is shown in Figure 16-6. Generally, thermistors are paired within a probe to provide backup. Each thermistor in a probe is hand-made and must be individually calibrated.

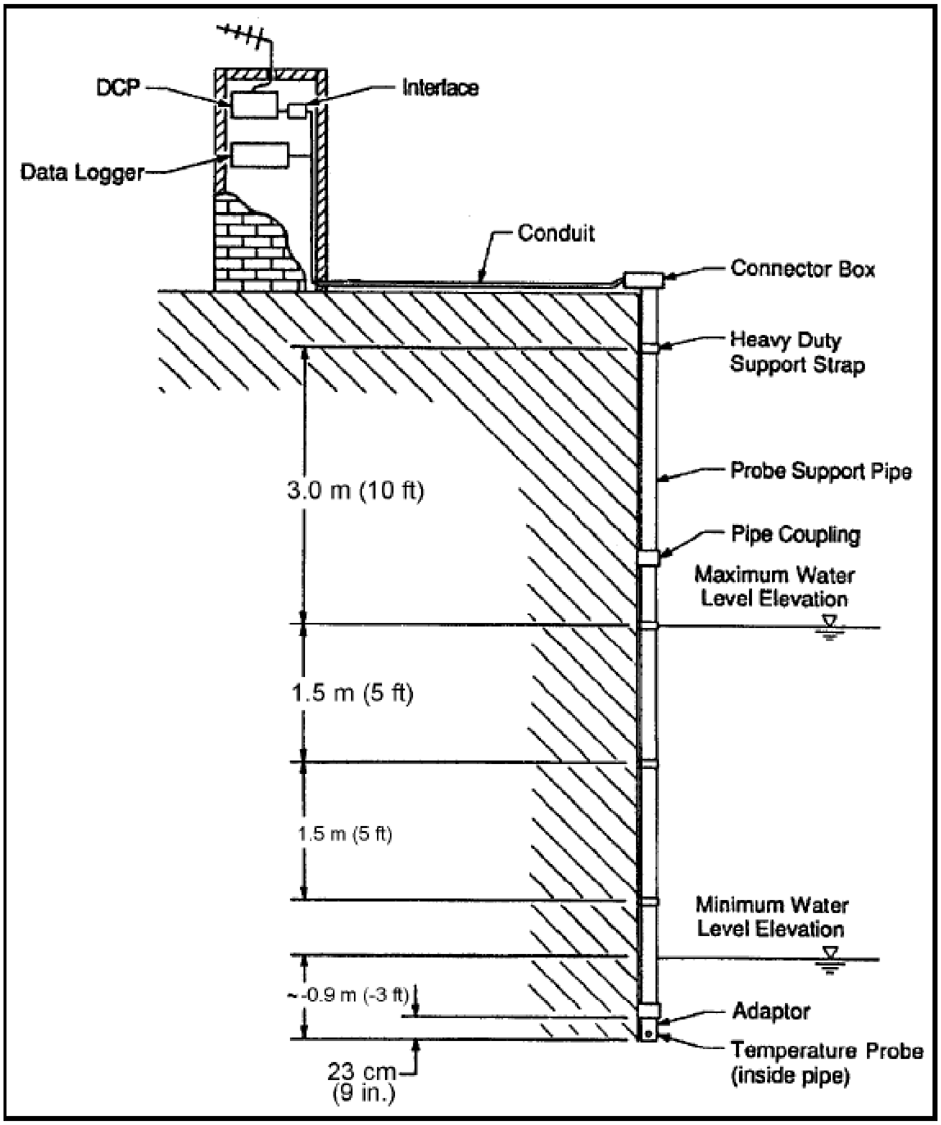

Figure 16-6. Typical water-temperature measurement system.

(1) The resistance of the calibrated thermistor is used in the Steinhart-Hart equation:

$$T = \frac{1}{A + B\ln R + C(\ln R)^3} \tag{16-1}$$

where A, B, and C are the thermistor constants (typically 8 significant figures), R is the measured resistance, and T is temperature in Kelvins. Thermistors are theoretically capable of a temperature accuracy within ±0.01–0.02°C. The thermistor probe support pipe is typically installed on a wall or pier in contact with the moving river water rather than in locations such as gage wells, locks, or other areas where the water may stand for long periods and freeze. The location should be protected from direct impact of drift and ice floes; the downstream sides of piers, cells, piles, pile dolphins, and ladder accessways, and recesses in walls parallel to the river are acceptable. A petrolatum-polyethylene gel-filled cable having a solid copper tape shield with three-pair 19-AWG conductors and a polyethylene jacket is recommended for connection to the thermistor probe. Cable expected to remain dry may be more flexible, such as a three 18-AWG, twisted, shielded pair with drain wire and polyvinyl chloride (PVC) outer jacket. Generally, a DCP can measure only voltages. Thermistors, however, change resistance in response to changing temperature. The DCP interface, therefore, is a simple voltage divider circuit that converts the thermistor resistance to a voltage. The interface is a rectangular box that is typically installed immediately adjacent to the DCP. Analog inputs to DCPs with scaling resistors should be avoided or the scaling resistors should be removed.

(2) Figure 16-7 shows a schematic diagram of the wiring of the interface box and the connections to the temperature probe and the DCP. The relation below (Equation 16-2) can be used to determine the resistance of a thermistor (R_i) in this configuration:

$$R_i = (10{,}000)\ \frac{V_i}{V_o - V_i} \qquad (16\text{-}2)$$

where V_i is the measured voltage across the thermistor, and V_o is the excitation voltage applied to the divider circuit. The applied voltage across the thermistor is kept low by the use of a diode. This is done to keep the electrical current in the thermistor to a minimum to prevent self-heating. The relatively large offset currents that may be introduced into the voltage divider circuits by the circuitry of the DCP itself result in an inaccurate voltage measurement across the thermistor. To correct for this, the voltage across a reference resistor, with a known stable resistance, is measured along with the voltage across the thermistor.

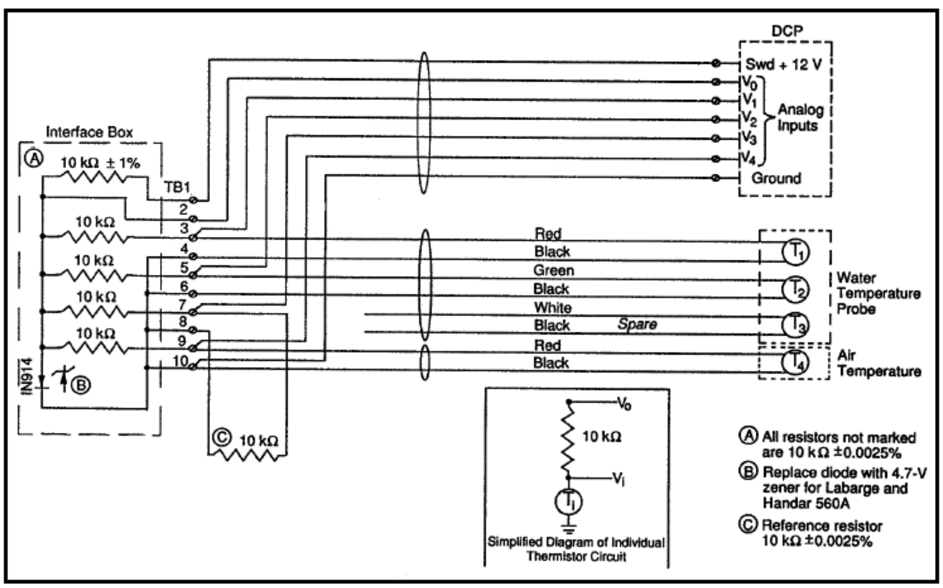

Figure 16-7. Schematic wiring diagram of DCP interface box.

(3) The measured voltage across the reference resistor V_f can then be used to calculate each thermistor's resistance by

$$R_i = \frac{(10{,}000)\ V_i}{2V_f - V_i} . \qquad (16\text{-}3)$$

The DCP manufacturer's input and output impedance specifications must be known and considered by competent electronics personnel for the proper design of the DCP interface box to ensure a trouble-free overall installation.

16-6. Ice Thickness

Ice thickness is currently most frequently measured either by drilling through the ice cover and measuring the thickness or by visual inspection from the shore or other vantage point. The shortcomings of both methods were pointed out earlier. Several other techniques have been used in this and other countries (Adams et al. 1986) that also require the observer to go out onto the ice or for the instrument to make physical contact with the ice. Fortunately, there has been considerable research into remote sensing of ice thickness and advances in instrumentation continue that will likely allow field implementation soon.

Figure 16-8. Standard CRREL ice thickness measuring kit.

a. Manual Ice Thickness Measurement. The standard CRREL ice thickness kit (Figure 16-8) contains a two-part iron bar used to test the ice for safety, an auger with carbide-tipped bit and bit brace for drilling holes, extension rods to increase the depth to which holes can be drilled, and a device to measure ice thickness. A small diameter auger is preferred because holes can be drilled faster, but a minimum diameter of 5 centimeters (2 inches) is recommended if velocity measurements are desired. Thickness is measured using a tape equipped with a hinged weight at the end (Ueda 1983). The weight and tape is lowered through the hole, usually until the weight hits bottom so that total depth of flow is known. The tape is then pulled upward until the weight encounters the ice bottom and catches on the ice. It is then read so that the thickness is known. The measurement can be complicated if frazil is present underneath the ice surface, but, with a little practice, the observer can differentiate between the frazil and solid ice. If frazil is present, both the depth to the bottom of the frazil and the bottom of solid ice should be recorded. After the tape is read, the weight is hinged, or folded, and pulled back up through the hole (Figure 16-9). This method is relatively quick and accurate, but it poses risks for individuals going out on the ice cover. Another disadvantage is that only a solid ice cover strong enough to support the weight of the observers can be measured; floating frazil or very thin ice cannot be measured. The thickness of an ice jam could be measured in this way, but unless the jam is grounded or frozen in place, it would be highly inadvisable to attempt such a task because of safety reasons.

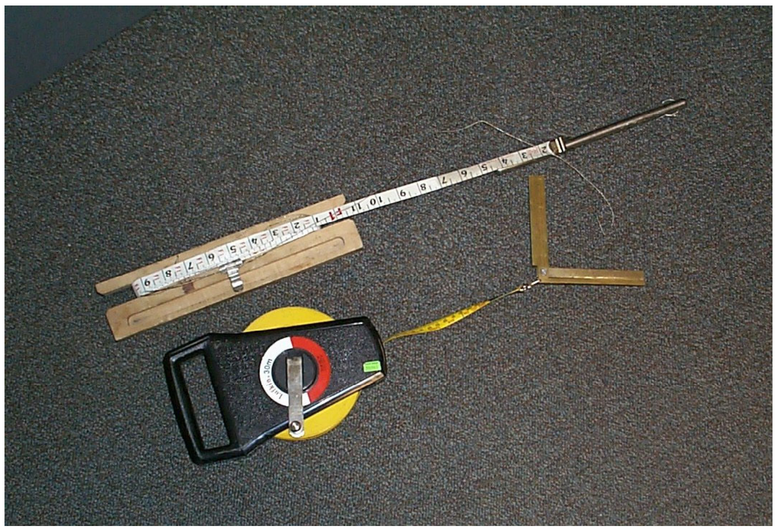

Figure 16-9. Ice thickness measuring devices.

b. Thickness Estimation Using Electrical Conductance. Sherstone et al. (1986) report on the use of "hot-wire" resistance gages to measure ice thickness in the MacKenzie Delta. The gages are installed after the initial formation of the ice cover. An 18-AWG chrome A resistance wire of known length is suspended from a platform above the ice surface through a hole drilled in the ice. The resistance wire is weighted on the bottom. A second, insulated, wire is connected to the bottom of the resistance wire. Once the hole refreezes, ice thickness can be measured by applying a current to the resistance wire, heating it, and raising the wire until the weight hits the bottom of the ice thickness. The ice thickness can then be determined by measuring the amount of resistance wire remaining above the surface. This method has the same disadvantages as the drilling method described above, with the added disadvantage that the wires can break.

c. Visual Estimates of Ice Thickness. Visual estimates of in-place ice thickness are highly subjective and large errors can be made. An indirect measurement of ice thickness can be made after the ice cover has broken up, when pieces of the broken ice cover that remain on shore can be measured. Observation must take place shortly after breakup, before warmer weather or rain can significantly reduce thickness. Ice jam thickness is often estimated on the basis of the height of ice shear walls, if they remain, after an ice jam releases. While these indirect methods of thickness measurement are helpful for future use, they are not applicable for making real-time measurements of thickness.

d. Pressure Transducer. Ford et al. (1991) report on the development and field testing of a floating drogue equipped with a pressure transducer and radio transmitter to measure ice thickness beneath ice jams. The drogue is released into the water upstream from the jam and floats downstream under the ice cover. The radio transmitter in the drogue reports the hydrostatic pressure at the top of the drogue, which allows jam thickness to be estimated. The position of the drogue can be estimated from shore through the use of loop antennas. Two drawbacks are that the drogues may become stuck within the jam, and the speed and trajectory of the drogue through the jam cannot be controlled. However, satisfactory results were obtained in the initial field testing, and the method holds promise for the future.

e. Radar. Radar systems have been used for various kinds of geophysical work for years, including the measurement of sea and freshwater ice thickness. Radar, in theory, detects ice thickness by determining the distance to the air/ice interface and to the ice/water interface; then, one is subtracted from the other and the difference is the ice thickness. The two most successful types of radar have been short-pulse (or impulse) and the millimeter-wave frequency-modulated continuous-wave (MMW FM–CW) systems (Yankielun 1992). Both are currently used by researchers at CRREL, and have the advantages and disadvantages discussed below.

(1) *Short-Pulse.* Short-pulse systems have been used for a number of years. As overall radar technology has grown, the ability to detect thinner layers of ice has increased. However, the best resolution of thickness to date has been about 10 centimeters (4 inches), which is about twice the minimum thickness for safe transit by one individual on an ice sheet (CRREL 1986). Riek et al. (1990) state that it is theoretically possible, under favorable conditions, to measure thicknesses of 3–4 centimeters (1–2 inches), using appropriate signal-processing algorithms. While units were originally developed and tested on the ice surface, most recent activity has centered on the use of the unit suspended from a helicopter. The use of radar from a helicopter has allowed long extents of river ice to be profiled in a relatively short time. The area “illuminated” by the radar unit for measuring ice thickness depends upon height of the antennae above the ice surface and the velocity at which the aircraft is moving (Arcone and Delaney 1987). The use of a global positioning system (GPS) unit in conjunction with the radar system is required for tracking movement in the horizontal plane. The GPS unit could be set up to continuously query position or to determine position only on user demand, depending on the needs (and data storage capability) of the observer. One limitation of the short-pulse system, besides minimum detectable thickness, is difficulty in the measurement of frazil and brash ice thickness, and ice jams. The irregular surfaces of brash ice and ice jams scatter the radar signal, and the high water content of frazil attenuates it heavily. Daly and Arcone (1989) attempted to indirectly measure the thickness of a brash ice jam by measuring the mean height of freeboard above the water surface using a short-pulse radar from a helicopter. They accomplished this by measuring the weak, scattered signal from the brash ice pieces and the strong signal from the water surface. They concluded that it would be possible to determine the relative changes in brash depth, but more accurate absolute thickness determination would require some type of empirical adjustment for brash ice porosity, thickness, and refractive index. The presence of frazil (and brash) ice can be detected by radar at high power and low frequency, but this results in a loss of resolution of the

ice thickness measurement (Arcone and Delaney 1987). In spite of this, Ismail and Davis (1992) report measuring the thickness of a 7-m-thick ice jam from the ice surface in New Brunswick using short-pulse radar. Another limitation of this radar system is that interpretation of the data currently requires highly skilled and experienced personnel (Dean 1981). Considerable work has gone into automating signal processing, but, currently, the signal is processed after the data are collected. If short-pulse radar is to be useful in the field, the system would need to process the signal and display ice thickness in real-time (or near-real-time), as well as to be able to store the collected information for later use. The collection of data requires a great deal of storage; as an example, O'Neill and Arcone (1991) point out that with a helicopter speed of 2 meters/second (6.6 feet/second) and a digitization rate of 25,000 samples/second, approximately 12.5 MB of data are produced per kilometer of survey.

(2) *Millimeter-Wave Frequency-Modulated Continuous-Wave*. The MMW FM–CW radar system suffers from most of the disadvantages of the short-pulse radar, but it can do things that the short-pulse radar unit cannot. The FM–CW system cannot penetrate water so it is unable to determine ice thickness once water begins to pool on the surface. However, this could be used to advantage if it were used to determine when a previously stable ice cover is nearing breakup. Because of its shorter wavelength, the MMW FM–CW system has been capable of profiling much thinner ice than has the impulse radar system. It can be mounted from a helicopter for ice thickness profiling (Yankielun et al. 1993), and research continues on mounting it from a fixed wing aircraft. This system is likely to be less expensive than the impulse radar system, as the radar front end can be found at most well-supplied electronics stores for under a few hundred dollars. Toikka (1987) also discusses the use of an FM–CW radar for measuring ice thickness. Cost is likely to be a major factor in bringing any radar system on-line in the near future. Yankielun (1992) estimates the cost of his FM–CW radar system at approximately $57,000 if all new components were purchased off-the-shelf. Even if the radar front end can be purchased for a few hundred dollars, a signal processing unit that costs several thousand dollars is still necessary.

f. Upward Looking Sonar. Rossiter and Crissman (1994) mention the possibility of using upward-looking sonar to determine ice thickness. The sonar sensor would need to be anchored to the riverbed below a level at which ice could not cause damage. This system would only be capable of point measurements and thus could be used to estimate ice speed but not direction.

g. Electromagnetic Induction. Another way in which ice thickness measurements have been made is electromagnetic induction methods. CANPOLAR (1985) reports on several manufacturers with electromagnetic induction instruments used for measuring ice thickness from the ice surface. They also state that electromagnetic induction methods appear to be the most promising technology for remote measurement of ice thickness, although a great deal of work is needed for a usable device. Arcone et al. (1987) report on the use of magnetic induction to detect frazil deposits. They report that the magnetic induction method would work best on frazil with low water content and work less well on shallow streams with bottom sediments, such as gravel or gravelly sand that could be confused with frazil. So far, magnetic induction instruments have not been used from an airborne platform.

16-7. Ice Movement and Velocity

a. *Ice Movement.* Corps personnel normally monitor the movement of river ice visually to determine when and where breakup may be occurring or where moving ice may affect navigation traffic or lock operation. Little automation of ice movement monitoring exists at the District level at this time. A remote means of monitoring ice movement has recently been developed by CRREL researchers and has been used in the field (Zufelt et al. 1995). A schematic of the ice motion detector is shown in Figure 16-10. Wires embedded in the ice are connected to the detector unit, which is then connected to a DCP, phone, or some other device capable of transmitting a signal. When the ice cover begins to break up and move, the wires are broken. The detector transmits one signal when the wires are whole, and different levels as each wire is broken. The multiple wire configuration provides redundancy to reduce the likelihood of a false alarm and to monitor more width of the river against breakup. The detector unit can be set up to handle complex situations, as described in Zufelt et al. (1995), or it can be as simple as a burglar alarm with built-in dialer attached to a telephone. The greatest advantages of the ice motion detector system are that it works around the clock at a minimal cost, typically only takes a few hours to install, and is simple to operate. One disadvantage is that the wires must be installed in the ice every year. Rachuk and Rickert (1986) describe the use of a similar concept, an array of sensors embedded in the ice, in Canada on the Athabasca River. The MMW FM–CW radar system described earlier can also detect ice motion, as well as ice velocity, with slight modification (Ferrick et al. 1995). It can be used in the period before a stable ice cover forms, unlike the unit developed by Zufelt et al. (1995).

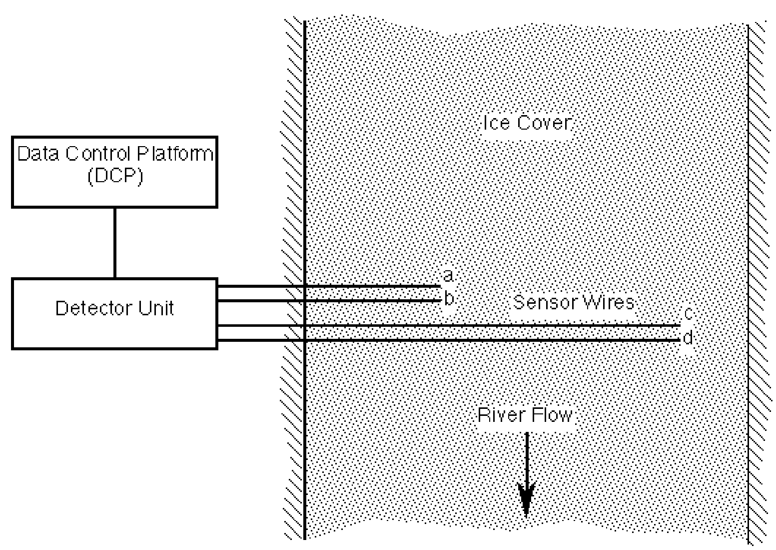

Figure 16-10. Schematic of ice motion detector connected to DCP. The detector returns different levels of response depending on whether wires a, b, c, or d (or various combinations) are intact, allowing the user to determine the extent of ice cover breakup and movement.

b. Ice Velocity. Ice velocity, while not typically monitored, has been measured by a variety of remote methods. It can be estimated by measuring the time required for an ice piece or other small particle takes to traverse a given length of river using a stopwatch and taped distance along the bank. Prowse et al. (1986) report a similar method used by the Hungarian Water Conservation Bureau in a reference grid is set up at a particular location in the river through the use of temporary markers in the water and fixed markers on land. Time-lapse photography obtained during freezeup and breakup is compared to the reference grid to estimate surface ice velocities and ice concentration (Figure 16-11). Prowse et al. also tested the use of false-parallax and image-digitizing photogrammatic techniques with large format cameras to determine ice velocities and found them to be quite accurate for surface velocity determination, but limited in value for conversion to ice discharge estimates. Images from 35-mm cameras were found to be adequate and much less expensive. Prowse and Demuth (1991) used a theodolite to track the movement of ice pieces to measure velocity. Ferrick et al. (1991) videotaped markers on an ice cover before and during breakup to obtain information on ice velocities.

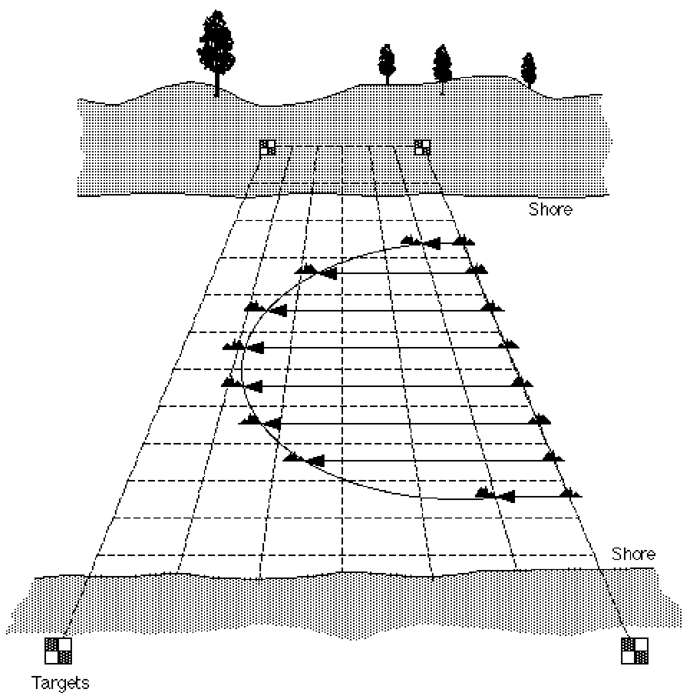

Figure 16-11. Photographic grid method for determining ice velocity and concentration.

16-8. Ice Extent and Concentration

a. Aeral Ice Extent. Areal ice extent may be monitored from a single vantage point or series of vantage points, but the accuracy of observer estimation decreases with increasing distance from the observer. The areal extent of ice can also be observed from aircraft and then documented by 35-mm still or digital photography, video, or by an individual marking the ice cover locations on a map. Evans and Mata (1984) provide useful guidance for obtaining hand-held aerial photography. Aerial videotapes are more convenient to take than overlapping hand-held photographs, if continuous coverage of a waterway is required, and are less expensive than vertical 23 × 23-centimeter (9 × 9-inch) aerial photographs. Guidance can be found in Meisner and Lindstrom (1985), Meisner (1986), and Maggio and Baker (1988). Table 16-1 compares hand-held aerial photography and aerial videotaping. Bank-to-bank coverage should be maintained while videotapes are being taken. Widths of the waterway to be taped should be used to determine the flying heights and focal lengths required to provide bank-to-bank coverage and to determine the maximum aircraft speed to avoid image blur caused by forward image motion and aircraft vibration (see Table 16-2). The best positioning for a hand-held camera or video camera to document the ice from aircraft is straight down, as is done with aerial photographs made for mapping. Oblique views are also very useful but do not readily allow for scaling of features from the film. The pros and cons of camera use are discussed further in USACE (1990).

Table 16-1
Two Methods for Monitoring Ice Conditions on Navigable Waterways

Method	Equipment	Costs*	Advantages	Disadvantages
Hand-held aerial photographs	35 mm camera Color film for slides or prints Maps for locating photos in flight Fixed-wing aircraft** (e.g., Cessna 172)	$300 $3–$8/roll for slides, $7 for prints $1.50 each $60–$80/hr	Good resolution Different films can be used Low costs, once initial purchases are made Supplies and equipment readily available Camera systems are portable and flexible No extensive training required; most everyone is familiar with cameras Photographer can select targets	Can't take photos during inclement weather Takes a few hours to get slides or prints Ice thickness not obtainable; best guess only Snow-cover obscures ice Quality of photos unknown until they are developed
Aerial videotapes	Camera for ½ in. VHS or Beta, 3/4 in. U-matic On-board monitor Video recorders Camcorder (VHS) High grade color videotapes (T-120) Maps for locating tapes in flight Fixed-wing aircraft** (e.g., Cessna 172)	$1200–$5000 $ 600 $2500 (½ in.), $5000 (3/4 in.) $1600–$2200 $7/tape $1.50 each $60–$80/hr	Continuous view of river Immediate availability of tapes Operator sees image during acquisition; could correct problems in flight Low cost No extensive training required; familiar to many people Playback technology widely available Can get slides and prints from tapes Supplies and equipment readily available Tapes can be reused Videographer can select targets, if taking obliquely	Lower resolution than photographs but sufficient to differentiate ice types Can't take tapes during inclement weather Ice thickness not obtainable; best guess only Snow-cover obscures ice

* Costs will vary; these are simply estimates (1988 dollars).
** Helicopters can be used but cost more per hour.

Table 16-2
Aerial Video Coverage Versus Pixel (Picture Element) Size, Altitude, and Aircraft Speed (Based on 2/3-inch Video Format)

SI Units								
Coverage (m)		Effective Pixel Size* (m)	Altitude (Feet Above Ground) Required for Various Lens Focal Lengths					Maximum Aircraft Speed** (km/h)
Width	Length		6.0 mm	8.5 mm	12.5 mm	16.0 mm	25.0 mm	
152	114	0.6	104	147	216	277	433	101
305	229	1.2	208	294	433	554	866	203
457	343	1.8	312	442	650	831	1,299	304
610	457	2.4	416	589	866	1,108	1,732	406
762	572	3.0	520	736	1,082	1,385	2,165	507
914	686	3.7	623	883	1,299	1,663	2,598	610
1,067	800	4.3	727	1,031	1,515	1,940	3,031	711
1,219	914	4.9	831	1,178	1,732	2,217	3,464	813
1,524	1,143	6.1	1,039	1,472	2,165	2,771	4,330	1,015
1,829	1,372	7.0	1,247	1,766	2,598	3,325	5,195	1,218
2,134	1,600	8.2	1,455	2,061	3,031	3,879	6,061	1,421
2,438	1,829	9.4	1,663	2,355	3,464	4,433	6,927	1,624
3,048	2,286	12	2,078	2,944	4,330	5,542	8,659	2,031
3,658	2,743	14	2,494	3,533	5,195	6,650	10,391	2,437
English Units								
Coverage (ft)		Effective Pixel Size* (ft)	Altitude (Feet Above Ground) Required for Various Lens Focal Lengths					Maximum Aircraft Speed** (knots)
Width	Length		6.0 mm	8.5 mm	12.5 mm	16.0 mm	25.0 mm	
500	375	2	341	483	710	909	1,420	55
1,000	750	4	682	966	1,420	1,818	2,841	109
1,500	1,125	6	1,023	1,449	2,131	2,727	4,261	164
2,000	1,500	8	1,364	1,932	2,841	3,636	5,682	219
2,500	1,875	10	1,705	2,415	3,551	4,545	7,102	274
3,000	2,250	12	2,045	2,898	4,261	5,455	8,523	329
3,500	2,625	14	2,386	3,381	4,972	6,364	9,943	384
4,000	3,000	16	2,727	3,864	5,682	7,273	11,364	439
5,000	3,700	20	3,409	4,830	7,102	9,091	14,205	548
6,000	4,500	23	4,091	5,795	8,523	10,909	17,045	658
7,000	5,250	27	4,773	6,761	9,943	12,727	19,886	767
8,000	6,000	31	5,455	7,727	11,364	14,545	22,727	877
10,000	7,500	39	6,818	9,659	14,205	18,182	28,409	1,097
12,000	9,000	47	8,182	11,591	17,045	21,818	34,091	1,316

* Effective pixel size based on 258 pixels per format width.
** To avoid forward image motion blur if not using shuttered camera or forward image compensation.

b. Ice concentration. Ice concentration (i.e., how much of the channel is covered by floating ice pieces) is estimated from visual observations from a structure, shore, or aircraft. Estimating an ice concentration suffers from the same disadvantages as estimation of areal ice extent. An additional disadvantage is that the estimate is highly subjective. Two individuals viewing the same event may interpret the concentration of ice pieces as being quite different, even if given guidelines demonstrating the differences between different levels of concentration. For quantitative measurements, a "frame-grabber" to capture and digitize videotaped images of moving ice can be used (Bjerke 1991). Using a computer algorithm, the digitized image is rotated to provide a vertical view, from which ice piece size and concentration can be determined.

(1) *Video.* Rossiter and Crissman (1994) describe the use of low-light-level television (LLLT) video cameras and marine radar for measuring ice concentration on the Upper Niagara River for the New York Power Authority and Ontario Hydro. Each method had a limited range of observation (less than 3 kilometers [2 miles]). The LLLT cannot be used in dark or snowy conditions and the imagery must be interpreted subjectively. Software must be developed to allow the marine radar to differentiate between moving and stationary ice, and the system was described as being more expensive than alternative methods. They also state that systems capable of observing an ice cover can also be used to estimate ice speed, if properly calibrated and if trackable ice features are present. The method described by Bjerke (1991) previously also shows promise for daylight measurements of ice concentration.

(2) *Satellite Imagery.* Another method of monitoring ice concentration, satellite imagery, currently has limited potential, but as satellite capabilities improve, so will the potential for monitoring ice conditions. Gatto et al. (1986) and Gatto (1988) attempted to describe ice conditions on the Ohio, Allegheny, and Monongahela Rivers and Illinois Waterway over a 13-year period using available Landsat images. There are disadvantages to using Landsat imagery: the number of usable images is limited by the long satellite repeat cycle and frequent cloud cover, river ice is not always apparent because the instantaneous field of view of the satellite sensors is sometimes insufficient to detect the amount and type of ice present, and computer analysis is necessary to evaluate the additional information collected by Landsat sensors (which "see" more than a standard camera does). McGinnis and Schneider (1978) discuss the use of Landsat, NOAA, and GOES satellites. NOAA and GOES provide much coarser resolution but offer daily extent, compared to 18-day extent by Landsat. However, geostationary satellite imagery is not of much use above 50° latitude, owing to distortion. The authors conclude that operational environmental satellites could be used to create an early warning monitoring system. Gatto (1993) suggests that the synthetic aperture radar (SAR) aboard the European Remote Sensing (ERS) satellite will be capable of providing data on river ice conditions that are necessary for navigating through ice and evaluating the potential for river ice jams and ice erosion along shorelines. He notes two limitations on the use of SAR: resolution prevents showing distinct images on rivers narrower than 30–35 m and on shallow streams with boulders above the water level, and the single band and polarization may limit the differences in ice it can detect. Shokr et al. (1996) report the use of ERS-1 SAR images to monitor sea ice conditions along the east coast of Canada and in the Gulf of St. Lawrence. They found that the images were useful in detecting the difference between ice and open water, but that roughness and other structural information about the ice was not consistent. Further investigation is needed to more fully develop the potential of SAR imagery. ASCE (1995) reports that EarthWatch, Inc., planned to launch a system capable of 3-meter (30-foot) resolution (panchromatic), while systems capable of 1-meter (3-foot) resolution were scheduled by late 1999. If this type of resolution will truly be available, remote monitoring of ice extent would be greatly enhanced, even if imagery would be available on a 2- or 3-week cycle. Computer analysis of this satellite imagery could be highly beneficial, but it is unknown what the processing requirements or acquisition costs may be for such fine resolution.

The processed information would need to be stored in a format that could be read by CADD or GIS users.

(3) *Radar.* A method that may be capable of interpreting ice conditions is that of monitoring active and passive microwaves from an ice surface. Melloh and Gatto (1990a) and Melloh et al. (1991) describe the use of passive microwave imagery to monitor river and lake ice conditions near Fairbanks, Alaska. The imagery was obtained from a Ka-band radiometric mapping system (KRMS) mounted from the bomb bay of an RP-3 aircraft. The KRMS differentiates between wet and dry snow conditions, and open water areas within ice covered rivers and lakes (Melloh and Gatto 1992). Although the KRMS was not able to readily distinguish freezeup ice jams from smooth ice, it could be useful for determining large-scale areal ice coverage. The KRMS also appeared capable of imaging fractures in the ice cover of a lake. Active microwave imagery was obtained with synthetic aperture radar (C-, L-, and P-band) aboard a DC-8 aircraft. Melloh and Gatto (1990a, 1990b) report that active microwave imagery can distinguish between rough and smooth ice covers and detect open water areas within an ice cover. They concluded that the C- and L-bands were better at determining surface roughness. In both instances, the systems tested by Melloh and Gatto were being developed. Each system may be potentially useful in the future, but further refinement of the instrumentation and further investigation into usability in other regions is needed. Additionally, a more convenient and less expensive platform than the RP-3 and DC-8 aircraft is needed.

16-9. Systems for Transmitting River Ice Data

An important aspect of data collection that may often be overlooked is the storage and retrieval of data. This section provides a cursory overview of what happens to data once they are collected, including transmission, display, evaluation, and storage. Existing systems are generally adequate for storage needs and will continue to be as computer systems evolve. The first step in storing data is transmitting those data once they are collected, whether they are sent from a DCP site hundreds of miles away or recorded in an observer's notebook across town. The trend is toward remote collection of data to reduce personnel costs and safety hazards. If data are to be remotely collected, this information needs to be transmitted to a central location for storage (and processing). A number of sites are already equipped to do this through the use of DCPs. The use of DCPs in the Corps is covered by policy contained in ER 1110-2-248 and ER 1125-2-308. Data collected at a DCP are transmitted via the Geostationary Operational Environmental Satellite (GOES) Data Collection System (DCS) operated by the National Earth Satellite Service (NESS) of the National Oceanic and Atmospheric Administration (NOAA). The Corps is limited to specific channels for data transmission and all data transmitters must be certified by NOAA/NESS before they are used. All transmission frequencies must be requested first through the Water Resources Support Center, Data Collection and Management Division (WRSC-C). Obviously, a data site cannot be selected and set up overnight if data are to be transmitted from the site via DCP. The use of the GOES/DCS also requires that only environmental data be transmitted; transmission of operational data, such as gate opening, is not allowed.

a. Remote sites may be queried by phone or radio instead of DCP transmission. Information could be downloaded from the on-site data storage device (e.g., a data logger) to a central computer through a modem. This technology has been commercially available for a number of years, and may prove more feasible and cost-effective as modem speeds continue to increase and phone transmission lines improve in quality. Cellular phones could allow data collection at sites with portable instrumentation or where telephone lines are unavailable. A cellular phone will only be effective, however, where there is adequate cellular coverage; many sparsely populated or rugged terrain areas will not have this. Radios can be used at remote sites for transmitting a warning signal, but radio signals may be susceptible to disruption in heavily populated areas or during severe weather.

b. Data collected manually could be sent to a central site via fax. The fax can be processed on the receiving end by use of optical character recognition (OCR) software in conjunction with a scanner (software does exist that allows a fax to be used as a scanner, but OCR-capability is unknown). While OCR software is quite good at reading typed pages, it fares more poorly with fax documents and even worse with handwritten documents. Eventually, OCR software will be able to handle fax and handwritten documents as well as typed documents.

c. Another possible method of data transmission that has exploded in usage recently is electronic mail, or e-mail. Most e-mail systems allow the sender to attach a file to a transmitted message. The sender and receiver must either use compatible e-mail systems or the sender must be certain that the e-mail system allows the file format integrity to be preserved as it passes through the gateway router. Nonetheless, e-mail allows for simple data transmission, and if a standard form were used, the data could be easily reduced.

d. Data can also be transmitted through the World Wide Web. A password-protected web site can be developed that will allow ice observations to be input directly into a database. The observations are then available to any who query the site. This system is currently used in Nebraska by ice observers (address http://cavent.nrc.state.ne.us/cgi-win/icejam.exe). It is expected that this type of data transmission will increase owing to its relatively low cost and high transmission speed.

16-10. References

a. Required Publications.

None.

b. Related Publications.

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ER 1110-2-248
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ER 1110-2-249
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Chapter 17
Navigation in Ice

17-1. Introduction

A vessel navigating in ice must tolerate stresses imposed by an environment that is not encountered by regular shipping. The vessel's form, power, structure, and propulsion system must be designed to withstand these stresses. In addition, the effect of the vessel on the environment must be considered, as well as the effect of the environment on the vessel.

17-2. Environment

In winter a vessel may encounter sheet ice, brash ice, frazil ice, pressurized ice, a pressure ridge, ice with snow cover, or a combination of all these forms. The easiest of these to deal with is sheet ice—homogeneous ice with fairly uniform thickness. A properly designed vessel can travel through sheet ice, up to some limiting thickness that is a function of installed power.

a. Brash ice. The second type of ice, brash, is broken ice that fills a shipping channel with pieces up to 1.8 meters (6 feet) in diameter (Figure 17-1). Brash ice may fill the channel completely or partially and it can be unconsolidated or consolidated and refrozen. This type of ice, because of its lack of homogeneity, restricts vessel movement differently than does sheet ice.

Figure 17-1. Channel filled with brash ice

b. Frazil ice. The third type of ice is frazil ice. Frazil is highly cohesive in its active state. If the water velocity slows beyond a certain point, the frazil crystals can agglomerate and form a mush that can eventually block the channel to a large extent as well as solidify partially.

c. Pressure in the ice. All of these forms of ice can restrict traffic further if the ice sheet is under lateral pressure. Lateral pressure can be caused by wind or water currents. Ice sheets can also push over each other and form a pressure ridge. Such a ridge can grow to extreme depths and virtually block a channel.

d. Snow on the ice cover. The various types of ice described above can also be found with a snow cover. A snow cover does not affect the mechanical properties of the ice to any great extent; however, a snow layer increases the friction between the ice and the ship's hull.

17-3. Vessel Shape

Most vessels are designed to maximize the volume of cargo that they can carry; they tend to be rectangular with minimum curvature of the hull, the extreme example being the rectangular barge. Icebreakers are specifically designed for breaking and clearing ice, and have angled bows, special shapes, and are usually highly powered. Between these extremes are the blunt-bowed ore carriers, the raked-bowed barges, and passenger vessels.

a. Hull resistance factors. The resistance a vessel encounters in ice depends on its hull shape. The efficiency of a particular hull depends on the forces involved in breaking and clearing ice. Basically, a vessel breaks the ice by riding on top of it, causing the ice sheet to fail from tension in the lower and upper layers. After the ship breaks the ice sheet, it must clear the ice fragments from the channel. This is done by pushing the fragments down or to the side. The resistance of the ice to breaking and clearing is a function of the friction between the vessel and the ice and of the lateral pressure in the ice.

b. Variation in hull resistance. The resistance encountered by the vessel increases as the width and length of the vessel increase, as the thickness and strength of the ice increase, as the velocity of the vessel increases, as the friction between the ship and the ice increases, and as the lateral pressure in the ice increases.

c. Barge-hull resistance. In the case of a tug and towed or tug-pushed barges, the shape of the forward part of the hull has the largest effect on the resistance. A wide vessel with a plumb, blunt bow that has a very rough surface will encounter extreme resistance. If the bow is so blunt that the ice cannot pass to the side or below the vessel, the ice will pile up in front of the vessel, forming its own "bow" shape, and will eventually cause such high resistance that the vessel will be unable to move.

17-4. Auxiliary Icebreaking Devices

Several different methods have been developed to facilitate icebreaking and ice navigation. The most promising methods are:

- Low-friction hull coating
- Hull bubbler systems

- Air-cushion vehicles
- Auxiliary icebreaking devices.

These systems have been developed and refined by the U.S. Army Corps of Engineers, U.S. Coast Guard, Canadian Coast Guard, and ice researchers, as well as in Finland and Russia.

a. Surface friction. Figure 17-2 shows the coefficient of friction of various coatings, as well as that of steel on ice. The polyurethane and epoxy (nonsolvented coatings) proved to be the most effective in friction reduction and coating endurance.

b. Hull bubbler systems. Hull bubbler systems have been installed on several European icebreakers and on the latest USCG small lake icebreakers. Bubbler systems work by interposing air and water between the ice and the hull of the vessel. Figure 17-3a is a schematic of the bubbler system. Figure 17-3b depicts its deployment on a USCG icebreaker. Figure 17-4 shows the results of full-scale tests of the bubbler system on a European icebreaking ferry.

c. Air-cushion vehicles. The air-cushion vehicle (ACV) is the most dramatic contribution of modern technology to icebreaking. The vehicles can skim over the ice and break it at speeds of 5 to 32 km/hr (3 to 20 mph). The icebreaking occurs both at low speeds of advance as shown in Figure 17-5 (top) and at higher speeds of advance (bottom). At high speeds, the critical speed of the craft deflects the ice sheet to the icebreaking point. At low speeds, the air cushion extends under the ice, displacing the supporting water. Deprived of its support, the ice sheet fails under the pressure of the air cushion. Tables 17-1 and 17-2 show the results of tests conducted by the Canadian Coast Guard on ACV's. These tests indicate that an ACV can break ice whose thickness is 90 percent of the cushion pressure expressed in inches of water. The ACV has significant potential for aiding ice-jam flood control in shallow rivers and estuaries where vessel draft is limited. An ACV placed in front of a conventional icebreaker will increase its effectiveness.

d. Auxiliary icebreaking devices. A device that has been used in Russia and has been evaluated in the U.S. is the ice cutting vehicle. Such a vehicle cuts the ice with some apparatus such as a circular saw or a high-pressure water jet. The weakened ice is then either conveyed up onto the vehicle and thrown over the side, or deflected beneath and to the side of the vehicle by underwater ice guides. Figure 17-6 depicts conceptual sketches of two possible ice cutting and clearing devices. These devices could be used to keep channels in narrow rivers between locks and dams clear of ice. Another device is the icebreaking prow, which is attached to a conventional towboat in the same manner as a barge (Tatinclaux and Martinson 1988). Vanes fastened to the front and bottom of the prow break the ice and guide the ice pieces underneath and to the sides of the prow, where the ice accumulates under the adjacent ice cover. The opened channel behind the vessel/prow combination is left largely ice-free.

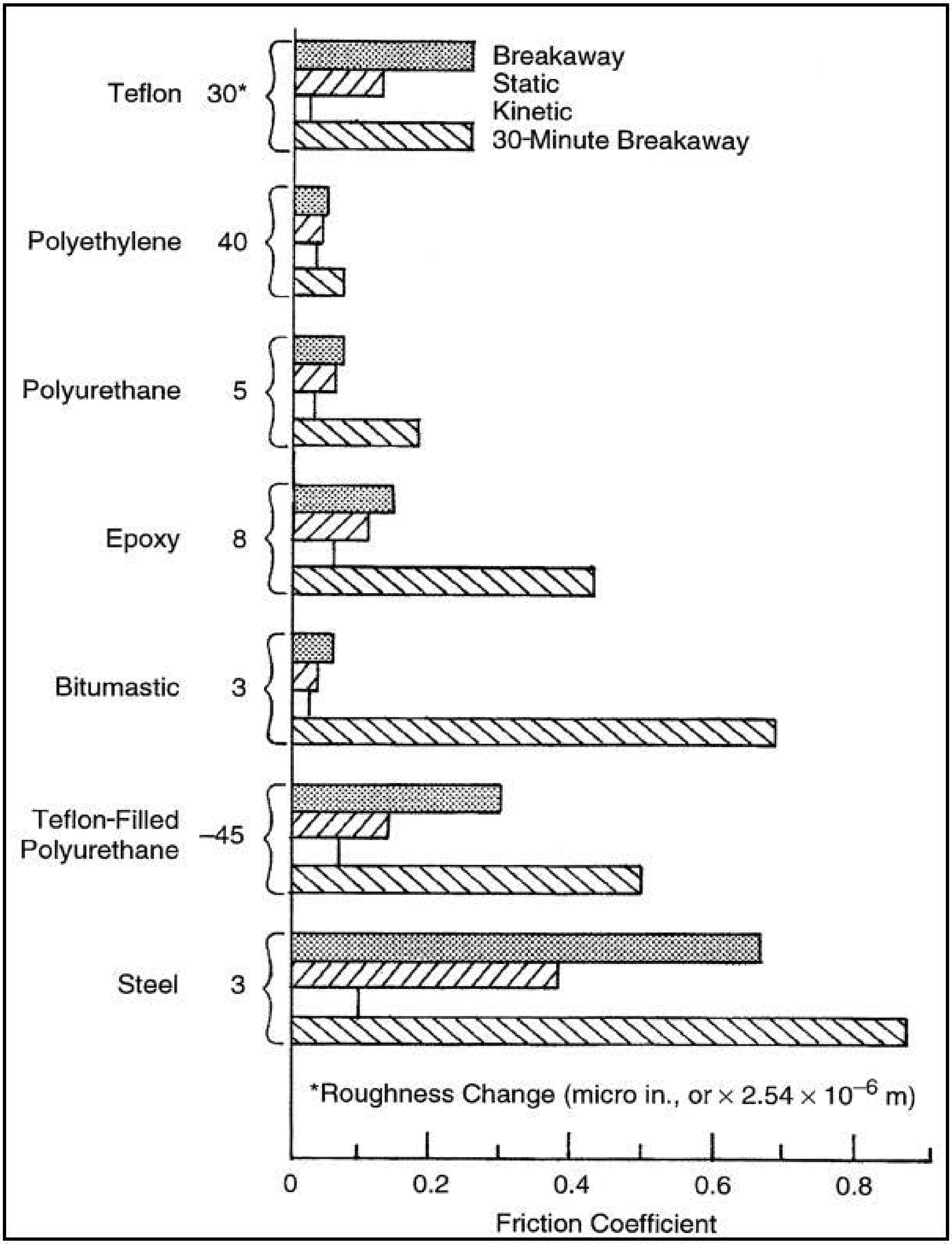
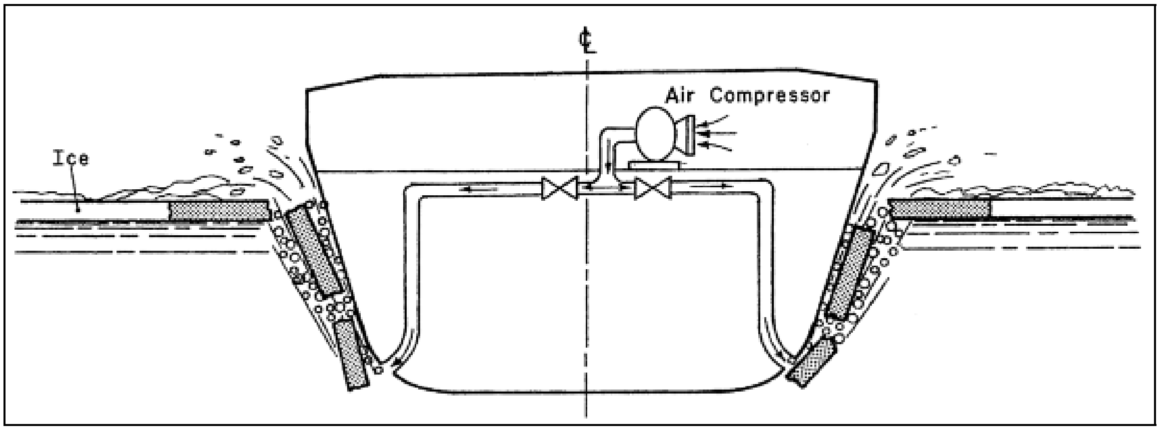
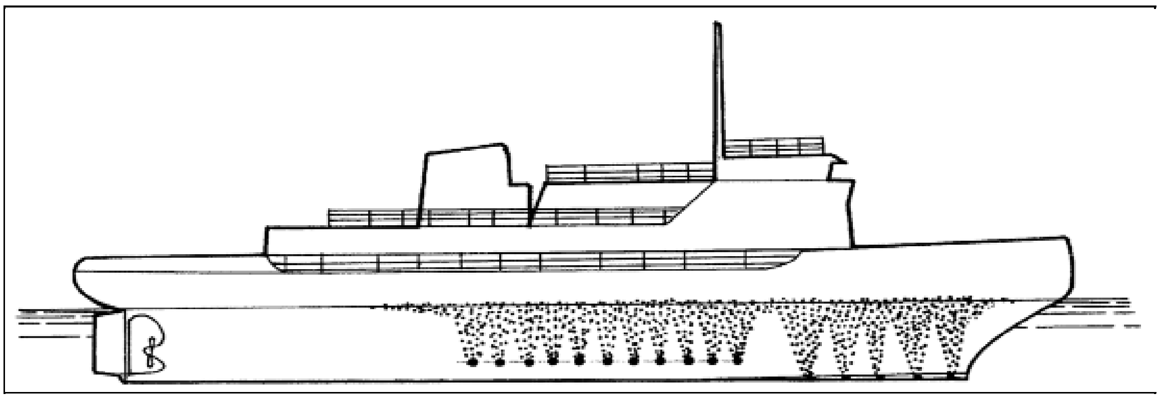


Figure 17-2. Coefficient of friction for steel and various hull surfaces on ice



a. Schematic



b. Bubbler installed on icebreaker

Figure 17-3. Hull air-bubbler system

Table 17-1
Air-cushion Vehicles Used in Trials and Operations

Vehicle	Gross Length m (ft)	Beam m (ft)	Vehicle Weight kg (lb)	Cushion Pressure kPa (in.) of H_2O
ACT-100	22.5 (73.8)	17.1 (56.1)	260,800 (575,000)	6.90 (27.7)
H-119	13.2 (43.3)	6.0 (19.7)	24,000 (53,000)	4.86 (19.5)
HJ-15	12.1 (39.8)	5.4 (17.7)	19,400 (42,700)	3.74 (15.0)
Voyageur	19.8 (65.0)	10.4 (34.0)	40,500 (89,300)	2.62 (10.5)
AC-80	6.0 (19.7)	3.5 (11.5)	1,300 (2,900)	1.0 (4.0)

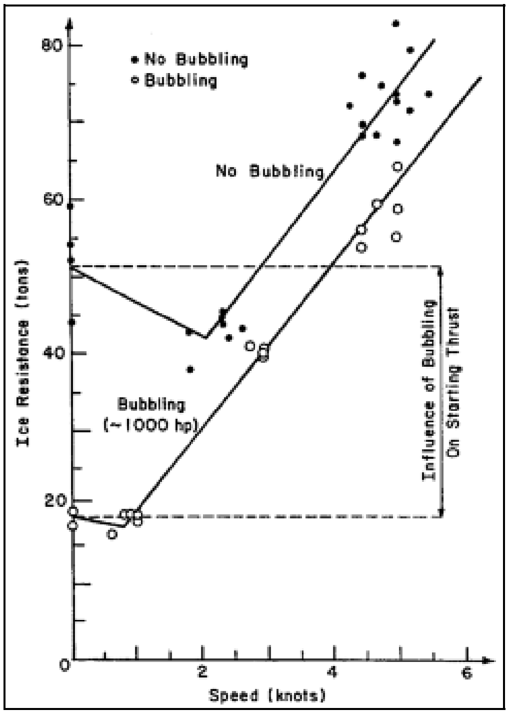


Figure 17-4. Air bubbler tests on a European icebreaking ferry

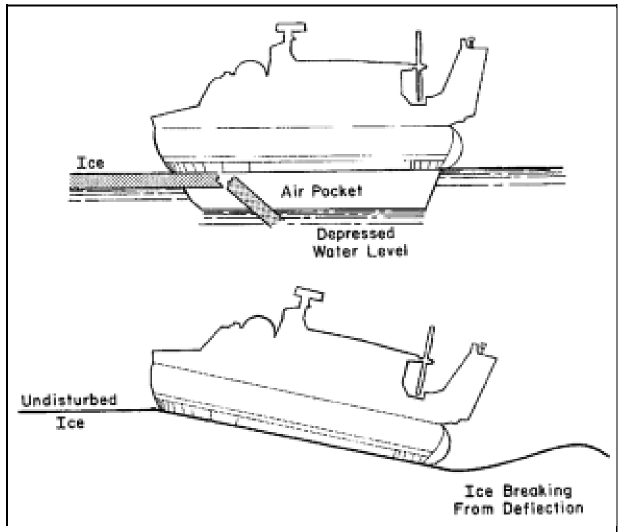
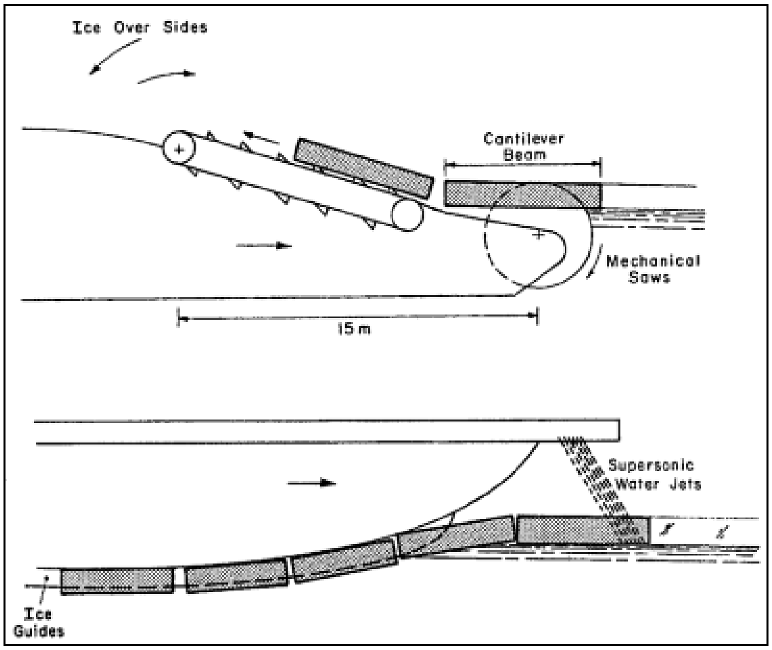


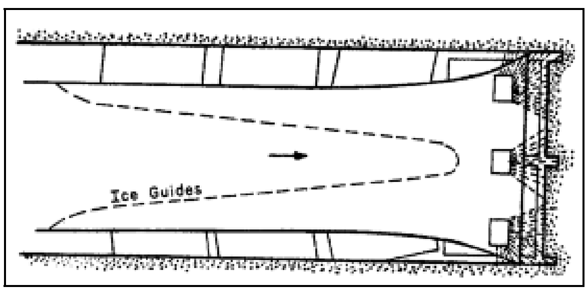
Figure 17-5. Air-cushion vehicle. *Top: Low speed icebreaking. Bottom: High speed icebreaking*

Table 17-2
Air-Cushion Vehicle Icebreaking Data

Vehicle	Date and Location	Ice Thickness, cm (in.)	Cushion Pessure kPa (in.) of H_2O	Speed km/h (mph)
ACT-100	1971 - YK	69 (27)	6.92 (27.8)	6-8 (4-5)
ACT-100	1972 - Tuk	51-56 (20-22)	6.23 (25.0)	6-11 (4-7)
H-119	1973 - Montreal	23 (9)	4.01 (16.1)	2-6 (1-4)
H-119	1974 - Toronto	23-25 (9-10)	2.64 (10.6)	6-10 (4-6)
HJ-15	1974 - Toronto	23-25 (9-10)	2.91 (11.7)	6-10 (4-6)
Voyageur	1974 - Parry Sound	23-25 (9-10)	2.49 (10.0)	8-11 (5-7)
Voyageur	1974 - Parry Sound	46-51 (18-20)	2.49 (10.0)	19-29 (12-18)
Voyageur	1975 - Montreal	up to 76 (up to 30)	2.0-2.5 (8-10)	19-50 (12-31)
Voyageur	1976 - Montreal	up to 102 (up to 40)	2.0-2.5 (8-10)	19-50 (12-31)
ACT-100	1976 - Thunder Bay	38-41 (15-16)	5.0 (20)	16 (10)
AC-80	1976 - Ottawa	20 (8)	1 (4)	8-10 (5-6)



a. Type 1



b. Type 2

Figure 17-6. Ice cutter

17-5. Summary

Vessels operating in ice must be given special consideration if they are to operate safely and efficiently. The vessel must have the power and structure to overcome the resistance and loads imposed by the ice environment.

a. Unassisted icebreaking. Properly shaped vessels with adequate power can break the sheet ice that is encountered on lakes and rivers. The primary problem is not so much sheet ice but brash and frazil ice that can fill the channel and cause unusually high resistance because of the friction between the ice and hull surface. This problem can be mitigated somewhat by a low-friction, high-wear coating.

b. Cooperative programs. To enhance winter navigation on lakes and rivers, additional assistance is often required in the form of icebreaking, ice clearing, ice control, and towing or kedging. This assistance usually is provided by self-help programs of private industry. In certain limited cases, assistance is also provided by government agencies (principally the U.S. Army Corps of Engineers and U.S. Coast Guard).

17-6. References

a. Required publications.

None.

b. Related publications.

Tatinclaux and Martinson 1988
Tatinclaux, J.-C., and C. Martinson. 1988. *Development of a River Ice Prow*, CRREL Report 88-9, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Chapter 18
Ice Control for Navigation

18-1. Introduction

Ice affects navigation when it is present in navigation channels, and it delays and interrupts navigation at locks and dams. Section I of this chapter focuses on ice in navigation channels. Many of the same nonstructural and structural techniques that were discussed in Chapter 3, *Ice Control for Reducing Flood Damages and Hydropower Operation*, are also discussed here. Ice problems at navigation locks and dams have been identified and grouped into 10 categories. These are discussed in Chapter 14. Floating brash ice hinders normal lock operations and can significantly delay barge movements into and through locks. Controlling brash ice is discussed in Section II of this chapter. Floating ice accumulations are often difficult to pass through dams to downstream reaches where the ice may pose fewer operational problems. Techniques for passing ice at navigation projects are discussed in Section III. Ice adhering to various lock surfaces interferes with the operation of lock machinery and can restrict the usable width of lock chambers. Techniques for removing and controlling ice adhesion are discussed in Section IV.

Section I
Ice Control in Navigation Channels

18-2. Nonstructural Ice Control in Navigation Channels

a. Introduction. Nonstructural ice control encompasses methods used 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. The attraction of nonstructural ice control methods is that they are generally inexpensive. Also, these methods are popular because of the perception that they can be applied on short notice. Furthermore, the basic concept of not placing a structure into the river has appeal, as it does not create an obstacle for navigation. 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. See Paragraph 3-1 for a more complete discussion.

b. Icebreaking Vessels

(1) *General.* Icebreaking vessels are limited to rivers that have sufficient draft for their passage. Also, river icebreaking vessels must have large power plants that not only can overcome ice–hull friction but also can produce large forward speeds (as much as 10 knots [5.14 m/s]) above the downstream water current (Bolsenga 1968). Underpowered icebreakers in swift flowing streams will not have enough speed, relative to the ice cover, to break the ice. Furthermore, intake designs for the engine cooling require special consideration to avoid blockage by the broken brash ice (Bolsenga 1968, Michel 1971). For breaking river ice, the following four types of vessels are typically used.

(*a*) Conventional icebreakers that break the ice in flexure by riding up on the ice cover.

(*b*) Ordinary towboats and towboats with reinforced frames and ice linings.

(*c*) Towboats or tugs that are fitted with icebreaking "plows" or prows designed for efficient icebreaking.

(*d*) Air Cushion vehicles.

(2) *Conventional Icebreakers.* Icebreakers are ships that have been designed specifically for traveling in ice-laden waters. This requires a hull that is stronger than those of conventional ships and constructed out of low temperature steel. The hull is shaped to facilitate the breaking of ice. Conventional hulls are designed to break the ice by riding the bow of the ship onto the ice, after which the ice breaks in flexure under the weight of the bow. Furthermore, to overcome the additional ice resistance, the propulsive power plants must be larger than what are used in conventional ships. Additional systems are also employed to improve the performance of the icebreaker, such as the following.

(*a*) Low friction hull coatings and cladding.

(*b*) Hull air lubrication systems.

(*c*) Hull heating at the waterline.

(*d*) Pitching systems that induce a rocking motion of the ship about the long axis of the hull.

(*e*) Water spray systems.

(*f*) Nonconventional hull forms to optimize icebreaking and clearing of a channel. Detailed discussion of these systems is beyond the scope of this Manual. A full treatment of icebreaker design is given in Sodhi (1995).

(3) *River Towboats.* Towboats are the mainstay of ice control on U.S. inland waterways, principally because they are on site when problems arise and they are very powerful (typically 2700–4600 kW [3600–8500 hp]). Ordinary towboats are limited to breaking ice thicknesses of 15 to 25 centimeters (5.9 to 9.8 inches) without damaging the hull (Bolsenga 1968). Thicker ice may be broken using explosives and then cleared using towboats. To extend the use of towboats in heavy ice, often 1.5-centimeter-thick (0.5-inch-thick) steel cladding is installed at the ice belt to reinforce the hull (Ashton et al. 1973).

(4) *Ice Prows.* The Dutch first used icebreaking prows in front of conventional ships for breaking ice on rivers and canals in the 1890s (Sodhi 1995). Ice prows have been used routinely since the early 1940s to break ice in Europe and the U.S. (Bolsenga 1968). In its simplest form, an ice prow can be a raked barge coupled to the front of a towboat (Figure 18-1). Typical prows are barges with the bow shaped to provide efficient icebreaking. The hull is also reinforced to withstand the ice forces.

(*a*) Icebreaking prows used in the former U.S.S.R. have knife edges at the front of the prow, and the hull shape pushes the ice to the side and under the adjacent ice cover (Tatinclaux and Martinson 1988). These are effective at creating a clear, smoothed edge channel, and can be used in both sheet and hummocked ice with reduced icebreaking power requirements.

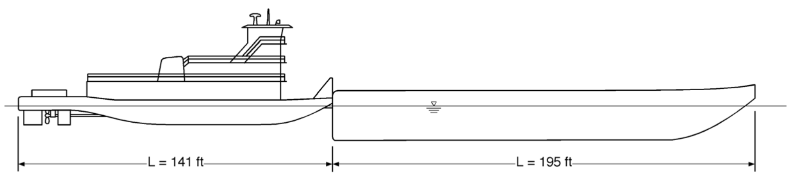


Figure 18-1. Tow with a raked barge used for breaking river ice.

(*b*) The Alexbow (Figure 18-2), designed by Scott Alexander in the 1960s, breaks the ice in uplift and deposits it on the adjacent ice cover. In field trials the bow form, pushed by a 1000-kW (1340-hp) tow, successfully broke ice up to 0.5 meters thick (1.6 feet think) at a speed of 2–3.5 knots (1.1-1.9 m/s) (Alexbow Ltd. 1967). However, field trials of the bow form conducted by the U.S. Coast Guard showed that it required considerably more power to break ice than conventional bow forms; trials in Canada, Europe, and the former U.S.S.R. confirmed these findings (Ashton 1986).

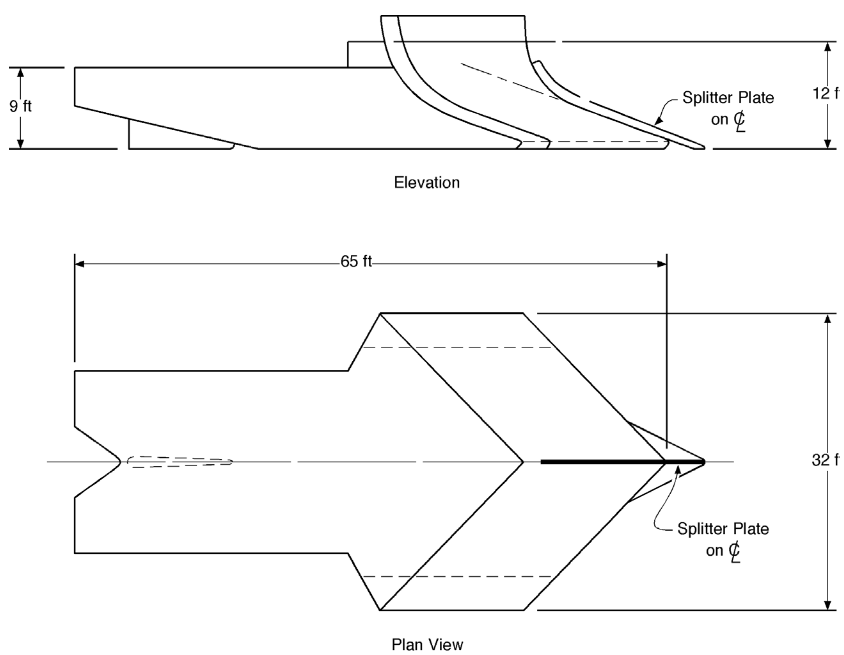


Figure 18-2. Alexbow ice prow.

(*c*) Air cushion vehicles (ACV) can also be pushed in front of a towboat to improve icebreaking capability. ACVs effectively reduce the icebreaking forces necessary when traveling through sheet ice, but they cannot be used in brash ice. Their great advantage is that they are not restricted by water depth and can break ice in shallow areas, such as river confluences.

(4) *Air Cushion Vehicles.* Air cushion vehicles (ACVs) are routinely used to break up river ice on tributaries to the St. Lawrence Waterway and on Lac St. Pierre. The ice can be broken by two mechanisms. Traveling at low speeds, the ACV pushes the supporting water out from under the ice, leaving the ice unsupported (Hinchley et al. 1991). The ice then fails under its own weight, and the broken swath is roughly equal to the beam of the craft. The maximum thickness

of ice that can be broken in this way is approximately 90% of the air cushion pressure, expressed as head of water. At higher speeds, the ACV sets up a standing wave about half the craft length astern in the ice cover, which moves with the speed of the craft, and breaks the ice at the crest of the wave. The resulting broken channel is considerably wider than the beam of the craft. The *Voyageur*—a 45-tonne (49.6 tons), 20-meter-long (66-foot-long) Canadian Coast Guard ACV with an air cushion pressure of 26 centimeters (10 inches) of water—traveling at a speed of 25 km/hr (15.5 mph)—is able to break sheet ice up to 1 meter (3 feet) thick on the tributaries to the St. Lawrence River. However, at low speeds the *Voyageur* is capable of breaking ice only 23 centimeters (9 inches) thick (Robertson 1975). ACVs are limited to breaking smooth sheet ice, because uneven ice surfaces damage the side skirts.

(*a*) Robertson (1975) conducted field tests using the *Voyageur* to break ice and reported this ACV was able to break over 250 ha/hr in 30- to 50-centimeter (12- to 20-inch) ice in open areas. In restrictive areas such as in harbors and around slips, the icebreaking rate was reduced to about 110,000 m^2/hr (1,184,000 ft^2/hr). The size of the resulting ice pieces was about 3 meters (10 feet) square.

(*b*) Though an ACV can open a track in an unbroken ice cover, the ice must be cleared by following vessels or water current (Tatinclaux and Martinson 1988). In long, narrow tracks running into the sheet, the ice can easily arch across the width, and water current alone cannot reliably clear the ice. Therefore, when ice clearing depends on water current alone, a more effective icebreaking strategy is to break the ice across the downstream edge of the cover by moving the ACV over the edge of the cover in circular motions, breaking off ice pieces that can then be carried away by the river current (Robertson 1975, Michel 1984).

c. Ice Bridging. Icebreaking vessels remove 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 control the flow of ice into a problem reach. 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. 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 a large 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. Paragraph 3-2*k* gives a complete discussion.

d. Thermal Suppression of Ice Growth. Ice covers deteriorate because of weakening and melting the ice cover owing to absorption of available thermal energy. 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. For example, 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 and industry 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 shipping could resume. Meanwhile, only 17 kilometers (10.5 miles) upstream. L&D 14 was experiencing no ice problems. The warm water discharge from a nuclear power plant located 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 months. Paragraph 3-3 gives more information on this topic.

e. Discussion. Section I of Chapter 3 of this Manual contains a complete discussion of non-structural solutions to ice problems for flood control and hydropower production. Many of the options outlines there are applicable to navigation also.

18-3. Structural Ice Control in Navigation Channels

a. Introduction. Structural solutions exist for a wide range of river ice problems. Ice control research and development during the last three decades has concentrated on sheet ice retention methods. The difficult problem of breakup ice control has received less attention, particularly on larger rivers. Section II of Chapter 3 provides extensive background.

b. Ice Control on Rivers and Waterways with Winter-Long Navigation. On the lower St. Lawrence River, where winter-long navigation extends as far upstream as Montreal, the ice management program depends in part on structural methods to retain and stabilize sheet ice. Here, the ice control effort has the goals of preventing the ice jams that have historically flooded Montreal and of ensuring safe and efficient navigation to the port of Montreal. At Lake St. Peter, 65 kilometers (45 miles) downstream from Montreal, the St. Lawrence River widens and flattens, significantly reducing the river's ice conveyance capacity. Here, nine artificial islands effectively stabilize the ice between the shore and the centrally located, dredged navigation channel. These islands, constructed of quarried rock, have base diameters of 40 meters (130 feet) and are spaced 762 meters (2500 feet) apart. Figure 18-3 shows an ice island on Lake St. Peter retaining sheet ice during the early spring. Perham (1983), Appendix B of this Manual, and Lawrie (1972) provided more detailed information. The five islands on the south side of the navigation channel were constructed after 1985. Initial construction and maintenance of the ice islands are costly. The islands must periodically be topped off to compensate for continual settlement in the soft lake sediments. Upstream of Montreal, three similar islands in Lake St. Louis prevent floes from entering the navigation channel during the early part of the navigation season (Perham 1983).

(1) The four booms in the northeast corner of Lake St. Peter, depicted in Appendix B, were carried away in the late 1970s by a large floe that rotated up from the southwest quadrant of the lake; it was not replaced until the late 1990's. Upstream of Lake St. Peter, 700- and 1000-meter-long (2300- and 3300-foot-long) booms stabilize the ice cover along the river's left side at Lanoraie and Lavaltrie. Most of the original timber booms have been replaced by booms made of 76-centimeter-diameter (30-inch-diameter) cylindrical steel pontoons that greatly increase ice capture efficiency and reduce cost.

(2) The overall goal of the islands and booms is to allow as little ice as possible to enter the navigation channel. The structural measures make up only part of the overall ice management scheme, however. Continual ice breaking and flushing efforts, combined with routine airborne surveillance, are also critical.

a. Ice island along the northern edge of the navigation channel to stabilize shore ice.

b. Closeup of the ice island. It is constructed of quarried rock, the top diameter being roughly 40 feet.

Figure 18-3. Ice island on Lake St. Peter.

(3) The Montreal Harbor ice control structure (ICS), located at the upstream limit of winter navigation on the St. Lawrence, consists of a row of concrete piers, spaced at 27-meter (88-foot) centers, over a total width of 2 kilometers (1.3 miles). Figure 18-4 is an aerial view of the structure. Originally, steel pontoons (1.7 meters × 1.8 meters [5.5 × 5.8 feet] in cross section) floated in guide slots between the piers, with the goal of initiating an ice cover as early as possible. Later, the pontoons were found to be unnecessary, as the piers alone promoted the formation of a stable ice cover in Laprairie Basin, upstream of the structure. This discovery was fortunate, as operation and maintenance of the pontoons were costly and difficult. Once formed, the ice cover behind the structure prevents floes and brash from contributing to potential jams in the navigation channel downstream of the city. In addition, the cover behind the ICS traps and stores much of the frazil generated in the Lachine rapids upstream of Montreal. Before construction of the Montreal Harbor ICS, the ice cover on Laprairie Basin formed only after the natural ice cover had progressed from Lake St. Peter up to Montreal (Donnelly 1966). Should the cover progress as high as Montreal, the ICS was intended to capture arriving ice from upstream to reduce the ice

jam flood threat to the city. Owing to successful ice breaking and flushing efforts by the Canadian Coast Guard, the ice cover has not reached the city since winter-long navigation began in the mid-sixties, so the structure has never been tested in this worst-case scenario. At a cost of $16 million Canadian in 1965, the Montreal Harbor ICS is possibly the most expensive ice control structure ever built (Donnelly 1966, Lawrie 1972).

**Figure 18-4. Montreal Harbor ice control structure.
(From Lawrie 1972.)**

(4) On the Trollhatte Canal in Sweden, ice booms, rock-filled cribs, and dolphins are used to stabilize sheet ice along the sides of the navigation channel. As with the lower St. Lawrence, winter-long navigation is the goal, from Sweden's west coast to ports on Lake Vanern. Ice breaking and flushing, bubblers, and lock wall heaters, along with airborne surveillance, complement the structural ice control methods (Solve 1986).

c. 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 timber boom is located on the St. Marys River, south of the locks at Sault Ste. Marie, Michigan (Figure 18-5). Since its first installation in the winter of 1975–76, the boom has performed well, with only minor modifications (Perham 1977, 1978, 1984, 1985). The boom's centrally located navigation opening allows the passage of downbound vessels while limiting the ice volume entering the constricted channel at the Little Rapids Cut. For the same purpose, a four-span timber boom with a navigation opening was installed in 1976 at the Copeland Cut on the Wiley-Dondero Canal near Massena, New York. The boom performed well during its first season of use (Uzuner et al. 1977), but no recent information on the boom's performance has been obtained.

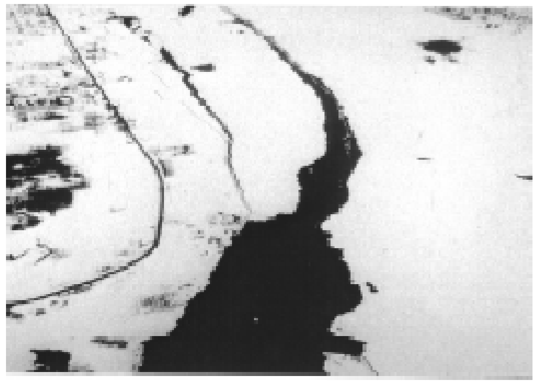


Figure 18-5. St. Marys River ice boom.

d. Sink-and-Float Ice Booms. Because the annual installation and removal of ice booms is costly, Fleet Technology, Inc. (2000) has developed a prototype sink-and-float boom. At the end of the ice season, the steel pipe pontoons are sunk in place for storage during the open-water season. To redeploy them, the pontoons are injected with compressed air, causing them to float back to the surface. An existing structure, similar in concept, protects the harbor entrance at Hokkaido, Japan, from drifting pack ice (Imaizumi et al. 1993). When there is no pack ice present, or during winter vessel transits in and out of the harbor, the pontoons lie on the seabed. The pontoons are refloated automatically by the injection of compressed air. Developed by Nishimura-Gumi Co., Ltd., the pontoons have a teardrop cross-sectional shape, minimizing the tendency for burial by deposition of sediment while resting on the bed.

e. Wiers. Submerged weir fields, known as bendway weirs, have been constructed on the Mississippi River. They direct flow towards the channel center, reducing erosion of the outside of the bend, and decreasing deposition in the channel, thus reducing the need to dredge. The St. Louis District has constructed weir fields on the middle Mississippi just below the Missouri River confluence and in the Dogtooth Bend upstream of the Ohio River confluence, both historical ice jam formation locations. Although observations are limited, these weir fields appear to have improved ice conveyance at these critical locations.

Section II
Floating Ice Dispersion

18-4. Introduction

The most notable problems with brash ice are its entry into lock chambers, often in heavy enough quantities to require separate ice lockages to pass the ice downstream, and its accumulation in miter gate recess areas, preventing the full opening of the gates. The most successful way to disperse ice is by means of high-flow air systems (Rand 1988). These systems may have up to three separate components, each with a specific function that increases the ease of lockage operations. (High-flow air systems are outgrowths of air bubbler systems intended to promote thermal thinning and weakening, i.e., melting, of ice.)

18-5. High-Flow Air Systems

a. Distributed Systems. Air manifolds should be placed in three specific locations around a lock to mitigate the problems of brash ice (Figure 18-6). First, a recess flusher should be placed in each gate recess; this will clear the recess area. The second manifold, called the screen, should be located just upstream of each set of miter gates. At the upstream edge of the gate forebays, there is typically a sill that runs across the lock chamber; place the screen on the downstream side of that sill. This screen helps prevent brash ice from entering the lock or, in the case of the downstream screen, clears ice from an area across the width of the chamber before the gate recess flushers are used. If there is some means for passing ice through or over a nearby spillway, the addition of a third type of manifold—a diagonal deflector in the upper lock approach—can be an effective way to direct the floating ice toward the spillway. This manifold is typically installed using divers and weights because the area cannot normally be dewatered.

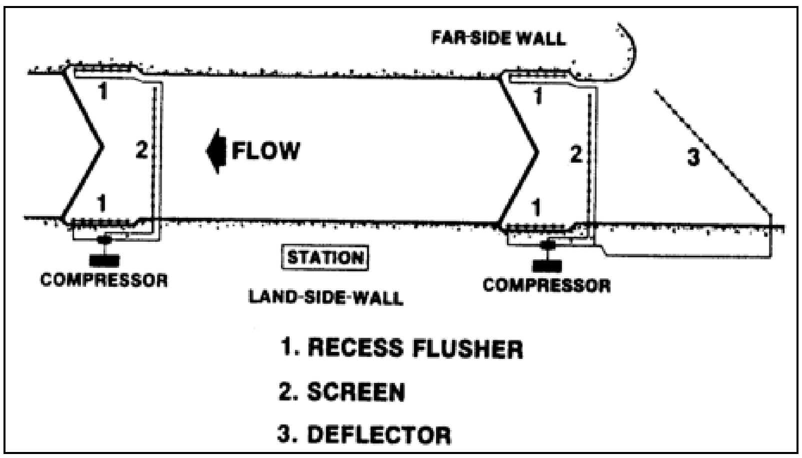


Figure 18-6. Schematic diagram of a complete high-flow air system, showing the locations for air manifolds at a typical lock. *Two compressors are shown, but one large compressor with long supply lines could also be used, assuming the supply lines are adequately sized.*

b. Single-point Systems. Single orifices can be placed on the back wall of a floating mooring bitt recess. A single air line discharging at the bottom of the recess provides sufficient water turbulence to prevent floating ice from being pushed and packed between the float and the recess walls.

c. Compressors. High flow are systems at Corps locks are typically supplied by compressors ranging in capacity from 200 to 1500 cfm (0.09 to 0.71 m^3/s), depending on the severity of the brash ice problems. Some systems have solenoid-activated valves, which allows the various manifolds to be controlled remotely.

18-6. Air System Components

Each of the major components of high-flow air systems are discussed to clarify what is required and to provide information on physical size and placement of the components.

a. Compressor. The air compressor of the size required is generally either diesel-powered or electrically operated. It can be either a permanent fixture or rented for the winter months. In a complete high-flow air system, the component requiring the most amount of air is the diagonal deflector. For a 33.5-meter-wide (110-foot-wide) chamber, a diagonal deflector manifold length of at least 61 meters (200 feet) is required. Design calculations (Paragraph 18-8) will indicate that a compressor of at least 21.2-m^3/min (750-ft^3/min) capacity must be available. No more than one manifold should be used at any one time.

b. Supply Lines.

(1) Pipes that run from a single, centrally located compressor to each end of the lock chamber must be large enough to handle the necessary air flow. One of the most common mistakes in designing an air system is undersizing the supply lines. Typically, at least a 7.6-centimeter-diameter (3-inch-diameter) schedule 40 pipe should be considered. If a supply length of over 152 meters (500 feet) is required, then a 10.2-centimeter (4-inch) pipe should be used for at least part of the total distance. Air control valves should be located at each end of the lock. Ideally, they should be remotely operated for easy use by the lock operator. The control valves allow the operator to selectively choose which air manifold to operate at any given time. An indicator should be provided to assure the operator that the valves are operating correctly.

(2) Supply lines from the control valves to the air manifolds submerged in the lock chamber vary in size, depending on the location of each manifold. The gate-recess flusher manifolds on the land wall require only a 5.1-centimeter (2-inch) pipe as a supply line (Figure 18-7). The gate-recess flusher manifold on the river wall, because of the added distance across the lock chamber to the manifold, needs to have at least a 7.6-centimeter-diameter (3-inch-diameter) supply line until the supply line reaches the far side of the lock chamber. The air screen going across the forebay sill requires at least a 7.6-centimeter (3-inch) supply line because of the volume of air being delivered (Figure 18-8). The location and placement of the supply lines may vary from lock to lock. It is best if the pipes can be located within the concrete walls, but if this is not possible, they should be located along the upstream edge of the gate-recess wall, protected from floating ice by steel plating.

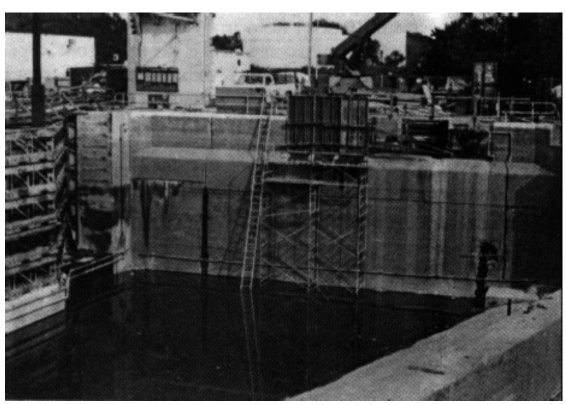


Figure 18-7. Flusher on the land wall of the upper gate recess composed of a supply line and manifold with orifices at Peoria Lock on the Illinois Waterway. *Note the vertical supply lines for the recess flusher of the river wall gate and for the cross-chamber air screen installed on the downstream-facing surface at the left (upper) end of the gate recess.*

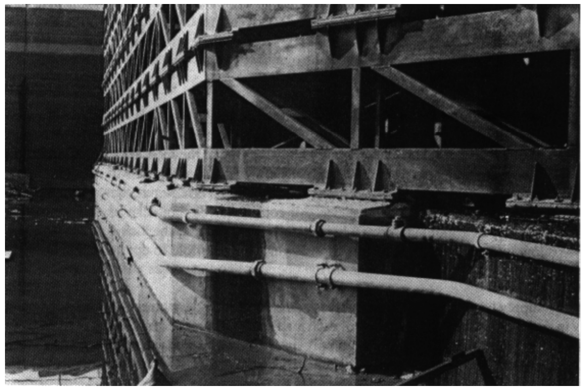


Figure 18-8. Downstream side of forebay sill, Peoria Lock.

c. Check Valves. At the bottom of the vertical leg of each supply line entering the lock chamber, an in-line, spring-loaded check valve should be installed to prevent water from passing into the manifold through the orifices, entering the supply pipe, and freezing near the water surface when the air lines are shut off. This check valve must be removable by divers for replacement or repair if required.

d. Manifolds. The manifolds for each of the systems vary with the number of orifices and the size of the pipe. The design of an air manifold should provide for an even and uniform air flow through its entire length. To achieve this goal, the total area of the orifices must be less than 25 percent of the cross-sectional area of the manifold.

e. Recess Flushers. The gate-recess flusher manifold differs from the other air manifolds because of the orifice spacing and pipe size. Laboratory and prototype analyses have shown that the spacing of the orifices should vary to provide more air near the quoin or pivot of the gate. The nominal spacings between orifices starting at the quoin end of the gate should be 1.2, 1.2, 1.2, 1.8, 2.4, 3, 3, and 3 meters (4, 4, 4, 6, 8, 10, 10, and 10 feet). The actual length of the manifold may vary because of lock constraints. Typically, in the locks on the Illinois Waterway, nine orifices are used.

f. Screens. The manifolds for the sill screens are designed with a 2.4-meter (8-foot) orifice spacing. For locks with a width of 33.5 meters (110 feet), a 29.3-meter-long (96-foot-long) manifold is used; 13 orifices are placed along that manifold.

g. Deflector. For a diagonal deflector in the upper lock approach area, a 61-meter (200-foot) manifold is recommended, with 26 orifices.

h. Orifices. Each orifice is a drilled hole in a hex-head stainless steel pipe plug, which is installed in a pipe tee in the manifold line. The inside of the plug is slightly chamfered, and there is a sharp edge at the outside surface. The orifices are aligned so that the air discharges vertically. Occasionally, the orifices might become plugged with silt, so the manifold should be regularly operated throughout the year to help the orifices remain free of dirt. The orifice diameter ultimately controls the amount of air discharged. From laboratory analysis, it is recommended that a design flow of 0.85 m^3/min (30 ft^3/min) be provided for each orifice. This will provide sufficient air to create the desired effect at the water surface. For all the systems installed on the Illinois

Waterway, 0.95-centimeter-diameter (3/8-inch-diameter) holes were drilled in the pipe plugs to serve as the orifices.

18-7. Effectiveness of the Air Systems

Experience gained from the use of complete high-flow air systems, as described above, has shown that the systems reduce winter lockage times, make for a safer operation, and keep the morale of lock personnel high. An average of 1 hour of compressor time is required to lock through an average tow. Some variation is experienced between individual operators, but all agree that a high-flow air system is an effective way to control floating ice problems at a lock (Figures 18-9 and 18-10).

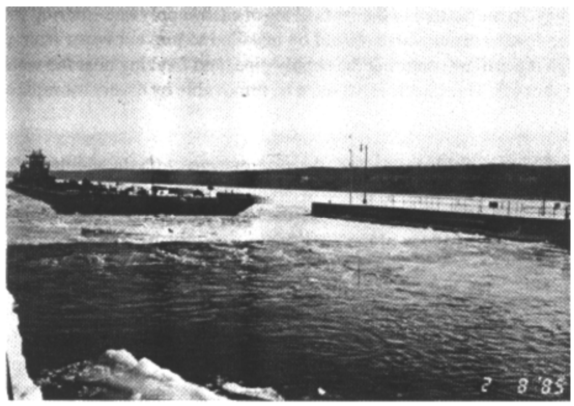


Figure 18-9. Upper screen in operation at Starved Rock Lock, Illinois Waterway.
Much brash ice is prevented from entering the lock chamber, even with the entry of downdbound tows.

Figure 18-10. Gate-recess flusher in operation at Starved Rock Lock.
The ice is flushed away from the recess area, allowing the miter gate to be fully opened.

18-8. Design of a High-Flow Air System

The parameters affecting the design of a high flow air system include: air volume and pressure available; effective length and size of the supply line; length and size of manifold line; depth of submergence; and orifice size and spacing. The air system analysis determines air discharge rates from an orifice by an iterative scheme that starts with a trial dead-end pressure. The analysis calculates the orifice discharge and pressure, starting from the end and working toward the supply point. After all the orifices are analyzed, the supply line pressure and air flow are calculated. The compressor pressure and flow rate necessary to sustain the supply line pressure and air flow are then calculated. The calculated compressor output is compared to the actual compressor output. The trial dead-end pressure is then adjusted and the analysis scheme repeated until the calculated and specified compressor outputs differ by no more than 1 percent. Changes in system parameters are made until the optimum design is obtained.

a. The calculations for optimizing the air system parameters are provided below. The initial trial dead-end pressure (P_d) is taken as

$$P_d = P_w + \frac{(P_c - P_w)}{4} \qquad (18\text{-}1)$$

where

P_c = true compressor pressure
P_w = $\rho_w g H$ = hydrostatic pressure
ρ_w = mass density of water
g = gravitational constant
H = submergence depth.

The subsequent trial dead-end pressure (P_d) is determined by

$$P_{d(new)} = P_w + \left(P_{d(old)} - P_w\right)\left(\frac{P_c - P_w}{P - P_w}\right) \qquad (18\text{-}2)$$

where

P = calculated compressor pressure
$P_{d(old)}$ = old trial dead-end pressure
$P_{d(new)}$ = new trial dead-end pressure.

The air discharge rate (Q_o) from the orifices is calculated by the discharge equation

$$Q_o = C_d \frac{\pi d^2}{4} \sqrt{2 \Delta P / \rho_a} \qquad (18\text{-}3)$$

where

C_d = discharge coefficient, sharp-edged circular orifice

d = orifice diameter
ΔP = pressure difference between inside and outside of diffuser line
ρ_a = mass density of air.

Finally, the pressure drop attributable to friction between orifices and in the supply line (ΔP_f) is calculated using the friction loss equation for turbulent flow conditions

$$\Delta P_f = \frac{f \rho_a \ell v^2}{D\, 2g} \tag{18-4}$$

where

f = friction factor
ℓ = equivalent length of pipe
v = air velocity
D = pipe diameter.

b. A computer program analyzing diffuser lines and nozzles gives a numerical simulation of air bubbler systems and is used for the air screen analysis. The input data include: diffuser line length and diameter, supply line length and diameter, orifice diameter and spacing, nominal compressor pressure, and submergence depth. The output from the program lists the following parameters: hydrostatic pressure, calculated output pressure, calculated compressor discharge, friction drop in diffuser line, friction drop in supply line, and excess dead-end pressure. To illustrate how changes in the system parameters affect the operating characteristics, Figures 18-11 and 18-12 show the effect on changes in the flow through an orifice with respect to changes in orifice diameters.

18-9. Example

A compressor with an output of 0.543 m^3/s (1150 ft^3/min) at 759 kPa (110 lb/in^2) was available for the high-flow air screen trials at the Soo Locks. Optimum air flow conditions could be obtained from a 5.1-centmeter-diameter (2-inch-diameter) manifold and supply line system with nozzles of 10-millimeter (0.40-inch diameter), spaced 3 meters (10 feet) apart. The manifold line was 5.1-centimeter (2-inch) galvanized pipe with 5.1- × 5.1- × 2.5-centimeter (2- × 2- × 1-inch) tee joints each 3 meters (10 feet) of pipe. A 2.5-centimeter (1-inch) stainless steel plug was mounted at each tee and each plug had a 10.3-millimeter (0.406-inch) hole drilled in it that acted as the nozzle or orifice. The supply line riser, which ran up the side of the lock, was also of 5.1-centimeter (2-inch) galvanized pipe. A flexible, quick-disconnect hose joined the bottom of the riser to the horizontal manifold line. Flexible hose was also used from the top of the riser to the compressor.

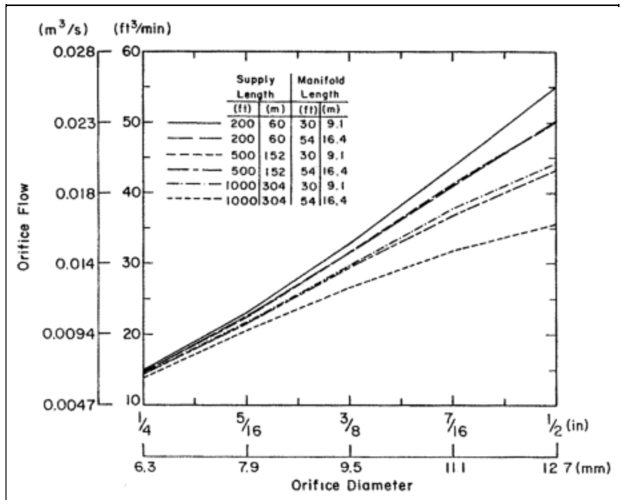


Figure 18-11. Performance curves for gate recess flushers, showing the average air discharge from each orifice plotted with respect to orifice diameter, for combinations of three supply-line lengths and at two manifold lengths. *The 5-centimeter (2-inch) diameter manifolds are either 9.1-meters (30-feet) nominal length for 17.1-meter (56-foot) wide locks, or 165-meters (54-feet) nominal length for 33.5-meter (110-foot) locks, submerged 6.1 meters (20 feet) below the water surface. Six orifices at nominal spacings of 1.2, 1.2, 1.2, 1.8 and 2.4 meters (4, 4, 4, 6, and 8 feet) are present in the 9.1-meter (30-foot) manifolds, and three additional orifices at nominal 3-meter (10-foot) spacings are present in the 16.4-meter (54-foot) manifolds.*

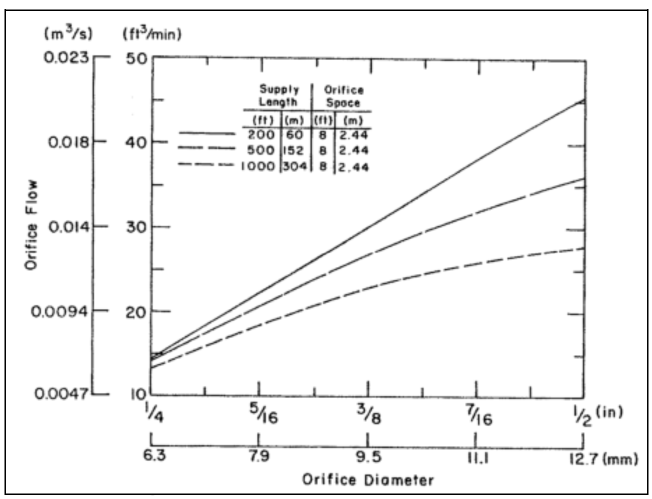


Figure 18-12. Performance curves for an air screen, showing the average air discharge from each orifice plotted with respect to orifice diameter, for three supply-line lengths. *The 6.4-centimeter (2.5-inch) diameter, 19.3-meter (96-foot) long manifold is typical for a 33.5-meter (110-foot) wide lock, and has 13 orifices at 2.4-meter (8-foot) spacings 6.1-meters (20-feet) below the water surface.*

a. The high-flow air screen was installed at the upper approach to the Poe Lock on the downstream, vertical face of an emergency stop-log gate sill. The sill is located about 61 meters (200 feet) above the lock gates. The riser line was installed in the stop-log recess in the wall. The width of the lock at this point is 33.5 meters (110 feet) and the height from the top of the sill to the top of the lock wall is 11.9 meters (39.2 feet).

b. The manifold line was installed at a depth of 10.5 meters (34.5 feet) in December 1977 and was assembled into four sections: two sections 8.46 meters (27.75 feet) long and two sections 7.47 meters (24.5 feet) long. Union connections joined the sections. The riser was assembled in one 11.7-meter (38.5-foot) section. The sections were light in weight; two to three people were able to move them by hand. All equipment for a hard-hat diver and the assembled pipes were placed on a 30.5-meter (100-foot) barge that acted as the working platform. The barge was positioned above the sill, and sections were lowered on ropes to the diver below who made the union connections and strapped the line to the concrete sill (Figures 18-13 and 18-14). One flexible hose coupling, from the diffuser to the riser, was also made underwater. The above-water installation process consisted of simply connecting a 15.2-meter (50-foot) flexible hose from the top of the riser line to the compressor. A 37,900-liter (10,000-gallon) fuel tank was placed beside the compressor to supply fuel (Figure 18-13) throughout the winter when delivery would be difficult.

Figure 18-13. Diver working to install air screen system.

c. The high-flow air screen was put into operation on 12 January 1978, when ice started to cause problems with lock operations. It was continuously available for service until 30 April 1978, except for a 5-day repair period in late March. By 1 May, ice no longer caused problems requiring the air screen, and the rented compressor was returned. During the 104 days of operation, the total running time on the compressor was 754 hours. Total consumption of No. 1 fuel oil was about 29,300 liters (7750 gallons).

d. The high-flow air screen demonstrated that it could hold back ice pushed ahead of downbound traffic. With ships in the 21.3-meter (70-foot) beam class, the ice was held back until the bow entered the air stream. The screen was not as effective with the wider 32-meter (105-foot) beam ships. Once the bow of a wider vessel passed the nose pier (about 40 meters [130 feet] upstream of the screen), the approach was just a little over 33.5 meters (110 feet) wide, so most of the ice remaining in the track was pushed into the lock by these larger ships. This problem possibly could have been solved by relocating the air screen upstream of the nose pier area and by providing some area for the ice to be pushed outside the vessel track.

e. The merits of the air screen cited by lock operating personnel, besides the reduction in vessel lockage time, were savings in wear and tear on the lock gate and operating mechanisms, and savings in the time and effort required to remove ice collars from the lock walls. (The ice collars at the Soo result in part from the vessels packing brash ice against the lock walls.)

18-10. Flow Inducers

A common technique to move ice in and around the lock is the use of a towboat's propeller wash to induce a flow that moves the brash ice. The towing industry assists itself and the Corps lock personnel on occasion; towboats break away from their tows and flush sections of a navigation project. Another type of flow inducer used in the past, a submergible mixer, develops a flow in the top layer of the water to aid in moving debris or floating ice. An example of this operation formerly existed at the Chicago Harbor Lock, where submergible mixers were attached near the sector gates. However, they have been removed. To prevent ice from accumulating in front of lock miter gates that are not functioning during the winter months, several Districts have made use of commercially available flow inducers designed for the marina industry for protecting docks. When ice is being locked, it is often difficult to flush brash from the area upstream of the filling and emptying ports. At the Soo Locks, this problem was solved by the construction of four 0.6-meter-diameter (2-foot-diameter) manifolds, located in the upper miter gates at the low pool level. With the chamber at low pool, the head differential creates surface jets that wash the ice downstream to an area where flow from the filling and emptying ports can move the ice the rest of the way out of the lock chamber.

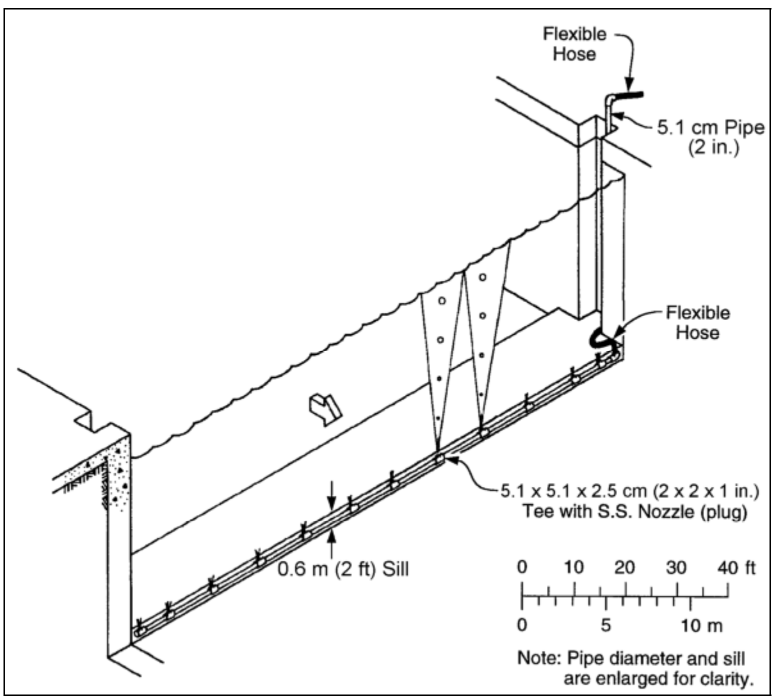


Figure 18-14. Schematic of an air screen.

Section III
Ice Passage Through Navigation Projects

18-11. Introduction

The question of holding ice or passing ice from one navigation project to the next is a subject of great concern on all river systems. A definitive position on this problem cannot be taken. It is clearly understood that growing a stable ice cover will reduce the overall quantity of ice grown because of the reduction in frazil generation. However, the broken ice within the frozen ship track has to be dealt with every time a vessel passes through. Just upstream of the locks is a particularly unfavorable spot to allow ice to accumulate. Almost every lockmaster will state that he wants to keep that zone above his lock clear. The specific policy, however, has to be addressed in each of the river systems.

18-12. Submergible Tainter Gates

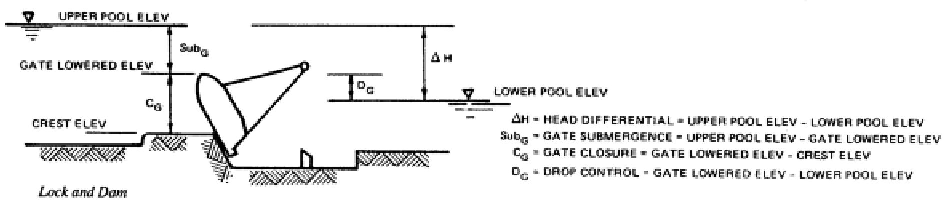
A case study of use of submergible gates at Corps projects was prepared by the Louisville District (U.S. Army 1985). Each of the project sites discussed in the study has a variety of dam gates. In the past, the use of submergible gates to pass ice in the former North Central Division was encouraged, whereas the former Ohio River Division did not allow the existing submergible gates to be operated. (These former separate divisions are now represented by the Great Lakes and Ohio River Division and by a portion of the Mississippi Valley Division.) The specific problems and comments regarding the varied use of submergible gates are well documented in the Louisville report. Figure 18-15 summarizes many of the submergible gates considered in the study. A 1989 rehabilitation project on the Illinois Waterway installed submergible gates at Marseilles Dam specifically for improving winter operations and ice passage. The major problem with passing ice is having sufficient water flow in the river system to open the gates, while maintaining adequate river stage. If broken ice is flowing toward the dam and the gates can be opened, a submergible gate will pass more ice than a nonsubmergible gate, given the same conditions. But it is more common that there is insufficient surface velocity to move ice toward the gate area. When this is true, the better ice passage characteristics of submergible gates provide no benefit. Moreover, ice bridging upstream of the gate, between the dam piers, is a common problem. However, a benefit of using submergible gates is that, because the gate is kept under the water, many gate freezeup problems are eliminated.

18-13. Roller Gates

Roller gates are used extensively on the Mississippi River. At most projects they are lowered to a fixed submerged setting in the late fall and are kept in that position for the duration of the winter. The pools are then maintained by adjusting tainter gates. At a few projects, the tainters are left to freeze in and the roller gates are adjusted, either submerged or with a bottom opening, to maintain upper pool stages. In the cases where the roller gates are used in the submerged mode in winter, they may assist in ice passage, functioning in the same manner as submergible tainter gates, but having the same limitations. Other problems associated with roller gates are largely related to the lifting mechanisms, in which ice interferes with lifting chains, guide channels, and gear racks. The side flanges of roller gates also tend to freeze to the concrete pier walls.

18-14. Conventional Tainter Gates

The openings required for ice passage at conventional tainter gates are usually quite large owing to the very high flow velocities needed to sweep floating ice downward to the bottom openings. As a result, except during periods of flood flow, these large openings normally cannot be used because of the likelihood of downstream scour at low tailwater stages. Thus, during the customary low-flow conditions of the winter season, ice passage at these gates is not feasible.



Lock and Dam (COE District)	*River*	*ΔH*	*Sub$_G$*	*C$_G$*	*D$_G$*	*Problem*	*Remarks*
Greenup (Huntington)	Ohio	32.0	7.0	28.0	25.0	Yes	Problem: stilling basin and sill erosion and vibration Solution: submerged operation eliminated, plans and specs for modification as of Dec 1978
Meldahl (Huntington)	Ohio	30.0	7.0	28.0	23.0	Yes	Problem: stilling basin and sill erosion and vibration Solution: submerged operation eliminated
Markland (Louisville)	Ohio	34.0	7.0	33.0	27.0	Yes	Problem: vibration and jet through stilling basin and across end sill Solution: gate stops added and spillway curve modified. Submerged operation eliminated
McAlpine (Louisville)	Ohio	37.0	7.0	12.0	30.0	Yes	Problem: bed-material abrasion of sill Solution: submerged operation eliminated, spillway curve modified
Cheatham (Nashville)	Cumberland	26.0	7.0	19.0	19.0	Yes	Problem: vibration Solution: submerged operation eliminated, design and modification being considered
New Cumberland (Pittsburgh)	Ohio	22.6	7.0	12.5	15.6	Yes	Problem: vibration, cavitation between gate and sill, and recreational craft hazard Solution: submerged operation eliminated
Pike Island (Pittsburgh)	Ohio	21.0	7.0	20.0	14.0	Yes	Problem: excessive leakage Solution: submerged operation eliminated
L&D no. 4 (Pittsburgh)	Monongahela	16.6	7.0	12.5	9.6	No	Movable crest or piggyback gate
Maxwell (Pittsburgh)	Monongahela	19.5	7.0	19.0	12.5	No	Movable crest or piggyback gate
L&D no. 11 (Rock Island)	Mississippi	11.0	8.0	12.0	3.0	No	13 gates
L&D no. 12 (Rock Island)	Mississippi	9.0	8.0	12.0	1.0	No	7 gates
L&D no. 13 (Rock Island)	Mississippi	11.0	8.0	12.0	3.0	No	10 gates
L&D no. 16 (Rock Island)	Mississippi	9.0	8.0	12.0	1.0	No	3 of 15 gates
L&D no. 17 (Rock Island)	Mississippi	8.0	8.0	8.0	0.0	No	8 gates
L&D no. 18 (Rock Island)	Mississippi	9.8	5.0	15.0	4.8	No	14 gates
L&D no. 20 (Rock Island)	Mississippi	10.0	3.0	17.0	7.0	No	6 of 40 gates
L&D no. 21 (Rock Island)	Mississippi	10.5	8.0	12.0	2.5	No	10 gates
L&D no. 22 (Rock Island)	Mississippi	10.5	8.0	17.0	2.5	No	1 of 10 gates
L&D no. 24 (St. Louis)	Mississippi	15.0	8.0	17.0	7.0	Yes	15-80 ft TG's, vibration, stress on trunion; submerged operation eliminated
L&D no. 25 (St. Louis)	Mississippi	16.0	7.0	18.0	9.0	Yes	14-60 ft TG's, vibration stress on trunion; submerged operation eliminated
L&D no. 26 (St. Louis)	Mississippi	24.0	3.0	27.0	21.0	No	30-40 ft TG's

Figure 18-15. Summary of submergible gates and their problems. *Many of these were considered in the Louisville District study of the use of submergible gates for passing ice (U.S. Army 1985).*

18-15. Gate Limitations in Winter

As detailed in Chapter 14, Paragraphs 14-4*g* through *i*, successful operation of dam gates in winter, regardless of types, is impeded by accumulated ice in the upstream pool, by ice buildup on gate and piers from spray and splashing, and by the freezing of leakage past gate seals. All of these factors combine to render ice passage through gate bays very difficult and unreliable, unless remedial measures, as discussed in the following, are employed.

18-16. Other Ice Passage Schemes

Ice can be successfully passed at some navigation locks having auxiliary lock chambers and bulkhead lift systems by skimming the ice over partially raised bulkheads. Figure 18-16 shows such an operation. This is an effective way to pass ice through the lock system, thus clearing the upper approach area.

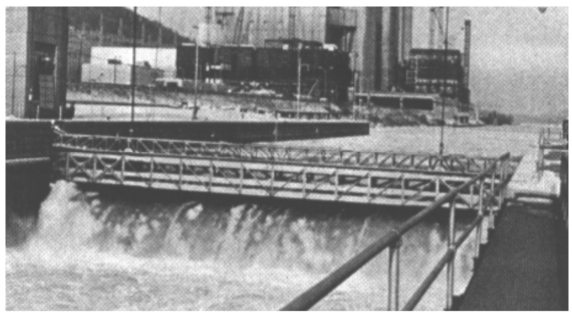


Figure 18-16. Ice passage at New Cumberland Lock on the Ohio River. *Raising the top bulkhead of the auxiliary lock chamber allows flow to carry ice out of the lock approach area.*

Section IV
Anti-Icing and Deicing at Navigation Projects

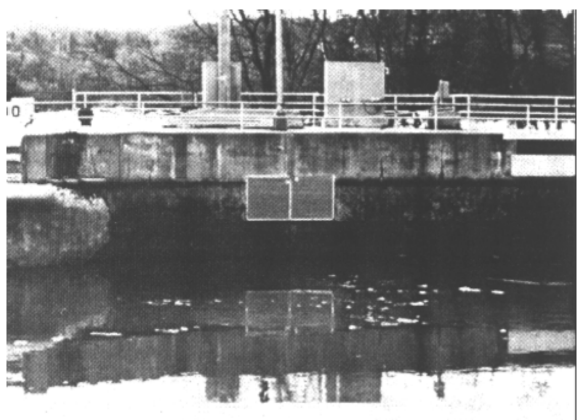
18-17. Introduction

As described in Chapter 14, the ice-related problems at navigation structures are severe during the winter months. Exposed mechanically operated systems may be frozen-in and become inoperable. The weight of ice formed on structures that need to be lifted or moved may become excessive so that the system becomes overloaded. Ice loads can also cause structural damage. Icing on the recess walls or gates of navigation locks prevents full opening of the gates. Ice formation on the chamber walls prevents full use of the lock width. Ice buildups on dam pier walls can obstruct the movement of the components of dam gates. Ice in any form causes safety hazards for personnel working on or near it. All of these ice problems involve ice formation on or adhesion to critical surfaces at locks and dams. Solutions to these ice problems at navigation projects currently are time-consuming and expensive. This section addresses several approaches to solving the problems of surface ice formation and adhesion.

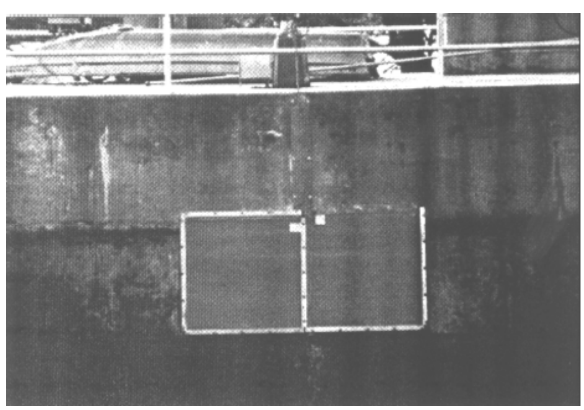
18-18. Electrical Heating of Lock and Dam Components

Ice adhesion on walls can be prevented by maintaining wall temperatures above 0°C (32°F), or ice collars can be shed periodically by raising the wall temperature intermittently. Possible arrangements include embedded (but removable) electrical heating cables within walls, direct placement of heat mats on walls, and heating dam gate side J-seals.

a. Embedded Electrical Heaters. The use of embedded electrical heaters that cannot be removed for replacement without major rehabilitation is *not recommended.* Almost every navigation project that has installed embedded electrical heaters has some heaters that have failed and cannot be replaced. The recommendation for those areas where embedded heaters are needed is a replaceable heat tape as described here. During a rehabilitation project, where the concrete walls are to be resurfaced, 1.9-centimeter-diameter (3/4-inch-diameter) stainless steel pipes should be installed, 15 to 20 centimeters (6 to 8 inches) on center, with the bottom ends sealed. At the top of the pier or along the top of the wall, the top ends of the pipes are accessible so that electrical leads can be run from one vertical pipe to the next. The tubes are filled with glycol to act as a heat-transfer fluid, once the self-regulated heat tape is inserted into the pipe. The heat tape can be cut to specific lengths by project personnel and inserted into the pipe. The heat tape is self-regulating and has an output of 121 W/m at 0°C (37 W/ft at 32°F). In the control circuit, timers and thermostats can be added to limit power consumption. If a heat tape fails, then a new length of heat tape may be cut and installed. The cut end should be sealed using heat-shrink tubing, and a cold electrical lead is added to the upper end. Alternate techniques of installing the pipes are by drilling vertical holes along the edge of a pier or wall (however, a major concern is the possibility of the hole breaking out) and by cutting vertical slots 7.5 to 10 centimeters (3 to 4 inches) deep in the wall.



a. General view.



b. Detail showing plate over vertical groove in wall (containing electrical leads) above heat mats.

Figure 18-17. Fiberglass-reincorced plastic heat mats installed on a miter gate recess wall at Starved Rock Lock on the Illinois Waterway.

b. Wall Heat Mats. Fiberglass-reinforced plastic heat mats have been placed directly on a vertical concrete wall at a lock to prevent ice from forming a collar in the gate recess area. The commercially available mats can be provided in any shape or size up to 1.2 × 2.4 meters (4 × 8 feet). Variable power ratings are also available. The mats shown in Figure 18-17 are 1076 W/m^2 (100 W/ft^2). These panels are each 1.2 × 1.2 meters × 0.6 centimeters (4 × 4 feet × 1/4 inch) thick. The mats are very effective in keeping the wall clear of ice. Material costs (1988) for such a mat material were about \$753/m^2 (\$70/ft^2).

c. Heated J-seals on Dam Gates. Heating the side J-seals improves their ability to reduce leakage past tainter gates, and thus reduce the associated buildup of icing on the walls and the gate structures. This method is easily adaptable at low cost to existing dam gates (using Huntington J-seal Mold No. 3493 or equivalent).

(1) This in situ heating system has been made up so that it can be inserted into the hollow channel of a J-seal; it keeps ice from forming on the seal and increases the flexibility of the seal at lower temperatures. With increased flexibility, the seal better conforms to irregular surfaces, thereby reducing leakage to the downstream side. With little or no leakage, ice formation on the cold, exposed downstream side is substantially reduced. Neither steaming nor "cindering" (i.e., pouring cinders in the water above the locations of the greatest leakages, so that the cinders flow toward the leaks and plug them) were required during tests of the in situ heating system at Starved Rock Lock and Dam on the Illinois Waterway, where it was installed during a recent dam rehabilitation.

(2) The self-regulating heat trace tape, 208 volts ac at 121 W/m at 0°C (37 W/ft at 32°F), was cut from a spool to a length of 5.5 meters (18 feet). The heat tape was sealed at one end. The other end had a cold electrical lead attached to connect to the electrical power. The J-seal and the inserted heater are shown in Figure 18-18. The 1988 cost of Huntington J-seal Mold No. 3493 was \$45.57/meter (\$14.50/foot). The seal was manufactured as of 1988 by Buckhorn Rubber[*], The self-regulating heat trace tape is widely available at an approximate 1988 cost of \$16.40/meter (\$5/foot). If both seals of a gate are heated and the heaters are operating at maximum power, the operating cost per day is \$2.24, assuming 1332 watts at \$0.07/ kWhr.

(3) Use of heated J-seals would not preclude the inclusion of embedded electrical heaters in gate pier walls in rehabilitations or new designs, because embedded heaters aid in keeping seal plates ice-free above or below the immediate seal-contact area, so that gates can easily be placed in any chosen position.

[*] 55 W. Techne Center Drive, Milford, Ohio 45150 (800-543-5454).

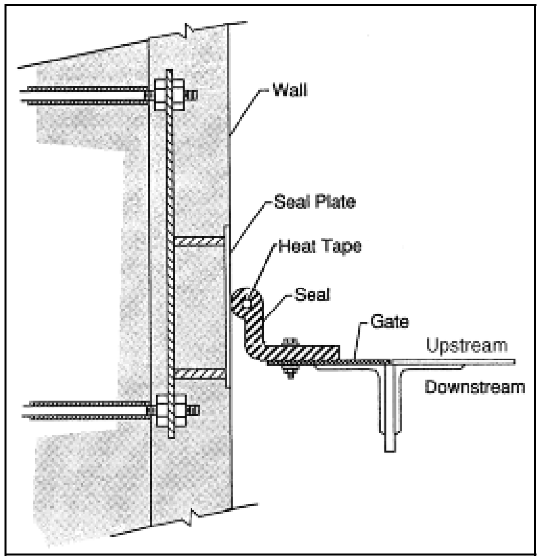


Figure 18-18. J-seal installation on a tainter gate

18-19. Providing Electricity for Heating to Locks and Dams

Electricity for the heating and deicing of lock and dam components can be supplied by the local electric utility. But since such energy is usually expensive, lower-cost sources of electricity are attractive. Two such alternatives are private hydropower projects installed at Corps navigation projects and, possibly, pre-packaged portable hydropower plants.

a. Installed Private Hydropower. It is the policy of the Corps of Engineers to cooperate with the Federal Energy Regulatory Commission in encouraging private interests to develop hydropower potentials at Corps navigation or flood-control dams. In these cases, the Corps usually has rights to certain portions of the power generated at no cost, as long as it is used for the benefit of navigation. In planning for use of this power, it is recommended that the power needs for ice control be considered and that the total power requirements for navigation be conveyed to parties exploring the feasibility of such private hydropower development.

b. Portable Prepackaged Hydropower. In those cases where private power development is not present or not likely to be developed, the use of dedicated, portable, packaged hydropower units as described below (if they are commercially available) should be investigated and compared to purchased power for meeting the needs of ice control at navigation locks and dams.

(1) A study conducted by the University of Iowa during the River Ice Management Program (Nakato et al. 1992) endorsed electrical heating as an attractive method for controlling ice, and suggested consideration of using a then-unconventional means of generating electricity onsite: prefabricated, portable, packaged power plants. The study described a concept in the development and demonstration stage (in 1988) for low-head micro-hydroelectric power plants. These packaged plants were of two sizes: one producing 500 kilowatts at a net head of 5.5 meters (18 feet) and a discharge of 11.3 m^3/s (400 ft^3/s), and the other a 1250-kilowatt unit operating with a 3.7-meter (12-foot) head and 42.5 m^3/s (1500 ft^3/s). These plants gain their portability by being barge-mounted. There is an anchored upstream barge providing the water intake, a siphon penstock, and a downstream barge that carries a submergible horizontal turbine. Trunnion-type

joints accommodate variations in upper and lower pool stages. There is no major construction involved for these devices to be installed; they can be placed in a variety of dam configurations, for example, in a gate bay of a navigation dam.

(2) Micro-hydroelectric power-plant output potentials, expressed in combinations of discharge, net head, and resulting power output, are listed in Table 18-1.

Table 18-1
Output Potential of Micro-hydroelectric Power Plants

Discharge m^3/s (ft^3/s)	Power Output (kW) (at 80% efficiency) at Net Heads of:			
	1.5 m (5 ft)	3.0 m (10 ft)	4.6 m (15 ft)	6.1m (20 ft)
7.1 (250)	85	170	255	340
14.2 (500)	170	340	510	680
28.3 (1000)	340	680	1015	1355
42.5 (1500)	510	1015	1525	2035
56.6 (2000)	680	1355	2035	2710

18-20. Mechanical Removal of Ice from Lock Walls

a. General. The experimental extension of the navigation season into the winter months on the Great Lakes created ice problems at the Soo Locks. Even under present operating-season schedules, ice poses many problems at the Soo Locks, as well as at many of the lock-and-dam projects on the Ohio River and its tributaries, on the Illinois Waterway, and on the Upper Mississippi River. Ice can adhere to lock walls, building up an ice collar at and below the high pool level, which can interfere with gate opening and closing and interfere with ship passage. For example, ice collars form at the 33.5-meter (110-foot) wide Poe Lock at Sault Ste. Marie, Michigan. Ships of the *Presque Isle* and *Roger Blough* class with their 32.0-meter (105-foot) beams encounter problems when the ice buildup along the walls becomes greater than 0.76 meters (2.5 feet) on each wall. Prior to the development of the ice cutting saw, discussed below, and the copolymer coating (discussed later in paragraph 18-19*a*), a number of methods were used with varying degrees of success to overcome this problem. Steam hoses work well but are extremely slow and require many man-hours. Backhoes have been used to scrape off the ice collar. This is faster then using steam, but still slow. Since the operator cannot see what he is doing he may miss some ice or scrape too deep and damage the lock wall. A high pressure water jet was able to cut off the ice, but the jet was noisy and somewhat dangerous, and the pressure pump was both expensive and difficult to maintain. The best solutions found to date used a copolymer coating, and an ice cutting saw. The ice cutting saw is discussed here.

b. Ice Cutting Saw. CRREL adapted a Bowdil coal saw (see Figure 18-19) to remove the ice collars (Garfield et al. 1976). The unit consisted of two parts: the cutting system, and the drive and propulsion system. The drive and propulsion system was a 48.5-kilowatt (65-horsepower) four-wheel-drive tractor, originally manufactured as a trencher (the tractor could be purchased without the trencher attachment). The drive line for the trencher was modified to accommodate the cutting system by extending the drive shaft and attaching a drive sprocket to its end. While in the cutting mode, the engine powered the shaft and sprocket directly and the drive wheels indirectly through a separate hydraulic drive system, so cutting power and propulsion power could be independently controlled. The system was deemed conditionally acceptable, with ice-collar cutting speeds in the range of 1.8 to 3.6 meters/minute (6 to 12 feet/minute).

Figure 18-19. Ice cutting saw at Poe Lock.

18-21. Surface Treatments to Reduce Ice Adhesion

There is a long history of study in this area for a variety of applications, but surface treatments that shed ice reliably and repeatedly have not yet emerged. The only chemical treatment that has been used successfully on a large scale for truly shedding ice is repeated application of chemicals that depress the freezing point of water. As far as concrete surfaces are concerned, the classic treatment for ice removal is repetitive application of sodium chloride or calcium chloride. Another ice-control method is a permanent or semipermanent chemical coating that reduces the adhesive force between the coated surface and the ice that forms on it. The ideal material would be one that prevented ice formation entirely. No known coatings do this, but some make the task of ice removal from coated surfaces easier. As an alternative to coatings to reduce ice adhesion, cladding surfaces with materials that shed ice more easily than concrete may be considered.

a. Copolymer Coatings. One successful material is a long-chain copolymer compound made up of polycarbonates and polysiloxanes. The most effective coating of the many that have been tested is a solution of polycarbonatepolysiloxane compound, silicone oil, and toluene. The mixture is highly volatile and leaves a thin coat of the copolymer and silicone on the surface to which it is applied.

(1) The copolymer coating was not to be applied to a concrete surface unless it was certain that the concrete behind the coating could resist frost action in a critically saturated condition. Proper application guidance for surface coatings to concrete can be found in *Maintenance and Repair of Concrete and Concrete Structures,* EM 1110-2-2002. The surface to be coated must be clean and dry. For concrete and metal surfaces (bare and painted), steam cleaning is sufficient; however, a detergent may be added to the water of the steam cleaner. This was done, for example, in one case where navigation lock walls were heavily coated with oil and algae. Once the surface is clean and dry, the solution can be sprayed on using an airless spray gun system (Figure 18-20). A single pass will deposit a coat 25 to 51 micrometers (1 to 2 mils) thick. Three coats are recommended for a coating thickness of about 127 micrometers (5 mils). Achieving this final thickness requires about 24.4 liters/100 m^2 (6 gallons/1000 ft^2).

Figure 18-20. Application of copolymer coating.

(2) Care has to be taken when mixing the solution. Toluene is a combustible material, so no electrical motor-driven mixer should be used. An air-operated drill motor fitted with a rod with mixer blades has worked satisfactorily. The fumes may also be a health hazard, so that a well-ventilated mixing area should be used. A 208-liter (55-gallon) drum fitted with a bracket to hold the drill motor is a suitable mixing container. Batches of up to 151 liters (40 gallons) can easily be handled. The liquid portions, toluene and silicone oil, are placed in the container first. Then the mixer is started and the copolymer powder is slowly added. Mixing continues until all solids are dissolved. Then the solution can be transferred to a storage container.

(3) Tests to determine the merits of an undercoating for the copolymer (on concrete surfaces that are worn and rough) show that an epoxy-type coating that acts as a filler over the rough concrete provides a better surface to which the copolymer adheres. Trials of the undercoating and copolymer were done at the Poe Lock, at the St. Marys Falls Canal, at Sault Ste. Marie, Michigan, at Lock No. 4 on the Allegheny River, and at the Starved Rock Lock on the Illinois Waterway. Maintenance and frequency of recoating requirements were monitored. The coating remained in good condition for at least three years.

b. Epoxy Coatings. Commercially available two-part epoxy coatings, which can be applied in wet environments, have been tested for ice-phobic characteristics. Several of these coatings perform equally as well as the copolymer coating. They are far more durable because they are an epoxy resin and a polyamine-based curing agent. The epoxy coating gives concrete ideal protection against the ingress of chloride ions, carbon monoxide, and other corrosive agents over the design life. The hard, smooth finish provides a very low friction coefficient, thus reducing the bond strength between ice and substrate.

c. Claddings. Cladding of wall surfaces by materials that shed ice easier than concrete is another approach to solving the problem of ice adhesion. In a demonstration at Starved Rock Lock in Illinois, a 1.2- × 2.4-meter × 1.2-centimeter-thick (4- × 8-foot × 1/2-inch-thick) sheet of high-density polyethylene was fastened to the curved part of the gate recess wall at the quoin end, at the ice-collar level. Hilti studs, 0.5 meters (20 inches) on center, were used for attaching the sheets. Ice formed on the polyethylene surface and the concrete surface equally, but far less effort was needed by lock personnel to manually remove the ice from the plastic material, because of the lower adhesion forces between the polyethylene and the ice. Problems were noted with ice being more difficult to dislodge where the studs protruded, but a redesigned fastening technique could overcome that problem. The polyethylene is not highly durable when pike poles or ice chippers have to be used extensively, though. The use of steam to dislodge the ice collars would eliminate the risk of this damage. The panels are easily and economically replaced, since their 1988 cost was only about $75/m^2 ($7/ft^2).

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a. Required Publications.

None.

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CHAPTER 19
Operational Solutions

Section I
Vessel Scheduling or Convoying

19-1. Introduction. Frequent vessel passages through ice-covered navigation channels under frigid conditions generate extra ice. In addition, the passage of vessels causes most of the ice grown along tracks opened by previous vessels to be broken into brash ice, which may collect as thick accumulations that eventually impede vessel movements. Field observations, results from ice-tank (laboratory) experiments, and numerical models have shown that navigation tracks opened by transiting vessels become covered with a rather porous layer of brash ice that is approximately 1.5 to 3 times the thickness of the surrounding sheet-ice cover. The greater the number of passages, the thicker the brash-ice layer is likely to become. In addition to hindering vessels, the accumulations of brash ice may form partial or complete ice jams in the navigation channel itself and parallel ridges beneath the ice cover adjacent to the navigation channel. Ice-tank experiments indicate that these ice jams and ice ridges form especially rapidly in shallow river reaches, where they may extend downward to the bottom of the channel. An additional problem that may affect towboats and barges transiting through level or broken ice is their propensity for entrapping and transporting brash ice beneath their flat-bottomed hulls. Ice-tank experiments have shown that the thickness of the ice accumulations on the flat bottoms of towboats and barges increases with decreasing velocity of the vessels, and also increases when lateral confinement (such as provided by ice ridges along the track) does not allow ice pieces to slide off the vessel bottom toward the sides.

19-2. Operational Choices. The problems outlined above suggest two general approaches for their control and mitigation. The first approach entails the use of mechanical methods for controlling brash-ice accumulations at specific channel locations, either by removal or breakup. Icebreakers could be used to loosen and break up such ice accumulations, and to ease transit conditions for commercial vessels, including towboats and barges. However, no icebreakers currently operate on the Ohio and Upper Mississippi Rivers, or on the Illinois Waterway. The second approach involves the optimum scheduling of tow transits and, possibly, the convoying or grouping of tows, which will minimize ice growth in navigation channels.

19-3. Transit Scheduling or Convoying. Results from laboratory experiments and numerical modeling indicate that the basic rule for minimizing the volume of ice grown in a navigation channel is to minimize the total number of transits or tow passages per day. However, the demands of navigation do not generally allow this to be done. Under the assumption that a certain number of transits must take place per day, numerical modeling has shown that varying the time interval between individual transits has no significant effect on the volume of ice grown. But convoying of vessels, i.e., having tows grouped together to transit one after the other, is a special case equivalent to a large, single transit. Under a convoying concept, only one icebreaking event per day would take place. Correspondingly, the total volume of ice produced in a waterway each winter would be minimized.

a Limitations. Ice-prone waterways may have relatively short periods of severe ice conditions. The river reaches between locks and dams in many locations are relatively short, resulting in frequent lockages of the tows. The vessels may have numerous and varied origins and destinations along the waterways, some of which may lack adequate docking and mooring areas where several tows could be assembled for convoying. Finally, upbound and downbound transits usually have equal frequency. Under these conditions, elaborate transit scheduling, requiring close coordination among the Corps of Engineers, the Coast Guard, and the navigation industry, is unlikely to be administratively or economically feasible.

b. Guidelines for Scheduling or Convoying Tow Traffic. For certain river reaches where ice accumulations are particularly severe, or for a given period when cold weather conditions are extreme, partial scheduling or convoying may be chosen as a temporary, expedient measure to help keep the waterway open and to expedite traffic. In such a convoy, normally the leading towboat would be the most powerful one. It is the vessel most likely to be able to do the required icebreaking in the difficult areas. It may also involve the widest tow configuration, thereby opening the navigation channel for the rest of the tows in the convoy. Finally, the most powerful boat may be capable of sustaining a speed sufficiently high to avoid ice accumulations underneath its own barge bottoms, as well as those of the following tows. The size of a convoy may be limited by the time required to pass it through a lock, rather than by the time required to move between two successive locks. While transit scheduling or convoying are not common approaches to alleviating winter transit difficulties in the navigable waterways of the northern United States, they should be considered when extraordinary local and short-term ice conditions are forecast or are at hand.

Section II
Operational Techniques at Locks and Dams

19-4. Introduction. Operational techniques to mitigate ice-related problems at locks and dams tend to be site-specific. Factors influencing the success of any operational technique include the geographical location of the project with respect to river features, the river system that the project is on, the location of the dam in relation to the lock, the presence of an auxiliary lock, the kinds of gates at the lock or dam, the presence or absence of an effective high-flow air system at the lock, the availability of a work boat assigned to the lock, the prevailing wind direction, the amount of winter navigation, and so on. The general problems caused by ice at locks and dams are summarized in Chapter 14: ice obstructing the upper lock approach, fragmented ice floes accumulating in miter gate recesses, ice adhering to lock walls and miter gate recess walls, inoperative floating mooring bitts, vertical check pin (line hook) icing, ice accumulating in the lower lock approach, difficult ice passage at dam spillway gates, ice buildup from spray at dam spillway gates, icing from leakage at gate seals, and ice accumulating on intake screens.

19-5. Physical Ice Removal. Several of the ice problems at locks and dams involve ice adhering to structure surfaces. When methods for the prevention of these ice buildups are not available, it may become necessary to resort to physical removal techniques. Chapter 20 gives a detailed discussion of this subject.

19-6. Methods Used at Locks. Operational techniques used to mitigate ice problems at locks are briefly listed below. The list of practices can always be enlarged by discussing any particular problem with the lock or maintenance personnel at neighboring project sites.

a. Upper Approach. Techniques to reduce upper approach ice problems include using an auxiliary lock with a bulkhead spillway to pass ice, ice lockages in the main chamber or an auxiliary chamber, diagonal high-flow air-screen deflectors, and towboat wheel wash. Other possibilities are the placement of barge traffic awaiting downbound lockage in appropriate configurations to deflect ice, using ice spillways near dams (if present) or using dam gates to pass ice, assuming sufficient flow is available for this purpose.

b. Miter Gate Recesses. To clear fragmented floes from around miter gates and recesses, towboat wheel wash, miter gate fanning, pike poles and ice rakes, or recess air flushers are used. If the techniques used to deflect floating ice away from the upper approach are effective, then the task of dealing with fragmented ice in the lock chamber and gate recesses will be reduced.

c. Lock Walls and Recess Walls. Ice accumulations or ice collars on lock walls and miter gate recess walls cause width restrictions, as noted earlier. To remove ice collars, or to prevent or reduce the ice growth, various techniques can be considered. If the pool elevation in the chamber is kept high except during lockages, the chamber wall temperature will be near the water temperature. On the other hand, if the pool is kept at a low level, more of the lock wall is exposed to the subfreezing air, allowing the wall to reach temperatures below freezing and thus allowing more ice to form. Removal of the ice is critical in the gate recess area. Common practices at many locks are the labor-intensive ones of using chippers, pike poles, and steam lances. Other techniques that may be available include low-flow bubblers, surface-mounted heat mats, embedded circulation loops of warm fluids, and mechanical tools like backhoes. In addition, see Chapter 20 for additional information.

d. Mooring Bitts. Floating mooring bitts typically freeze in place because of floating ice being pushed into the bitt recess area, as well as because of ice buildup on tracks and related rollers. Currently, personnel at many locks secure the bitts in the top position, not using them during the winter months. This, of course, leaves the bitts unavailable while lock traffic may still be in need of them. The techniques of using a single-point air bubbler or replaceable embedded electric heaters have been developed but are not yet widely adopted. Additional safety systems should be added so that if a floating bitt becomes frozen in the submerged position, it will not be launched skyward when the ice melts.

e. Check pins. Vertical check pins are typically iced over and are forgotten until spring. Lock personnel rely on mooring points on the top of the lock wall to secure the lines during the winter months. Constant monitoring of the lines by deck hands is required. No operational technique appears feasible, other than steaming or chipping the ice on the check pins.

f. Lower approach. The final lock ice problem is the accumulation of ice in the lower approach. Typically, this is not a serious problem for lock personnel. It is possible to stage tows waiting to be locked up in such a manner as to block the encroachment of ice. Water discharge when lowering the lock chamber level helps to clear the immediate lower approach area.

19-7. Methods Used at Dams. Operational techniques used to handle the icing problems associated with dams are much the same as those used at locks. Comments on specific practices at dams are given here. Many dams have been equipped with embedded electrical heaters along gate sealing surfaces. Unfortunately, these heaters have a record of frequent failure, and a new technique has been designed for the installation of a removable heater that is easily exchanged if it becomes inoperative (see paragraph 18-16*a*). Steam lances are commonly used in dam deicing. This is a time-consuming operation but it can be effective. Cindering the dam gate seals (i.e., applying coal cinders to the water above the gate, which then flow toward and plug the gaps at the seals to reduce water leakage) helps to prevent the formation of larger ice deposits on the downstream side of the gate. A new method that has been proposed is a heater inserted in the hollow channel of a J-seal to keep the seal material flexible (see paragraph 18-16*c*). The increased flexibility makes a better seal, eliminating or reducing leakage and ice formation on the downstream side of the gate. The types of gates and their lifting devices are largely site-specific, and techniques used to operate them in winter are developed with time and experience. Typically, submergible gates operated in the submerged position have the fewest operational problems from ice during the winter months. Problems experienced with submergible dam gates are identified in *Submergible Gate Use Within the Corps: Case Histories* (U.S. Army 1985). In many instances, operational techniques now used by lock and dam operators are also described in that report.

Section III
Operational Use of Thermal Resources at Locks and Dams

19-8. Introduction. There is often interest expressed in making beneficial use of energy or thermal resources that may already be present in the vicinity of navigation projects. By this is meant either energy introduced into waterways by man-made sources, or energy that might be extracted from the natural environment (the latter sometimes being called unconventional energy sources).

19-9. Man-Made Energy Sources. Man-made sources of warm water on rivers are often present that either already suppress some ice formation or may be used to cause some ice suppression. The most significant source is the release of cooling water from thermal power plants, which amounts to 150 to 200 percent of the energy produced as electricity. Another source is the release of water from reservoirs that contain slightly warmer water at depth, such that downstream flows may be several degrees above freezing. In addition, there are other less significant sources such as the discharge of treated sewage and warm waste water from industrial processes. While direct application of these thermal energy resources at navigation projects may be difficult, their effects may be helpful in diminishing ice problems in the vicinity of locks and dams. For a complete analysis of the effects on ice covers produced by these thermal energy sources, see Chapter 3, *Ice Control*, paragraphs 3-8 and 3-9.

19-10. Unconventional Energy Sources. Conventional energy sources, such as electricity from public utilities, or the burning of hydrocarbon fuels for heating (either direct heating, or indirect heating such as for generating steam), can be viewed as comparatively expensive sources of energy for ice control at lock and dam installations. Therefore, consideration has sometimes been given to unconventional energy sources, such as sensible heat from groundwater, heating of a transfer medium by solar energy, or electricity generated from wind energy. A study was conducted during the River Ice Management Program to evaluate the feasibility of using energy from either groundwater, sunlight, or wind to achieve typical ice removal or ice prevention tasks at lock and dam projects (Nakato et al. 1988). In general they found that there is very little promise in pursuing the development of the unconventional energy sources that were examined (groundwater, solar energy, or wind energy). The study concluded that none offered great promise over other more conventional means of ice control at locks and dams.

a. Groundwater heat. Heat energy in groundwater appears to be an attractive energy source. Groundwater is readily available in the vicinity of most rivers. Its temperature is generally near the average annual air temperature for any particular site, meaning that it is well above 0ºC (32ºF) for nearly all of the inland waterways of the conterminous United States. But the appeal of groundwater is diminished by practical problems involved in extracting and applying its heat, and by the fact that, in the colder areas where heat energy is needed most, the groundwater temperatures are lower. Several approaches for applying the heat contained in groundwater were investigated for preventing or relieving ice buildup on lock components. Both the method of whole-lock heating and the method of heating the water adjacent to the lock walls were ruled out almost immediately as requiring unreasonable amounts of energy. Only the method of circulating warm groundwater through pipes embedded in lock walls to raise the wall temperature was close to being practical. This approach features heating the mass of the walls first, which then lose the heat energy to the air. A significant drawback is that the mass of the walls absorbs so much heat as to make the approach unattractive.

Table 19-1
Energy Transferred by Groundwater to Lock Wall

Pipe Size cm (in.)	Flow per Pipe L/s (ft^3/s)	Energy Transferred in 61-m (200-ft) Pipe Run (kW)	Water Temperature at end of 61-m (200-ft) Pipe Run ºC (ºF)
2.5 (1)	0.63 (0.022)	37	0.1 (32.2)
2.5 (1)	0.95 (0.033)	57	0.2 (32.4)
5.1 (2)	2.52 (0.089)	136	1.2 (34.2)
5.1 (2)	3.79 (0.134)	200	1.4 (34.5)

(1) Assume that groundwater at 14ºC (57ºF) is flowing through an embedded pipe, and the pipe-wall temperature is constant at 0ºC (32ºF) throughout its length. This simulates the pipe being embedded in a lock wall that is massive compared to the pipe, and in the vicinity of 0ºC (32ºF) throughout its mass. Two sizes of pipe and two flow amounts for each size were analyzed. Table 19-1 shows how much energy is transferred from the groundwater to the surround-

ings of the pipe (i.e., the lock wall mass) in a pipe length of 61 meters (200 feet). Also shown is the temperature of the groundwater at the end of the 61-meter (200-foot) run.

(2) Note that the values in Table 19-1 are just to keep the pipe-wall temperature at 0ºC (32ºF). The real case would be to keep the temperature of the lock wall at or above 0ºC (32ºF); consequently, even larger flows and energy transfers would be needed. Depth of pipe embedment and pipe spacing would be important factors in determining how much larger the flows would have to be. Also, note that if the groundwater was at a lower temperature or moving at lower flow rates, or both, there could be danger of freezing near the end of a 61-meter (200-foot) pipe run. This would indicate the need for shorter pipe-run lengths.

(3) An operational application of embedded pipes would call for several parallel pipes running horizontally at the ice-collar location on the wall, each pipe run having a length of, say, 200 feet, and with the pipes being placed end-to-end with other pipes to cover the entire lock length. The example values above indicate that unless the groundwater temperature is very high, water temperatures decrease toward 0ºC (32ºF) too quickly (i.e., in too short a distance in the pipes) for this technique to be practical. It appears that other heat sources, such as steam or electric heating, may be more attractive for embedded wall heating systems.

b. Solar Energy. In general, the study found that the use of solar energy to assist in keeping lock and dam installations ice-free in winter was not practical. From assumptions based on using standard types of liquid-heating solar collectors, and three values of incoming solar radiation typical of clear-sky daily averages during winter in the Upper Mississippi and Ohio River basins, efficiencies and temperature increases in the heat-transfer liquid were calculated. Efficiency drops markedly as air temperature decreases. In addition, cloudy days, the requirements for storage of heat (to make it available when needed, such as at night), and the capital costs of very large collectors and associated equipment all would combine to discourage extensive consideration of solar energy for lock ice control, in view of the performance levels that can be anticipated.

c. Wind Energy. For most locations, normal fluctuations in wind make extraction of its energy unreliable unless some means of energy storage is available. Theoretically, the immediate power output (without storage) from a wind turbine is proportional to the third power of wind speed. Practically speaking, wind turbines often are subject to system controls to minimize the difficulties of extreme variability of power output. In any case, sample calculations illustrated the amounts of power potentially available from wind. For many locations on the inland waterways, an average winter wind speed may be represented by 14.5 km/h (9 mph). A wind turbine having 6.1-meter (20-foot) diameter blades and operating at 50 percent efficiency in this wind condition can generate an average power output of about 0.6 kilowatts, according to commonly used formulas. This means that five or six such wind turbines would be needed to provide power for continuous operation of the comparatively small (3.0 m^2 [32 ft^2]) lock-wall heating panels discussed in paragraph 18-16*b* and shown in Figure 18-12. As with solar energy, the variability of the energy source and the capital costs of the installations and equipment combine to make wind energy use for ice control at locks unattractive.

19-11. References

a. Required publications.

None.

b. Related publications.

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CHAPTER 20
Control of Icing on Hydraulic Structures

20-1. Introduction.

a. As described in Chapter 14, the ice-related problems at hydraulic structures are severe during winter months. Exposed mechanically operated systems, such as spillway gates, may be frozen-in and become inoperable. The weight of ice on structures that need to be moved (e.g., dam gates) may become excessive so that the lift system becomes overloaded. Ice loads can also cause structural damage. Icing on recess walls or gates of navigation locks prevents full use of the lock width. Ice buildup on dam pier walls can obstruct the movement of the components of the dam gate. Ice accumulation on water intakes, either municipal or hydropower, reduces the capacity to pass water through the intake, leading to water shortages or reduced power production. If the intakes become completely blocked, they may sustain structural damage. Ice buildup on walkways poise a safety hazard to personnel. All of these ice problems involve ice formation on or adhesion to critical surfaces on hydraulic structures.

b. Through careful consideration of the wintertime operation of a hydraulic structure, many icing problems can be eliminated during the design phase. For example, gate machinery and strut arm pivot points often can be relocated during the design phase to place them out of the water or splash zones, so that they do not become wetted and then covered with ice. Furthermore, icing of dam gates is often a result of small quantities of water leaking by seals. This is not an issue during warm conditions, but this small, steady flow of water can lead to sizeable ice accumulations in the course of just a few cold days (see Figure 20-1) rendering equipment inoperable until the ice is removed. Careful attention to seal design can help avoid these problems.

c. Unfortunately, not all of the icing problems can be designed out of a project, and some form of icing control needs to be employed to maintain winter operations. This chapter addresses several approaches to solving problems resulting from ice adhering to components on hydraulic structures. These include heating surfaces to prevent ice formation or reduce ice accumulation, improved sealing of gates, application of surface treatments to reduce the force required to remove ice from the surface, and mechanical methods for removing ice. Guidance for the design and installation of these systems is provided.

20-2. Heating of Components.

a. Introduction. The most reliable method for controlling icing is to keep the temperature of the surface to be protected above 0°C (32°F). This method is most effectively integrated into the hydraulic structures during the original design and construction of the project. Yet, there have been many successful retrofits of heating systems into existing structures.

(1) Heat has been used for years at hydraulic structures to control icing. Typical methods include steam lances, heat tracing embedded in concrete walls, and mineral insulated (MI) heaters installed under steel side-seal rub plates. Though these have proven effective, they all have demonstrated limitations. Steam lances pose the same problems as pike poles and other manual methods in that they are very labor intensive and slow, and they frequently place personnel in hazardous locations on the lock or dam. Placing heat where it is needed using heat tracing is desirable, yet the practice of embedding heat tracing in concrete typically provides only a short-term benefit, as the heaters burn out after relatively short service and cannot easily be replaced. Placing side-seal rub plate heaters that have replaceable electric elements on dam gates was beneficial, but the limited area that was heated did not entirely prevent the gates from freezing shut.

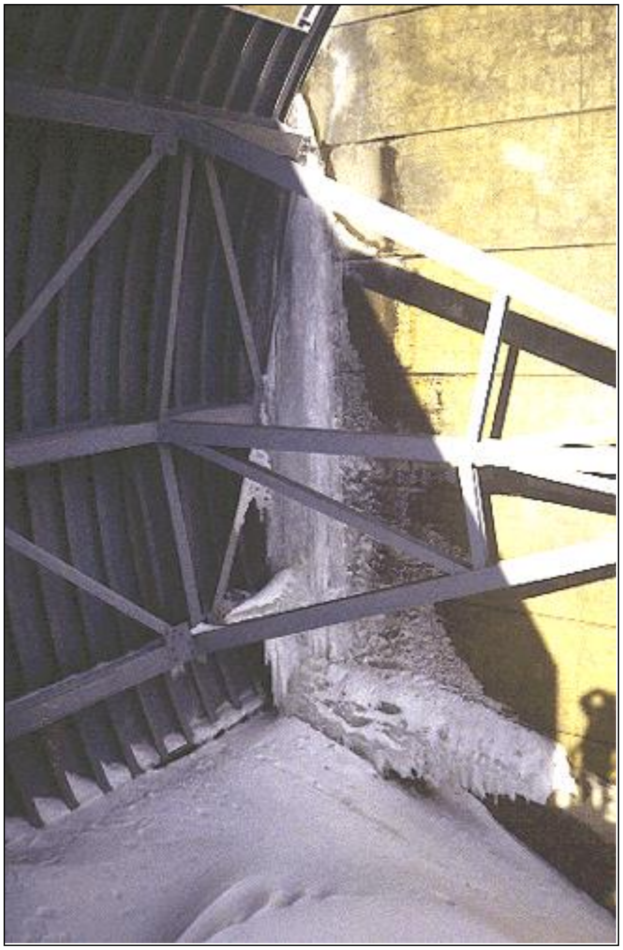

Figure 20-1. Column of ice formed on the downstream side of a tainter gate from water leaking past the side seal. The ice forms a bridge between the gate and pier. Such accumulations prevent movement of the gate. To restore normal gate operations, the ice needs to be removed by melting, chipping, or cutting. Photo of Gavens Point Dam, Yankton, SD.

(2) For example, Figure 20-1 shows ice accumulated on the downstream side of a tainter gate at Gavins Point in Yankton, SD. These gates had heaters to prevent the side seal from freezing to the steel rub plate. However, because of the low heat conduction of the surrounding concrete, the heat from the 10-kW elements remained confined to the vicinity of the rub plate. Water leaking by the side seal froze and then formed an ice bridge between the gate and pier wall, freezing the gate solidly in place. To prevent the gate from freezing, the heater needs to extend over an area large enough to melt most, if not all, of the ice off of the wall and gate. The enclosure for the heater must have high conductivity (e.g., that of aluminum or steel) so that the heat is distributed uniformly over the area. Furthermore, provision for easily replacing the heater elements when they fail must be designed into the enclosure. Heaters can be turned on in the fall and thermostatically controlled throughout the winter.

(3) This paragraph provides guidance for sizing of heater systems and basic design considerations for installing heaters in concrete walls, gates, sills, intakes, and other critical components.

b. Heater Sizing. Most of the surfaces that need to be protected from ice can be classified under three general categories: walls, gates, and intakes. What follows are basic design calculations for computing the heat loss associated with each of these three categories, which is then used to determine the minimum power required to protect the component from ice. The formulas presented provide an estimate of the heat loss for many situations but are not applicable to all situations. For complicated geometries, two- or three-dimensional heat transfer calculations may be required and computational methods, such as finite element codes, can be employed to determine the heat loss from the surface to be protected.

(1) *Walls*. Typically, it is the concrete walls of lock or dam piers that require de-icing. Ice accumulation on lock walls (Figure 14-4) are a result of fluctuating water level, resulting in a progressive thickening of the ice with each successive filling and emptying of the lock chamber. On dam piers, often leakage of water by the side seals of the gate result in long columns of ice forming a bridge between the gate and pier on the downstream side of the gate (Figure 20-1). What follows are design calculations for proper sizing of surface heater panels that can keep ice from forming on such concrete walls.

(a) The geometry of a typical heater panel installation is shown in Figure 20-2. The heat loss from a heating panel mounted on the surface of a wall is the combination of the convective heat transfer to the air and the conductive heat transfer into the wall. The heat panel source has to provide enough power to maintain the temperature of the surface above freezing despite these heat losses. The power requirements for the heating panel are simply the sum of these two losses

$$q_{\text{total}} = q_{\text{air}} + q_{\text{wall}} \tag{20-1}$$

where:

q_{total} = required heating power of the panel [W m^{-2}]
q_{air} = heat lost to the air [W m^{-2}]
q_{wall} = heat lost to the wall [W m^{-2}].

The heat loss to the air is computed from (in SI units)

$$q_{air}(\mathrm{W\ m^{-2}}) = h(T_{surface} - T_{air}) = h\Delta T = h27 \quad (20\text{-}2)$$

where:

T_{air} = ambient air temperature [°C]
$T_{surface}$ = surface temperature of the wall or heater panel surface temperature [°C]
h = average convective heat transfer coefficient [W m^{-2} K^{-1}].

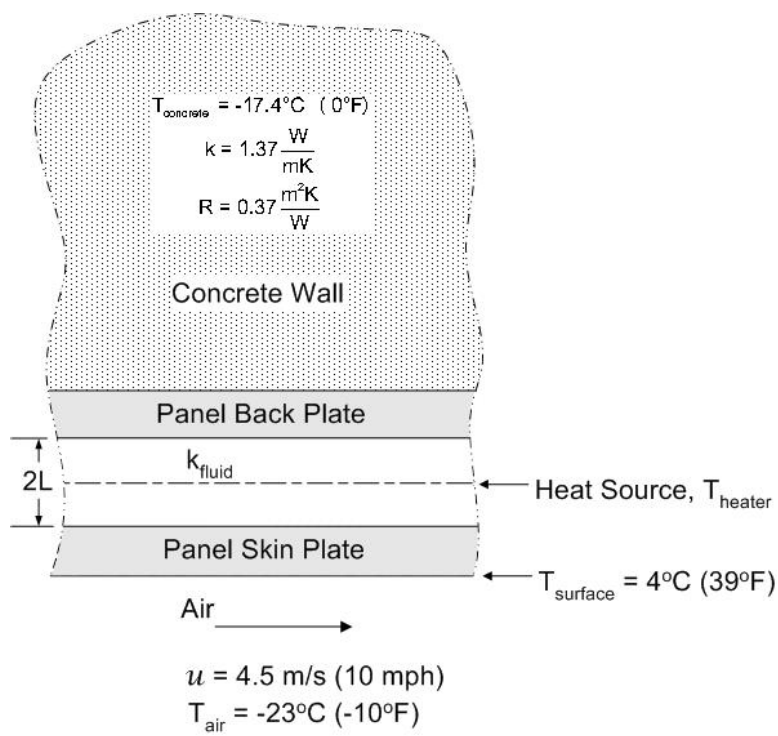

Figure 20-2. Geometry of a typical wall heater panel. The space between the skin and back plates of the heater is filled with a fluid with a thermal conductivity of kfluid. This fluid is commonly air, but can also be glycol.

(b) For design, the air temperature is taken to be –23°C (–10°F). For extreme conditions a lower air temperature may need to be used, yet within the continental United States this seems

adequate. The surface temperature is 4°C (39°F), yielding ΔT = 27°C. Ideally, it would be better to be able to maintain the surface temperature closer to the freezing point (e.g., 1°C); however, owing to uneven heating of the surface, there are quite often cold and hot spots on the heater panel. Experience has shown that designing wall heaters using $T_{surface}$ = 4°C keeps even the cold spots on the heater panel above freezing.

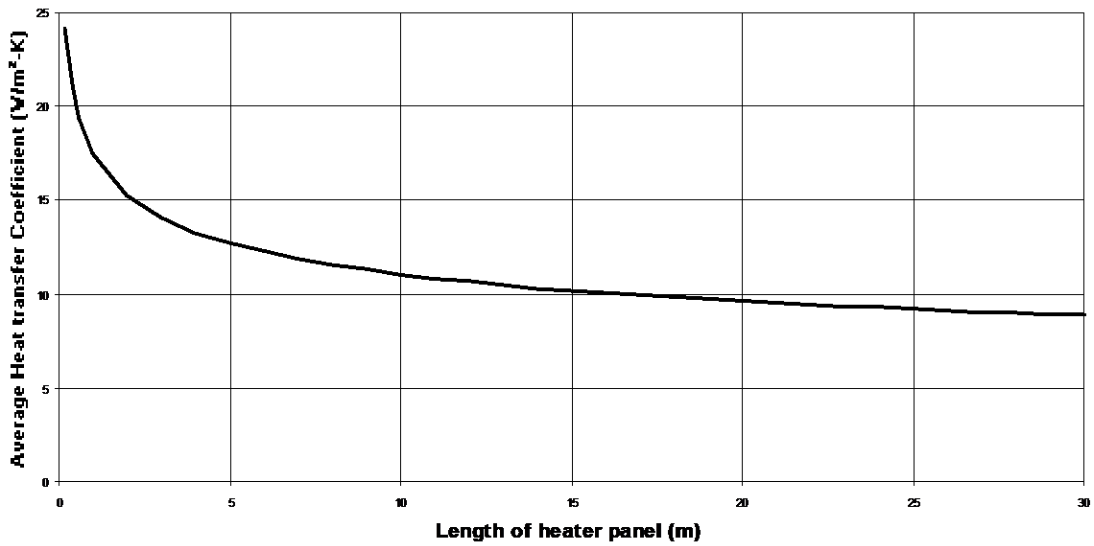

Figure 20-3. Estimate of average heat transfer coefficient in air from a flat surface as a function of the length (long-axis) of the heater panel based on the Chilton-Colburn Analogy. This is based on wintertime air properties of: air temperature –23°C (–10°F), Prandtl Number of 0.72, a kinematic viscosity of 1.14×10–5 m2/s, and thermal conductivity of 0.022 W/m K. For this chart an average wind speed of 4.5 m/s (10 mph) is used.

(c) Figure 20-3 gives approximate values of the average heat transfer coefficient, based on the design air temperature (–23°C) and a design wind speed of 4.5 m/s (10 mph), needed for computing the heat loss to the air using equation 20-2. In extreme climates, it may be desirable to use a higher value for the design wind speed, in which case the heat transfer coefficient in equation (20-2) can be computed from

$$h(\text{W m}^{-2}\text{K}^{-1}) = 0.0296 \frac{\left(\dfrac{ux}{v_{\text{air}}}\right)^{4/5} \text{Pr}^{1/3}\, k_{\text{air}}}{x} = \frac{5.26u^{4/5}}{x^{1/5}} \qquad (20\text{-}3)$$

where:

h	=	average heat transfer coefficient [W m^{-2} K^{-1}]
u	=	wind speed [m s^{-1}]
x	=	length of heater panel (long axis) [m]
v_{air}	=	kinematic viscosity of air (1.14×10^{-5} m^2/s)
Pr	=	Prandtl number for air (0.72)
k_{air}	=	thermal conductivity of air (0.022 W/m K)

Equation 20-3 is based on the Chilton-Colburn Analogy (which is a reasonable approximation of the average heat transfer coefficient over a flat plate) and was used to compute the curve given in Figure 20-3.

(d) To estimate the heat loss into the wall

$$q_{\text{wall}}(\text{W m}^{-2}) = \frac{T_{\text{heater}} - T_{\text{wall}}}{R_{\text{wall}}} = \frac{T_{\text{heater}} + 17.4}{0.37 + L / k_{\text{fluid}}} \tag{20-4}$$

where:

T_{wall}	=	the temperature of the concrete in the wall, -17.4°C (0°F)
R_{wall}	=	thermal resistance of the wall [m^2 K W^{-1}]
L	=	half the thickness of the fluid in the panel (Figure 20-2) [m]
k_{fluid}	=	thermal conductivity of fluid in the heater panel [W m^{-1} K^{-1}]

To use Equation 20-4, an estimate of the temperature of the heater needs to be obtained. Typically, the skin plate is made out of metal (aluminum or steel), so the thermal conductivity of these are much higher than the fluid and T_{heater} is approximately

$$T_{\text{heater}}(\text{C}) = T_{\text{air}} + \left(T_{\text{surface}} - T_{\text{air}}\right)\left(1 + \frac{hL}{k_{\text{fluid}}}\right) = -23 + 27\left(1 + \frac{hL}{k_{\text{fluid}}}\right) \tag{20-5}$$

where h is determined from Figure 20-3 or Equation 20-3. Values for the thermal conductivity of the fluid in the panel are given in Table 20-1.

Table 20-1. Values for the thermal conductivity of typical fluids in the heater panel.

Fluid	Thermal Conductivity, k_{fluid} (W/m K)
Air	0.026
Gycol	0.25
Water*	0.57

**Water may fill a panel immersed under water, but it is not recommended for a panel that may operate in air.*

(2) *Gates*. Another chronic problem arises when ice forms on a gate. This can freeze the gate in place so that it cannot be moved (see Figure 20-1) or a large amount of ice accumulates on the gate and increases the weight of the gate so that the lift machinery is overloaded. Also, ice collars can form on lock gates preventing the gate from fully recessing into the wall, thereby restricting barge width. The heat transfer for many of the situations where ice forms on a gate can be classified in two cases:

(a) Water on one side, air on the other.

(b) Similar fluid on both sides of the gate.

(3) In both of these cases only the situation where the gate is closed (the water velocity is less than 0.6 m/s [2ft/s]) is considered. The reason for this is the heat losses associated with water flowing over a heated surface (velocity greater than 0.6 m/s) are so large that operational costs associated with keeping the surface ice-free are prohibitive. Thus, the standard operating procedures for the heaters and gates should take into account that heaters will be ineffective when the gates are open. This will be discussed further in Paragraph 20-2b. In the following two subparagraphs, design calculations for sizing the heaters for closed gates are provided.

(a) Heat Loss from a Closed Gate, Water on One Side, Air on the Other. Figure 20-4 shows the basic geometry of a heater panel mounted on a closed gate. The total heat loss is the sum of the heat lost to the water and air

$$q_{\text{total}} = q_{\text{water}} + q_{\text{air}} \tag{20-6}$$

where:

q_{total} = required heating power of the panel [W m^{-2}]
q_{water} = heat lost to the water [W m^{-2}]
q_{air} = heat lost to the air [W m^{-2}].

(b) Using the design conditions of u = 4.5 m/s (10 mph) (wind speed) and an air temperature of –23°C (–10°F), the heat loss to the air can be computed using equation 20-2, where the heat transfer coefficient is determined from Figure 20-3. For conditions other than what is specified in Figure 20-3, the heat transfer coefficient can be determined from Equation 20-3. The heat loss to the water is computed from

$$q_{\text{water}} = \frac{T_{\text{heater}} - T_{\text{water}}}{\dfrac{1}{h_{\text{water}}} + \dfrac{L}{k_{\text{fluid}}}} \tag{20-7}$$

where:

h_{water} = heat transfer coefficient for water interface [W m^{-2} K^{-1}]
T_{heater} = temperature of heater plate [°C]
T_{water} = water temperature [°C]
L = half the thickness of the fluid in the panel [m]
k_{fluid} = thermal conductivity of fluid in the panel [W m^{-1} K^{-1}].

(c) The water temperature is 0°C (32°F); the heater temperature is determined from Equation 20-5 and k_{fluid} is given in Table 20-1. The heat transfer coefficient for the water is determined from

$$h_{\text{water}}(\text{W m}^{-2}\text{K}^{-1}) = 0.0296 \frac{\left(\dfrac{ux}{v_{\text{water}}}\right)^{4/5} \text{Pr}^{1/3}\, k_{\text{water}}}{x} = \frac{1060}{x^{1/5}} \tag{20-8}$$

where:

u = water velocity (0.6 m/s or less)
x = length of heater panel (long axis) [m]
v_{water} = kinematic viscosity of water (1.76×10^{-6} m^2/s)
Pr = Prandtl number for water (13)
k_{water} = thermal conductivity of water (0.57 W/m K).

Equation 20-8 is based on the Chilton-Colburn Analogy and provides a reasonable estimate of the average heat loss to the water.

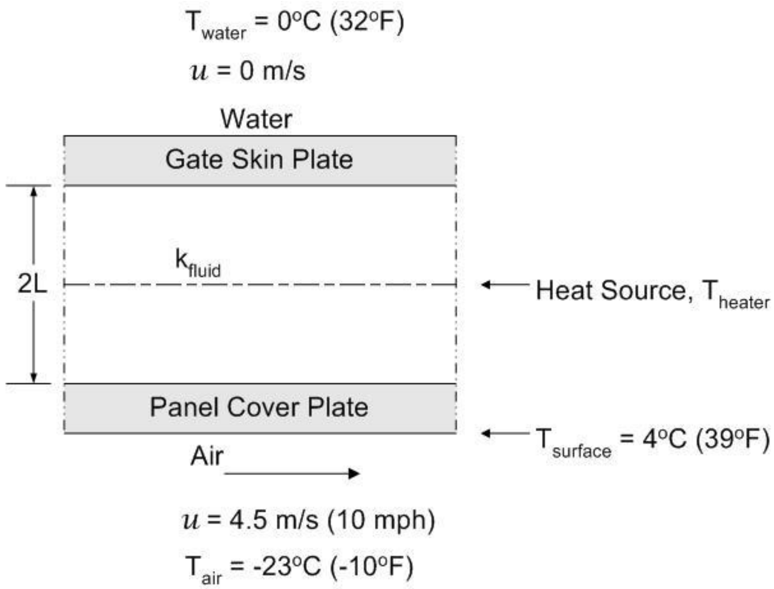

Figure 20-4. Geometry of a typical gate heater panel. The space between the panel cover and gate skin plates of the heater is filled with a fluid with a thermal conductivity of k_{fluid}. This fluid is commonly air but can also be glycol.

(d) Heat Loss from a Submerged Gate, Fluid the Same on Both Sides of the Gate. In some instances, ice will accumulate on a gate that is fully submerged in water (water is on both sides of the gate). This is usually the result of frazil ice being present in a river that becomes deposited on the gate and freezes the gate in place. Ice can also accumulate on a gate that, for part of the time, is partially submerged, and for part of the time, is in air. An excellent example of this is a lock miter gate, where the ice accumulates during cyclic filling and draining of the lock chamber. In this situation, the heaters may be used to shed the ice off of the gate while the chamber is empty and the gate is fully submerged in air. The heat transfer calculations that follow provide a means to determine the heat loss for these cases. A typical heater configuration for this situation is shown in Figure 20-5. The heat loss to the surrounding fluid can be computed from

$$q_{\text{total}} = 2q_{\text{fluid}} = 2h_{\text{fluid}}(T_{\text{surface}} - T_{\text{fluid}}) \quad (20\text{-}9)$$

where:

q_{fluid} = heat loss to surrounding fluid [W m^{-2}]
T_{surface} = surface temperature of skin plate, 4°C (39°F)
T_{fluid} = temperature of the surrounding fluid (water or air) [°C]
h_{fluid} = heat transfer coefficient for the fluid [W m^{-2} K^{-1}].

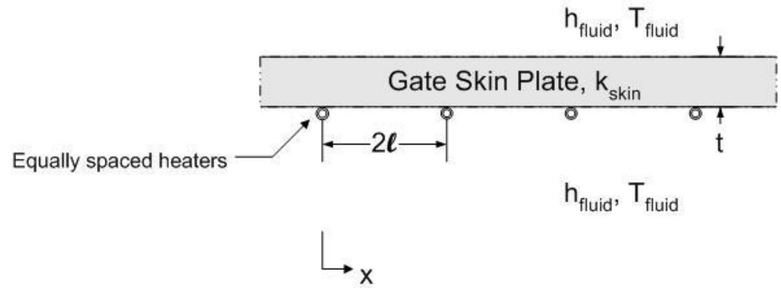

Figure 20-5. Heater configuration for a gate fully submerged in a fluid. The heaters are mounted to the back of the skin plate with a spacing of 2*l*. The heaters are treated as point sources.

(e) Again, the design temperature for the skin plate is 4 C°(39°F). The temperature of the fluid depends on the fluid type (water or air). Table 20-2 provides design temperatures for the fluid. For a panel operating in air, the heat transfer coefficient can be determined from Figure 20-3 or Equation 20-3; in water, the heat transfer coefficient can be determined from a modified form of Equation 20-8

$$h_{\text{water}}(\text{W m}^{-2}\text{K}^{-1}) = 0.0296\frac{\left(\dfrac{ux}{v_{\text{water}}}\right)^{4/5}\text{Pr}^{1/3}k_{\text{water}}}{x} = \frac{1590u^{4/5}}{x^{1/5}} \tag{20-10}$$

where:

u	=	water velocity (> 0.1 m/s or 0.3 ft/s)
x	=	length of heater panel (long axis) [m]
v_{water}	=	kinematic viscosity of water (1.76×10^{-6} m^2/s)
Pr	=	Prandtl number for water (13)
k_{water}	=	thermal conductivity of water (0.57 W/m K).

Table 20-2. Design values for the temperature and velocity for water and air.

Fluid type	Temperature, °C (°F)	Velocity, m/s (mph)
Water	0 (32)	Site specific
Air	–23 (–10)	4.5 (10)

(f) Equation 20-10 is based on the Chilton-Colburn Analogy. To use Equation 20-10, an estimate of the water velocity in the proximity of the gate is required. For velocities below 0.1 m/s (0.3 ft/s), a conservative estimate of h_{water} is obtained if u = 0.1 m/s is used. Generally, the water velocity is not zero in the vicinity of a gate because of turbulence from flow through adjacent gates or intakes, and wave action. An estimate of the water velocity near the closed gate can be made based on the average water velocity in the river on which the project resides. This can be determined from

$$u = Q_{winter}/A \tag{20-11}$$

(g) where Q_{winter} = winter time discharge on the river [$m^3\ s^{-1}$], and A = cross-sectional area [m^3] of the river at the project. Once an estimate of the heat loss at the gate is determined, the spacing and number of the heater elements can also be determined by treating the skin plate as a fin with point sources of heat spaced at regular intervals across the plate. The spacing of the heat sources needs to be close enough so that the dip in temperature between the sources stays above 0.5°C. The heater spacing, 2*l*, and size of individual heaters are both a function of the number of heaters on the surface of the skin plate, that is

$$Q = \frac{q_{\text{total}} WL}{N} \tag{20-12}$$

Q	=	size of each heater (W)
q_{total}	=	total heat loss from gate (W/m^2) (from eq. 20-9)
W	=	width of the heater panel (m)
L	=	length of the heater elements (or height of the heater panel) (m)
N	=	number of heaters in the panel.

The heater spacing is 2*l*, as indicated in Figure 20-5, and is determined from

$$l = W/(2[N+2]) \tag{20-13}$$

(h) In Equation 20-12, both Q and N are not known and need to be iteratively solved for. To do this a constraint on the spacing has to be applied to assure the minimum temperature on the panel surface is at or above 0.5°C. This constraint is applied by understanding that the basic heat transfer equation for this geometry is a fin of length, *l*, with the tip of the fin having an adiabatic boundary condition and the heat source is located at the root of the fin (i.e., the fin has periodic symmetry about the tip and root). Applying the analytical solution for a fin of this geometry, one can use the following iterative procedure to determine Q, N, and l:

- Step 1. $$m = \sqrt{\frac{h_{\text{fluid}} P}{k_{\text{skin}} A}} \tag{20-14}$$

where:

h_{fluid} = convective heat transfer coefficient [W m^{-2} K^{-1}]
k_{skin} = thermal conductivity of the skin plate (or fin) [W m^{-1} K^{-1}]
P = perimeter of the fin section = 2(L+t) [m]
A = area of the fin section = Lt [m^2]
t = thickness of skin plate [m].

- Step 2. Make an initial guess for *l*. A good starting point is around 0.2 m (0.7 ft).

- Step 3. $N = W/(2l) - 2$ (20-15)

- Step 4. Solve for Q using Equation 20-12.

- Step 5. $$T_{\text{b}} - T_{\text{fluid}} = \frac{Q}{\sqrt{h_{\text{fluid}} P k_{\text{skin}} A}\ \tanh ml} \quad (20\text{-}16)$$

where T_{fluid} = fluid temperature, and T_{b} = temperature at the root of the fin.

- Step 6. $$T(l) = T_{\text{fluid}} + (T_{\text{b}} - T_{\text{fluid}})\frac{1}{\cosh ml} \quad (20\text{-}17)$$

where $T(l)$ = temperature on the skin plate at a distance *l* from the heater.

- Step 7. Check to see if $T(l)$ =0.5°C. If it is less than 0.5°C, *l* needs to be reduced, if it is greater than 0.5°C, *l* needs to be increased.

- Step 8. Continue Steps 2 through 7 until the condition at Step 7 is satisfied.

(i) Following this procedure does not provide a unique combination of *Q*, *N*, and *l*. However, the size of the heater, *Q*, is limited by what is available in the market, so choice of *l* must be controlled to give a *Q* that can be supplied by available heating equipment. As a starting point heaters that provide 1 kW/m (0.3 kW/ft) or more are commonly available. However, consultation with heater vendors is advised to get a more accurate determination of available heater capacity.

(4) *Intake Trash Racks*. Frequently, frazil ice accumulates on intake trash racks for municipal water or power tunnel intakes. This can reduce the flow through or completely block the intake. Figure 20-6 shows the basic geometry of a typical trash rack configuration on an intake.

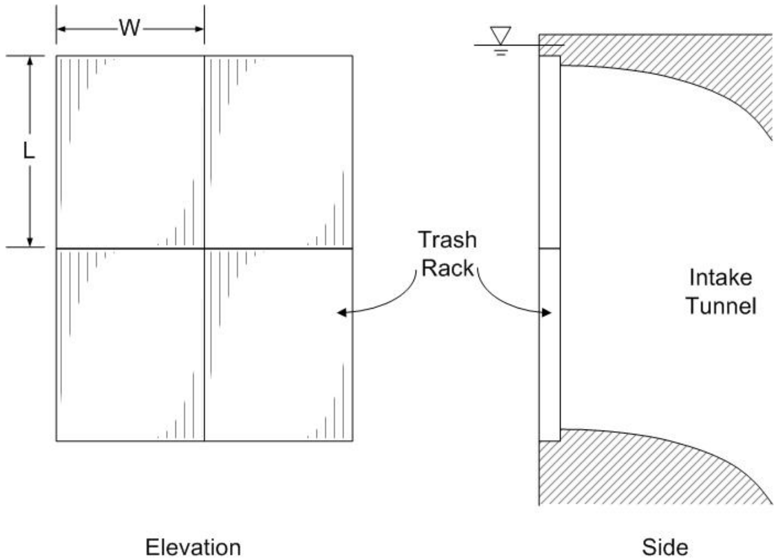

Figure 20-6a. Typical trash rack configurations. An intake with trash racks covering the opening.

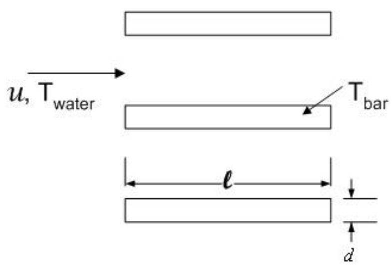

Figure 20-6b. Typical trash rack configurations. Detail of the fluid flow and heat transfer conditions around the individual bars on the trash rack.

(a) Logan (1974) provides an analysis of the heat needed to keep the trash rack bars free of frazil ice accumulations and is summarized here. The heat loss, Q, from the bars is computed from

$$Q = hPL(T_{\text{bar}} - T_{\text{water}}) \tag{20-18}$$

where:

Q = heat loss [W]
h = average het transfer coefficient [W m^{-2} K^{-1}]
L = length of the trash rack bar [m]
P = perimeter of the cross-section of the bar, $2(d + l)$ [m]

l = width of trash rack bar [m]
T_{bar} = temperature of the bar (0.5°C)
T_{water} = water temperature (0°C).

(b) The required heat transfer coefficient, h, is determined from

$$h(Wm^{-2}K^{-1}) = 0.6\frac{k_f}{d}\sqrt{\frac{ud}{\nu}}\,\mathrm{Pr}^{0.31} = 551\sqrt{\frac{u}{d}} \tag{20-19}$$

where:

k_f = thermal conductivity of water at the freezing point (0.55 W m^{-1} K^{-1})
d = thickness of the trash rack bar [m]
Pr = Prandtl Number (13)
u = water velocity [m s^{-1}]
ν = kinematic viscosity of the water (1.76×10^{-6} m^2 s^{-1}).

(c) The water velocity, u, passing through the trash racks is on average

$$u = Q_{intake}/(ML[W\text{-}dN]) \tag{20-20}$$

where:

u = water velocity passing through trash rack [m s^{-1}]
Q_{intake} = volumetric flow rate through the entire intake [m^3 s^{-1}]
M = number of trash racks covering the intake
L = height of an individual intake trash rack [m]
W = width of an individual trash rack [m]
N = number of bars in an individual trash rack
d = thickness of bars [m].

(d) Using Equations 20-17 through 20-19 allows the heat required to keep ice off of a single trash rack bar to be determined. The heat required for the entire intake is

$$Q_{total} = NMQ \tag{20-21}$$

(5) *General Remarks*. Table 20-3 lists typical power requirements, based on data obtained from heaters that are in service. This provides a rough guide for the power needed for the various applications described above. Also given in Table 20-3 is an estimate of the energy consumed for each ice shedding cycle, based on it taking approximately 15 minutes from the time the heaters are turned on until the ice releases from the surface. This is important as it gives an indication of the operational cost (i.e., the cost of fuel or electricity needed to operate the heater panels).

Table 20-3. Power and energy requirements for complete removal of ice using various heather types (after Haehnel et al., 2002).

Heater type	**Power density (kW/m^2)**	**Energy density (kJ/m^2)**	**Approximate response time (min)**
Wall heater panels on riverine structures (in air)[1]	0.6–0.7	540–630	15
Heater panels on riverine structures (immersed)[2]	4.5	3900	15
Trash rack heaters (immersed)[3]	2–6.7	—	Used in continuous anti-icing mode

[1]Haynes et al. (1997), Bockerman and Wagner (1998).
[2]Haehnel and Clark (1998).
[3]Billfalk (1987), Reid (1928), Samsioe (1924), Ruths (1924), Logan (1974), Daly et al. (1992).

c. Heater Design.

(1) *General Design Guidance*. It is also important to make provision for the heaters to be serviceable. The use of embedded electrical heaters that cannot be removed for replacement without major rehabilitation is *not recommended*. Almost every navigation project that has installed embedded electrical heaters has some heaters that have failed and cannot be replaced. Some approaches to providing replaceable heaters are described in the following subparagraphs.

(a) In some cases, the heaters can only be replaced by divers. When this is true, the heaters need to be easily accessible and require that little dexterity is necessary in doing the replacement. Consideration should also be given to having the same size fasteners for cover plates and heater clamps, so the divers need only use one size wrench to replace all of the heaters. Furthermore, the heater enclosures should be designed to provide easy access to the heaters once the covers are removed.

(b) Another consideration when designing for replaceable electrical heater elements is the routing of the power feed cables and location of junction boxes. Careful consideration needs to be given to this to make sure that the junction is above the water line and that feeding the cold leads in and out of the conduits is easily done.

(c) Another consideration is the type of material used in the heater assemblies (i.e., aluminum vs. steel). The conductivity of aluminum is significantly higher than steel and will allow the individual heater elements to be spaced further apart and still provide uniform heat on the surface to be protected. For example, in one application, by using an aluminum cover plate, the heaters could be spaced 15 inches apart, while a steel plate of the same thickness required a

heater spacing of 2.5 inches. Yet, thicker aluminum plates are required to provide the same structural integrity as steel plating. Thus, careful consideration of the type of material used and the environment it is being subject to is required to balance these design considerations.

(d) Paramount to designing an effective icing control system is identifying where the ice may form and how it will affect operations. This allows identification of where heaters are needed and the size of the area that needs to be heated. In the case of existing projects, this is generally easy to determine by inspection. However, for submerged components (e.g., tainter valves), it is more difficult to determine where heaters will provide the greatest benefit as the locations where the ice forms cannot be viewed during normal operations. Furthermore, in the case of new projects, it is often difficult to assess in advance where ice will form and how it will affect operations. Yet, from experience several chronic problem areas have been identified and are as follows:

- Tainter gate side-seal or rub plate and pier or lock walls.
- Trunion arm.
- Gate skin plate.
- Intakes.

(e) The following subparagraphs address basic design considerations for protecting these components with heaters.

(2) *Rub Plate and Wall Heaters*. It is preferred that rub plate heaters be imbedded in the walls so that they are flush with the surrounding concrete. If it is necessary for these panels to be surface mounted (i.e., retrofitted to a project), special consideration needs to be given to avoiding the forces of debris, water, ice, barges, etc., that can tear the panel off the wall.

(a) For tainter gates that have water on the upstream side and air on the downstream side, ice columns, as depicted in Figure 20-1, frequently form because of the water leaking past the side seal. The heater needs to be wide enough to melt the ice adhering to the pier wall. In the case of retrofits, the required width of the heater panel can be estimated from photographs such as Figure 20-1 or from actual measurements made on the structure. For new construction, it is difficult to estimate in advance how wide the ice column will be. Experience has shown that generally the heater panel needs to be at least 1.2 m (4 ft) wide and, for new construction, it is recommended that the heater panels be at least this wide, i.e., the heater should extend 1.2 m downstream of the side seal and follow the arc of the gate from the water level to the bottom of the gate as shown in Figure 20-7. Figure 20-8 shows a sketch of the cross-section of a heater panel embedded into a pier wall. The faceplate serves as both a rub plate and a heat conduction path to uniformly distribute the heat over the area to be protected. The use of rigid conduit for housing the heater elements is consistent with established practice for rub plate heaters used on existing projects. However, in Figure 20-8 the heated area is increased to eliminate, not only the ice in the immediate vicinity of the side seal, but also the entire width of the ice column.

(b) A removable cover plate should be provided at the bottom of the conduit to facilitate access to the bottom of the heaters in the rare event that the heaters burn in half and the lower part of the heater needs to be pulled out from the bottom. Consideration needs to be given to whether or not the cover plate at the bottom of the heater conduit will be sealed or not, and if it is not sealed, whether or not it is open to the downstream side (tail water) or upstream side. If the bottom is sealed or open to the tail water, the heater must be designed to operate in air. If the bottom is open to the upstream side, the heater can be specified as an immersion type because the pipe will be filled with water. If the bottom remains open so that water can fill all or part of the pipe, care must be taken to assure that the heaters remain on throughout the winter months and that the temperature in the pipe is maintained above the freezing point to prevent the possibility of water freezing and expanding in the conduit and damaging the conduit, rub plate, or surrounding concrete. This requires continuous monitoring of the heater operation through the winter and the capability to detect a burned-out heater and rapidly replace it.

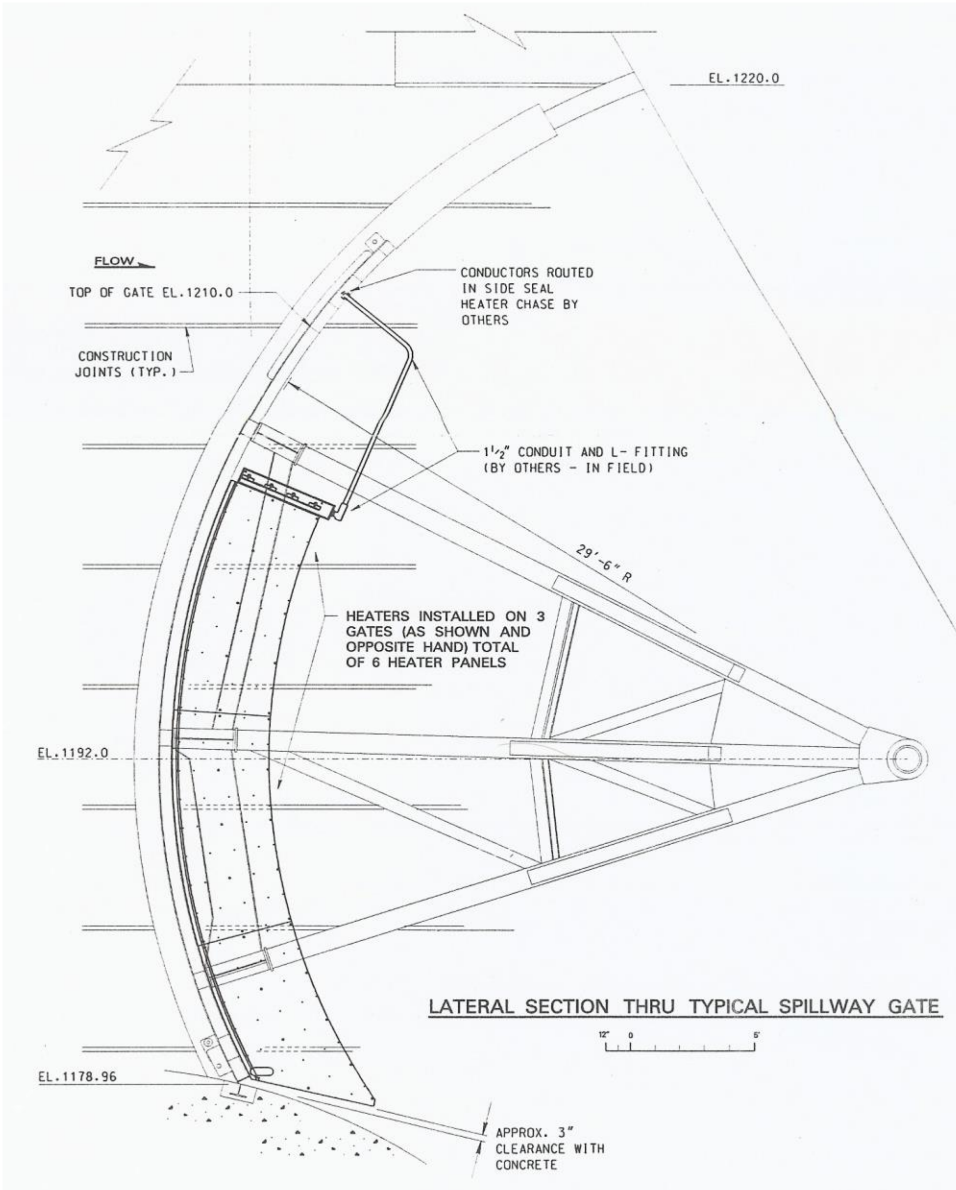

Figure 20-7. Heater panel installed on the pier wall just downstream of the rub plate on the Gavins Point Dam, Yankton, SD (Bockerman and Wagner, 1998).

(c) No insulation is put in the wall for this application. The thermal conduction of the concrete behind the heaters is quite low and comparable (within an order of magnitude) to typical insulations. In this application, the added benefit of using additional insulation—beyond what the concrete provides—is not offset by the added complexity of inserting insulation into the pier wall.

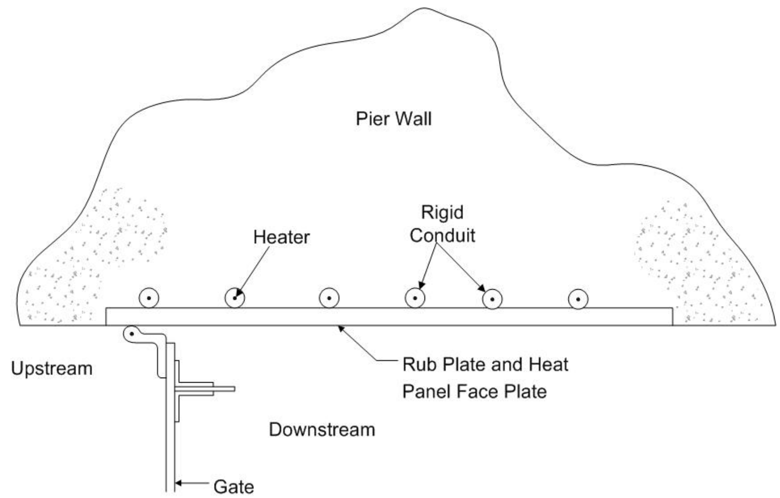

Figure 20-8. Cross-section of a heater panel embedded into a pier wall.

(d) For gates that are fully submerged in water, as shown in Figure 20-9, frazil ice can collect and bridge between the upstream side of the skin plate and rub plate. The heater geometry depicted in Figure 20-8 can be used in this case as well, with the exception that the faceplate extends upstream of the gate rather than downstream. The length of the heater area generally does not need to be as long in this situation as the frazil does not tend to form columns of ice that extend several feet up the wall; rather, the ice bridge formed by frazil is more local and extending the face plate 0.3 to 0.5 m (12 to 18 in.) upstream of the seal should be adequate.

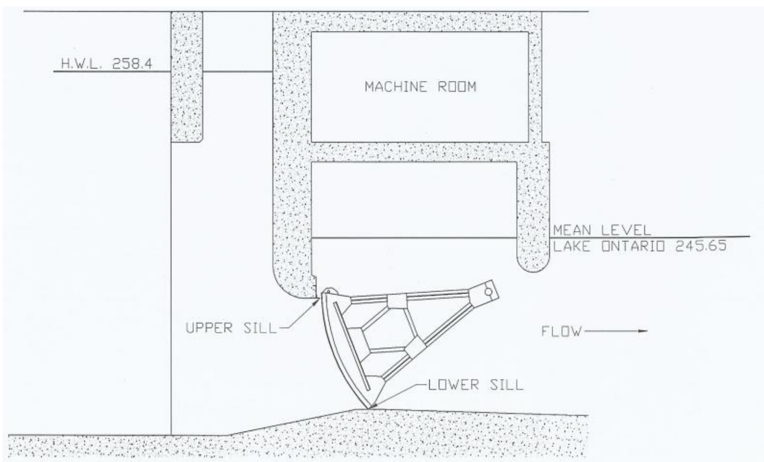

Figure 20-9. Submerged tainter gate (Haehnel and Clark, 1998).

(e) There are many areas where heating of the concrete wall is desirable, such as lock walls and gate recesses, to shed ice that has accumulated on these walls, thereby inhibiting normal operations. As with rub plate heaters, it is preferred that wall heaters be imbedded in the walls so that they are flush with the surrounding concrete. If it is necessary for heater panels to be surface

mounted to the wall, special consideration needs to be given to avoiding the forces of debris, water, ice, barges, etc., that can tear the panel off the wall. The heat required for this application can be determined using the calculations outlined earlier.

(f) The recommendation for those areas where embedded electrical wall heaters are needed is a replaceable heater element as described here. During a rehabilitation project, where the concrete walls are to be resurfaced, 1.9-cm-diameter (3/4-in.-diameter) stainless steel pipes can be installed, 15 to 20 cm (6 to 8 in.) on center, with the bottom ends sealed (similar to the geometry shown for rub plate heaters in Figure 20-8). At the top of the pier or along the top of the wall, the top ends of the pipes are accessible so that electrical leads can be run from one vertical pipe to the next. The tubes may be filled with glycol to act as a heat-transfer fluid, once the heater element is inserted into the pipe. However, use of glycol is not always permitted by environmental concerns. Alternate techniques of installing the pipes are by drilling vertical holes along the edge of a pier or wall (however, a major concern is the possibility of the hole breaking out) and by cutting vertical slots 7.5 to 10 cm (3 to 4 in.) deep in the wall, and then grouting the pipes into the wall.

(g) Consideration should be given to thermally linking the pipes together via a surface mounted plate as shown in Figure 20-8 for rub plate heaters. This will provide more uniform heating of the wall surface and more reliably shed the ice from the wall. Without this, the heater spacing needs to be very small to avoid hot and cold spots on the wall.

(3) *Trunion Arm Heaters*. Ice that bridges between the trunion arm and pier wall can be mitigated with heaters mounted directly on the trunion arm. The location of the heaters should span the length of the trunion arm that may be submerged (either while the gate is opened or closed) during the winter months. A sketch of the construction of such a heater is shown in Figure 20-10. The heaters used for this must be designed to operate both in and out of water (waterproof, non-immersion heaters). The heaters can be either MI cartridge heaters or heat cable. Use of a closed-cell foam insulation as indicated will minimize the heat conduction away from the heated face of the arm and help to reduce the power consumption during heater operation.

(a) The heat transfer requirements for these heaters are very similar to other heaters in service on lock and dam walls in the United States, as described in Haehnel et al. (2002). Based on this work, heating requirements of 4.5 kW/m2 are sufficient for submerged applications, which is consistent with the trunion arm heaters described in Haynes et al. (1997).

(b) The heater element can be held in place using suitably sized EMT (electrical mechanical tubing) clamps (or some equivalent clamping device). The cover plate should be removable to allow easy service and replacement of the heater elements.

(c) The power supply cable for these heaters can be routed up the trunion arm and pier wall

to a common start/stop station. The cable should be housed in rigid conduit along the trunion arm and pier wall; flexible conduit will need to be used to transition from the conduit on the trunion arm to the conduit on the pier wall.

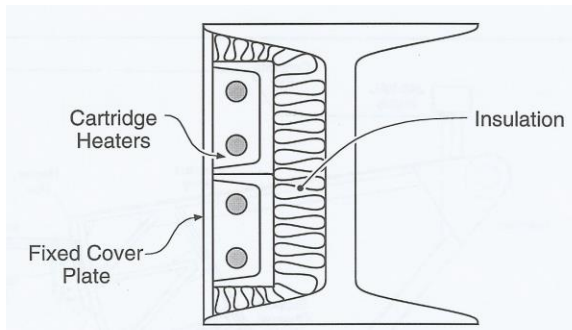

Figure 20-10. Heater construction for a trunion arm. The heater cover plate faces the pier wall (after Haynes et al., 1997).

(4) *Skin Plate Heater*. For a submerged gate, as depicted in Figure 20-9, frazil ice can accumulate on the gate skin plate and cause bridging of ice between the upstream side of the gate and pier walls. This can be eliminated using a skin plate heater system. The heating requirements can be determined using the analysis given in Paragraph 20-2*b*(2)(*b*), and Table 20-3.

(a) Figure 20-11 provides sketches of two possible heater configurations for skin plate heaters. In Figure 20-11a, the heater is shown to follow the arc of the gate skin plate and is housed in square tubing. Mounting the heaters vertically on the gate facilitates easy removal and replacement when the heaters need to be serviced; the heaters are simply withdrawn from the top of the gate. The tubes are not sealed at the bottom; this allows water to come up into the tubing. It is recommended that a removable stop be installed at the bottom of the tubing to prevent the heater from dropping out the bottom of the gate. There should be a gap of 0.8 to 1.3 cm (0.3 to 0.5 in.) between the bottom of the tubing and the stop to allow water to flow into and out of the tubing. The stop will help prevent the bottom of the heater element from being buffeted by turbulent flow and debris as well. This stop can be removed to allow extraction of the heater from the bottom if the heater fails midway and burns in half. Though this rarely happens, it is difficult to extract the lower section of the failed heater if some provision is not made to do so. To facilitate this the bottom of the tubing needs to terminate 8 cm (3 in.) or more from any obstruction (e.g., I-beams or other structural elements) located at the bottom of the gate to give room enough to bend and pull the heater element out the bottom of the tubing.

(b) The heater arrangement shown in Figure 20-11b works well when there is a large area free of structural reinforcing on the backside of the skin plate. The heater is held in place with EMT (or similar) clamps and covered with a back plate (not shown) to protect the heater element from debris and water turbulence.

(c) The routing of the power supply cable is sketched in Figure 20-11 as well, indicating an approximate routing of the cable, from the face of the gate to the upper trunion arm. From there, the cable would be routed along the pier wall to a start/stop station at the top of the pier. It is anticipated that the cable will be housed in rigid conduit mounted on the trunion arm and pier wall. However, to allow for rotation of the gate about the trunion, a flexible section of conduit will be needed to transition from the trunion arm to the pier wall.

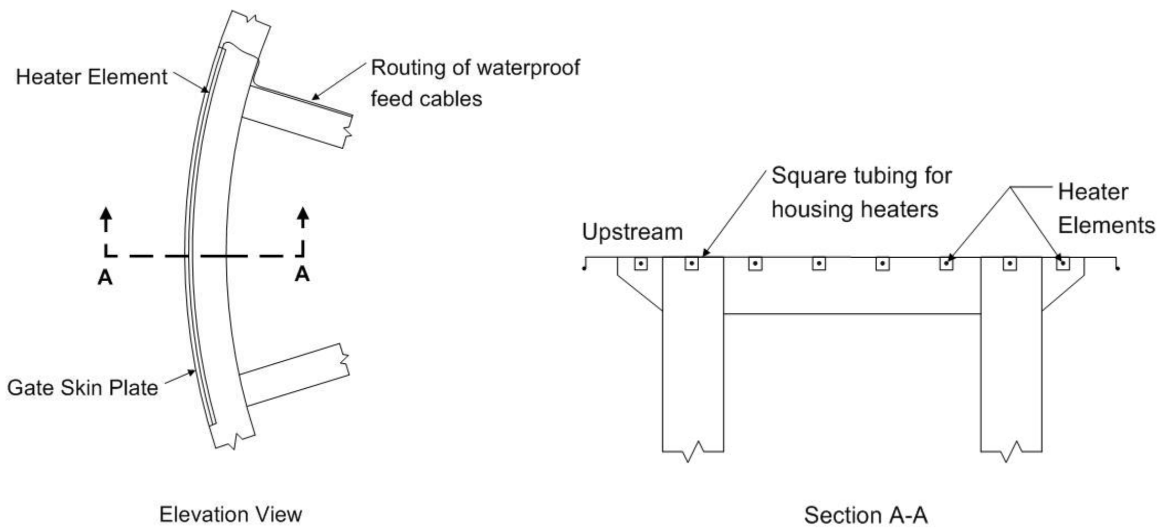

Figure 20-11a. Two skin plate heater designs. Heater elements housed in square tubing bent to follow the arc of the gate.

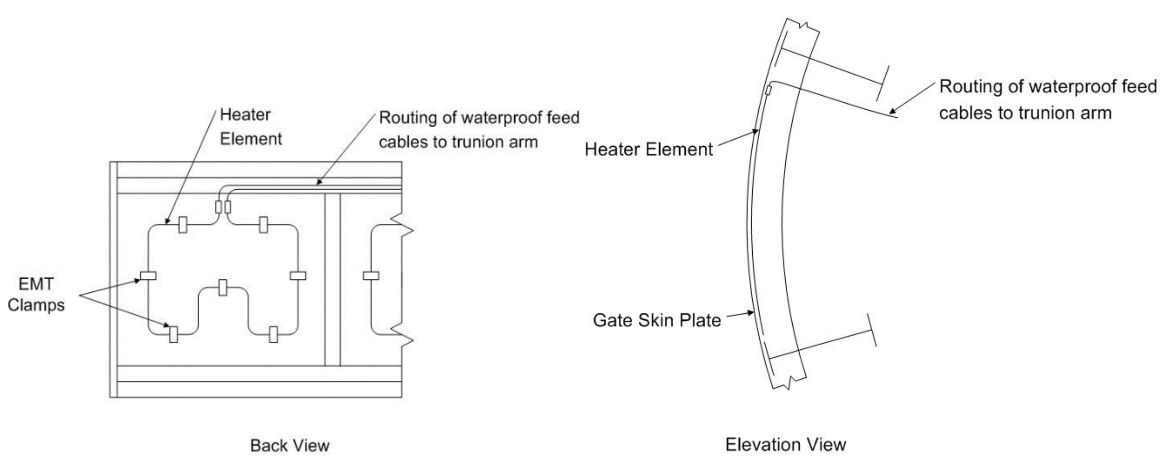

Figure 20-11b. Two skin plate heater designs. Heater elements attached to the downstream side of the skin plate using EMT clamps.

(d) Careful consideration needs to be given to the type of heater (immersion or non-immersion) for this application. If the heaters will operate only while the gate is fully submerged (e.g., the geometry shown in Figure 20-9), then immersion type heaters are appropriate. If this is the case, a safety switch should be included in the control circuit to disable the heaters if the gate is brought above water level. In some applications, the heaters may be required to operate while they are only partially submerged. In this case non-immersion, waterproof heaters must be used.

(5) *Intake Trash Racks*. Historically, the most effective method to eliminate ice accumulation on trash racks is to discharge warm water just upstream of the intakes. This keeps the water from being supercooled when it enters the intake, allowing the frazil to pass through the intake without sticking to the bars. The most efficient way to do this is to use waste heat (e.g., discharged cooling water from an industrial or power plant) to heat the water upstream of the gate. Barring the availability of waste heat to prevent icing on the trash rakes, heating the trash rack bars themselves is an effective way for preventing frazil ice buildup. Daly et al. (1992) show that this can be done by placing heaters on the leading edge of the bars, as shown in Figure 20-12. Paragraph 20-2*b*(3) and Table 20-3 can be used to determine the heater size required for this application.

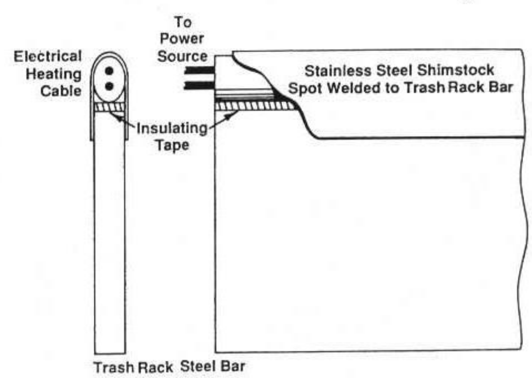

Figure 20-12. Intake trash rack heater system (after Daly et al., 1992).

(a) The specified heater diameter needs to be small enough to allow the heater to be slid in and out of the spacing between the shimstock sheathing and the trash rack bar. This allows for replacement of failed heaters without overhauling the trash racks. The shim stock needs to be thick enough to withstand damage from ice, debris, and normal operations. Field tests used sheathing that was 0.25 millimeters (0.01 inch) thick (Daly et al., 1992). Special consideration needs to be given to routing of the cable bundle from the top of each trash rack section to the top of the intake because, for a sizable intake, there may be several hundred individual heaters mounted on the trash rack. One method is to route the cable bundle to the top of the wall through a steel electrical cable raceway recessed into the wall. This raceway may need to be specially designed for this to allow its cover to be removed and the cable installed without having to unscrew the cover from the raceway. One possible approach is to make a cover that slides in a grove over the raceway, such that it can be removed from the top of the intake.

(b) Also, special consideration needs to be given to the cables exiting the top of each bar and then being routed back along the top of each trash rack section so that the cables are not exposed to the buffeting of the turbulent flow through the intake, or debris striking the intake. Also, if trash rack rakes (described in Paragraph 20-5*c*) are to be used the cables need to be routed such that they will not interfere with drawing the rakes up the full length of the trash rack assembly.

(c) Generally, these would be immersion type heaters. However, in some cases, the top foot or more of the intake may be above the water line. To avoid this condition, it is suggested that in new construction, the elevation of the intake be below the water elevation. If these heaters are to be applied to an existing intake, it may be necessary to have waterproof, non-immersion heaters at the top of the intake, and immersion type heaters in the remaining part of the intake.

(d) The total heat requirement to run all of the heaters mounted on a trash rack can be on the order of 1 MW or more. Thus, it is recommended that these be used only when there is a threat of frazil ice blocking the intakes, which is when the water temperature is below freezing. To determine when the water is supercooled requires very precise temperature measurement (to only –0.01°C), so typically the water temperature is not monitored that closely, rather the heaters are thermostatically controlled to come on when the water temperature drops below 0.1°C.

d. Operational Guidance.

(1) *Gate Freeze-up*.

(a) It must be noted that the gate heaters are sized for when the gate is closed. Once the gate is opened, the heat loss increases dramatically owing to the high flow through the gate. This may result in the gate freezing in place once opened, because the heaters cannot keep the gate warm enough. Thus, it is recommended that if spillway gates need to be used when the air temperature is below freezing, that they be lifted completely out of the water. Then, once they need to be closed, they must be completely closed, so that the heaters can effectively keep the gate ice free.

(b) Alternately, the gates may be "exercised" once they are open to prevent substantial ice accumulation from building up and bridging between the gate and pier wall. This requires the gate be moved at least hourly so that hoists can break free the small amount of ice that accumulates while the gates are stationary.

(2) *Intakes*.

(a) If the intake is for the power tunnel of a hydroelectric plant, it is important to consider safety regarding operating the turbines when there is a potential for frazil ice in the river. Frazil ice can stick to the trash rack bars and form an ice bridge across the bars reducing or completely stopping the flow through the trash racks. If this were to occur, the differential head across the

track rack can be sufficient to cause it to fail. It is advisable that the trash racks be designed to not fail if they become fully blocked leaving, only air inside the power tunnel and water on the other side, so that in the event that they become fully blocked by frazil ice they will not fail and cause damage to the intake, wicket gates, or turbine.

(b) It is also advised that the differential pressure head across the trash racks be measured at all times. Provided they are not blocked, the differential head will be zero. As the trash racks become blocked by frazil, the differential head will increase, indicating that a problem is developing and that action needs to be taken to prevent further ice accumulation.

(3) *Heater Controls*. In the control circuit, timers and thermostats can be added to limit power consumption. It is recommended that the heaters be thermostatically controlled to minimize power usage, which requires the temperature sensors (e.g., RTD type) be located on or near the heaters and controllers that will accommodate temperature feedback control.

(a) For gate and wall heaters, the temperature sensors are typically located between heater elements and mounted on the surface to be protected by the heaters. These sensors need to be located about midway along the length of a heater element so that the measurement is representative of the general temperature distribution on the surface to be protected. These also should be housed in a conduit to allow replacement when they fail. For the trash rack heaters, the temperature sensor should be located in the water with the cable in protective conduit and the sensor head protruding into the flow.

(b) Surface mounted RTD sensors should be used for the skin plate and trunion arm heaters. These may conveniently be held in place with a threaded fastener. For the rub plate heaters, a cartridge style RTD may be more suitable. This can be slid into a conduit embedded in the wall.

(c) For intake trash rack heaters, a cartridge type RTD sensor may be used. It can be housed in a rigid conduit that extends down into the water flow. The conduit serves to protect the sensor and cable from debris damage. The tip of the RTD sensor can protrude out the end of the conduit into the water and is held in place with a water-tight cable clamp. It is recommended that water not be allowed to get into the conduit as it may rupture the conduit when it freezes. The conduit housing the RTD sensor can be fastened to the concrete wall that is adjacent to the intakes.

(d) It is not always necessary to run heaters continuously. Often the needed benefit can be achieved by cycling though the heater banks at regular intervals to shed the ice that has accumulated in the intervening time. This requires breaking the heater system into logical subsections that can be controlled through a timing circuit. Set up in this manner, the entire heater system not only requires less power, but also less energy, while still providing the desired protection.

(4) *General Guidance*. Some heater manufacturers recommend that electrical heaters remain on year-round when they are in air to prevent excessive moisture from building up on the heaters and causing oxidation and corrosion. Using thermostatic control, the power required during the summer months to keep the heaters dry will be substantially reduced. If the heaters are cycled off, the manufacturer recommends that they be brought back online in stages, rather than bringing them up to their rated output all at once.

(a) As the cold leads for the heater elements are all terminated in a start/stop station enclosure (located in a machine room), the condition of the heaters can be readily evaluated from top side by checking the electrical resistance of the heaters using an ohmmeter, to detect an open circuit, or current meter, to determine if the heater performance has degraded. In the former case, the heater has completely burned out and the circuit is open, which can be detected with an ohmmeter. More often heater performance degrades over time, which can be monitored by measuring the current drawn by the heater. At the rated current, the heater puts out the rated heat capacity. As the current draw of a heater decreases, so too does the heater output, and the heater system will no longer be able to keep the surface it is protecting ice free. Because the current draw of a heater element is directly proportional to the heat given off, one can estimate the reduction in heater performance by

$$Q_{\text{actual}} = Q_{\text{rated}} \frac{A_{\text{measured}}}{A_{\text{rated}}} \qquad (20\text{-}22)$$

where:

A_{measured} = measured current draw of heater [amps]
A_{rated} = rated current of the heater [amps]
Q_{rated} = Rated heat output of the electrical heater element (W)
Q_{actual} = Actual output of the heater element (W).

If the heater capacity is over-designed by a factor of S, then the element needs to be replaced when

$$\frac{A_{\text{measured}}}{A_{\text{rated}}} \leq \frac{1}{S} \qquad (20\text{-}23)$$

where S = factor of safety for heater system.

(b) The cold leads for electrical heaters must be clearly marked as to which heater it is connected. This will allow identification of which type of heater needs replacement, and where it is located, simplifying the replacement process. This is particularly important when the heaters need to be replaced by divers, enabling the divers to know exactly which heaters need to be re-

placed and where they are located before they begin their dive.

(c) Though heating the surface by pumping a heated fluid through pipes embedded in a wall or on the surface of a gate is possible, such systems tend to be more complicated for this application than use of electric heaters. The average surface heat requirements for such systems can be determined using the guidance provided in Paragraph 20-2*b*. However, use of a simple single phase (e.g., liquid water or glycol) fluid-based system will not provide uniform heating on the entire surface that needs to be protected as the heat exchange will behave very much like a parallel flow heat exchanger, owing to the water and ice on the heater surface not rising significantly above freezing temperature. Consequently, the entrance end of the system would have a large temperature difference (and therefore a large heat flow, *q*) between the heater fluid and the surface to which the ice adheres. As long as ice is present, this temperature difference (and *q*) will diminish along its length as the fluid cools and the surface the ice adheres to remains at or below freezing temperature. This will lead to areas that are much warmer than freezing and other areas that do not heat above freezing. The ice will not release from the areas that do not heat above freezing if the spatially average heater requirements outlined in Paragraph 20-2*b* are used to size such a single-phase fluid system. To provide uniform temperature across the protected area requires changing the heat transfer area in the piping between the fluid entrance and exit—a much more complicated system to design and install. A two-phase (e.g., steam and condensate) system would provide more uniform heating of the surface that needs to be de-iced; however, delivery of high quality steam from a remote centralized boiler to the areas to protect and collection/return of the condensate to the boiler will require careful design of the pipe layout to avoid condensate plugs forming or condensate freezing within the system. Some additional concerns related to the use of fluid-based systems include:

- Use of toxic substances, such as ethylene-glycol, that can leak into the environment.
- Use of water that can freeze and burst the pipes in the wall if the pump system fails.
- Corrosion of the pipes.

If fluid-based systems are to be used, these concerns need to be addressed.

20-3. Controlling Water Leakage by Seals.

a. Heated J-seals on Dam Gates. Heating the side J-seals improves their ability to reduce leakage past tainter gates, and thus reduce the associated buildup of icing on the walls and the gate structures. This method is easily adaptable at low cost to existing dam gates (using Huntington J-seal Mold No. 3493 or equivalent).

(1) This in situ heating system has been made up so that it can be inserted into the hollow channel of a J-seal; it keeps ice from forming on the seal and increases the flexibility of the seal at lower temperatures. With increased flexibility, the seal better conforms to irregular surfaces,

thereby reducing leakage to the downstream side. With little or no leakage, ice formation on the cold, exposed downstream side is substantially reduced. Neither steaming nor “cindering” (i.e., pouring cinders in the water above the locations of the greatest leakages, so that the cinders flow toward the leaks and plug them) were required during tests of the in situ heating system at Starved Rock Lock and Dam on the Illinois Waterway, where it was installed during a dam rehabilitation.

(2) The self-regulating heat trace tape, 208 VAC at 121 W/m and 0°C (37 W/ft at 32°F), was cut from a spool to a length of 5.5 m (18 ft). The heat tape was sealed at one end. The other end had a cold electrical lead attached to connect to the electrical power. The J-seal configuration is shown in Figure 20-13. The 1988 cost of Huntington J-seal Mold No. 3493 was $45.57/m ($14.50/ft). The seal was manufactured as of 1988 by Buckhorn Rubber, 55 W. Techne Center Drive, Milford, Ohio 45150 (800-543-5454). The self-regulating heat trace tape is widely available at an approximate 1988 cost of $16.40/m ($5/ft). If both seals of a gate are heated and the heaters are operating at maximum power, the operating cost per day is $2.24, assuming 1332 W at $0.07/ kWhr.

(3) Use of heated J-seals would not preclude the inclusion of embedded electrical heaters in gate pier walls in rehabilitations or new designs, because embedded heaters aid in keeping seal plates ice-free above or below the immediate seal-contact area, so that gates can easily be placed in any chosen position.

b. Side Seal Heaters, Seal Design, Cinders. The performance of the J-bulb seal can also be improved by increasing pre-load and providing a softer seal. Also, the seal depends on hydraulic head to work properly, that is why seals tend to leak near the top of the gate where the head is small and seal better further down. Factors that will impact the extent of leakage are:

- Proper seal installation.
- Surface corrosion of the mating rub plate surface.
- Seal damage.
- Seal wear.
- Silt and debris caught between seal and mating surface.
- Stiffening of the seal due to aging.
- Unevenly resurfaced mating surface.

(1) All of these factors make it difficult to have zero leakage in any seal design. An incremental improvement in sealing may be achieved by resurface the mating surface with stainless steel.

(2) As mentioned above it is common practice at many projects to use cinders to prevent leakage by the side seal on tainter gates. This is done by dropping handfuls of cinders from the surface into the water over where a seal is leaking. By trial and with experience, the leak can be

plugged. This is often done in the fall and prevents ice accumulation along the side seal through the winter provided the gate remains closed. However, once the gate is moved, the seal is broken, the cinders are lost, and the procedure needs to be re-done to seal the gate again. Thus, for gates that need to be regularly moved throughout the winter months, this may not be a viable solution.

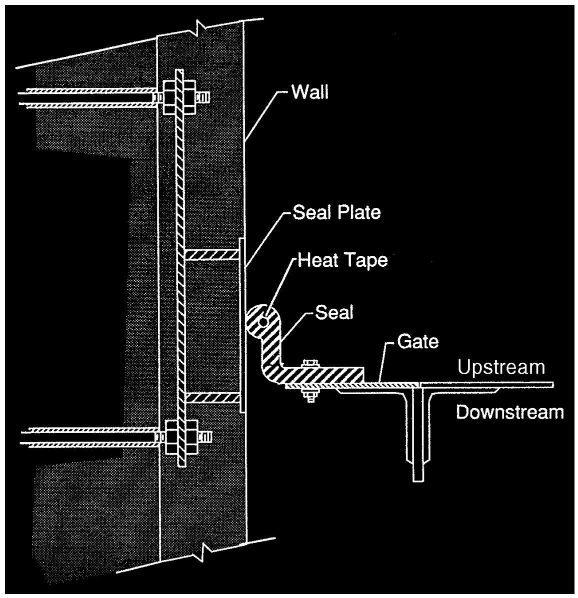

Figure 20-13. J-seal and J-seal heater installation on a tainter gate.

20-4. Surface Treatments to Reduce Ice Adhesion.

a. Materials. There is a long history of study in this area for a variety of applications. The only surface treatment that has been used successfully on a large scale for truly shedding ice is repeated application of chemicals that depress the freezing point of water. As far as concrete surfaces are concerned, the classic treatment for ice removal is repeated application of sodium chloride or calcium chloride. Use of these on hydraulic structures is almost universally not acceptable because of environmental concerns. Another ice-control method is a permanent or semi-permanent coating that reduces the adhesive force between the coated surface and the ice that forms on it. The ideal material would be one that prevented ice formation entirely. No known coatings do this, but some make the task of ice removal from coated surfaces easier. While many available coatings and claddings reduce the ice bond strength significantly, most of the available products do not reduce the bond strength enough to eliminate the need for additional methods of ice removal. To have the ice shed off a vertical surface under its own weight, the adhesion strength must be less than the shear stress that the ice exerts on the wall. For example, the adhesion strength of the ice to the substrate would have to be less than 5 kPa for a 0.6-m-wide ice collar to fall off a vertical surface under its own weight. Recent advances in low adhesion, or low-energy, coatings are demonstrating bond strengths at or near this range (Figure 20-14), though some coatings see a degradation in the performance as they weather (Figure 20-

15). Low-energy materials may best be applied as system enhancements for other methods, such as heat, steam lances, and pike poles. Note that care must be exercised when using mechanical methods to remove ice from a coated surface since the coatings can be abraded or chipped.

(1) Numerous materials, coatings, and paints are commercially available that are advertised to have low-friction or non-stick properties. Some of these coatings are also marketed as ice-phobic (i.e., significantly lowering the adhesion strength of ice). The ice adhesion strength for many of these coatings and materials has been measured in the laboratory to rank their relative performance using the test procedure of Haehnel and Mulherin (1998). Included in these evaluations is the measured ice adhesion strength of common paints used by the Corps of Engineers to protect steel members on hydraulic structures. Both vinyl-based paints (used at freshwater projects) and epoxy paints (used mainly for salt/brackish water applications) were evaluated. Because the paints used by the Corps have been primarily developed for their high durability, it was considered unlikely that the low-adhesion coatings would replace them, but instead would be applied over the Corps paints to reduce ice adhesion to the surface. Consequently, some of the laboratory tests were designed to simulate this condition, and ice-phobic coatings were layered over samples already having the Corps paints applied.

(2) An alternate means of protection might be to clad an area with a low-adhesion material. Consequently, the ice adhesion strength for several candidate plastic cladding materials, such as Teflon™, acetal, and polyurethane, have also been measured. Table 20-4 lists the paints, low-adhesion coatings, and materials evaluated. These tests were all conducted at –10°C.

(3) Comparisons of the adhesion strengths of these different coatings and claddings are shown in Figure 20-14. The best performing material evaluated to-date is Antice™, which drops the adhesion strength by a factor of 200 over bare steel and aluminum surfaces.

(4) Figure 20-14 presents results for tests conducted on pristine samples. To better understand the effects of weathering on material performance some of the better performing materials were subjected to environmental conditions. In one study the effect of weathering on ice adhesion, pristine plastic and coated samples were mounted in a navigation lock chamber on the Mississippi River near St. Louis, MO (Lock and Dam 25), and exposed to field conditions, including cyclical wetting and drying and abrasion from moving ice, sediment, and debris, for the about a 4-month duration through the 2001–2002 winter and spring seasons (late December – through early April). Not all of the materials presented in Figure 20-14 and Table 20-4 were subjected to these weathering tests because they were not available at the time. More recently a new coating was tested according to ASTM tests B117 (salt fog exposure) and D2247 (100% humidity exposure) to evaluate its weatherability.

Table 20-4. Materials and coatings evaluated at CRREL to measure the adhesive shear strength of ice (after Haehnel et al., 2002).

Material	Composition
Kiss-Cote 1083	Kiss-Cote 1083 (polydimethyl siloxane) used on aluminum samples. KISS-COTE, Inc. 12515 Sugar Pine Way Tampa, FL 33624 Phone: (813) 962-2703 http://www.kiss-cote.com/
Kiss-Cote ML	Kiss-Cote MegaGuard LiquiCote (polydimethyl siloxane) used on aluminum samples and painted steel samples. KISS-COTE, Inc. 12515 Sugar Pine Way Tampa, FL 33624 Phone: (813) 962-2703 http://www.kiss-cote.com/
BMS 10-60	BMS (Boeing Material Spec) 10-60 polyurethane over BMS 10-11 epoxy primer. http://www.boeing.com/companyoffices/doingbiz/environmental/high_solids.html
Wearlon	Wearlon Super F1 (water-based, methyl silicone copolymer epoxy). Environmental Coatings P.O. Box 405 Maryville, IL 62062 Phone: 888-Wearlon www.environmentalcoatings.com
Type V MIL-PRF-24635E Navy Coating or PSX-700	Siloxane and polyurethane epoxy produced by: Ameron International Protective Coatings Group 201 North Berry Street Brea, CA 92821 Phone: (714) 529-1951 http://www.psx700.com/
Interlux Brightside	Polyurathane alkyd. International Paint Inc. 2270 Morris Ave Union NJ 07083 Phone: (908) 686-1300 http://www.yachtpaint.com/usa/
TroyGuard	Fluoropolymer suspension and mineral spirits in clear acrylic urethane paint. The additive is produced by:

Material	Composition
	Troy Corporation 8 Vreeland Road Florham Park, NJ 07932-0955 Phone: (973) 443-4200 http: www.troycorp.com Tested coating with Troyguard EX527 additive was produced by: Niles Chemical Paint Company, 225 Fort Niles, MI 49120 Phone: (616) 683-3377
TroyGuard/ polyurethane	Fluoropolymer suspension and mineral spirits in BMS 10-60 polyurethane paint The additive is produced by: Troy Corporation 8 Vreeland Road Florham Park, NJ 07932-0955 Phone: (973) 443-4200 http: www.troycorp.com
Inertia 160	Trimethyl hexamethylenediamine epoxy. International Paint Inc. 6001 Antoine Dr Houston TX 77091 Phone: (713) 684-1254 http://www.international-marine.com/
Envelon	Resin-based ethylene acrylic acid copolymer thermoplastic. Thermoset Applications Group Dow Plastics The Dow Chemical Co. 2040 Willard H. Dow Center Midland, MI 48674 Phone: (800) 441-4369 http://www.dow.com/plastics/
Slip Plate #1	Natural graphite coating in mineral spirits. Superior Graphite Co. 10 South Riverside Plaza, Suite 1600 Chicago, IL 60606 Phone: (312) 559-2999 http://www.graphitesgc.com/
WC-1-ICE	Saturated polyester resins in fluoropolyol with PTFE and organofunctional silicone fluid additives, modified with a fluorotelomer intermediate, and activated with a trimer of HDI. 21st Century Coatings, Inc. 4701 Willard Ave., Suite 109 Chevy Chase, MD 20815

Material	Composition
	Phone: (301) 657-6230 http:www.fpu-coatings.com
SA-RIP-4004	Saturated polyester resins modified with fluorotelomer intermediates activated with a biuret of HDI. S&A Fernandina, Inc. 3601 Crow Court Jacksonville, FL 32259 Phone: (904) 230-1799
51PC951	A fluorinated polyurethane coating, suitable for both in-air and in-water immersion, produced and sold by 21st Century Coatings (Canada) LLC
R-2180	A two-part silicone elastomer dispersed in xylene, produced and sold by NuSil Technology, LLC (http://www.nusil.com/PDF/PP/R-2180P.pdf).
HybridShield	A one-part, moisture cured resin that cures to form a clear film and is produced and sold by NanoSonic, Inc. (http://www.nanosonic.com/product/hybridshield-icephobic/)
Antice	An anhydra coating produced and sold by Oceanit (http://www.oceanit.com/products/anhydra)
Corps Paints	
V-103c	Vinyl resin, type 3 (20), carbon black (1.5), diisodecyl phthalate (3.4), methyl isobutyl ketone (36.0), toluene (39.1% by weight). Indmar Coatings Corporation 237 West Main St Wakefield VA 23888 Phone: (757) 899-3807
V-766e	Vinyl resin, type 3 (5.6) and type 4(11.6), titanium dioxide and carbon black (13.0), diisodecyl phthalate (2.9), methyl isobutyl ketone (32.0), toluene (34.7) ortho phosphoric acid (0.2 % by weight). Indmar Coatings Corporation 237 West Main St Wakefield VA 23888 Phone: (757) 899-3807
V-102e	Vinyl resin, type 3 (18.2), aluminum powder (8.3) diisodecyl phthalate (3.1) methyl isobutyl ketone (33.8), toluene (36.6 % by weight). Indmar Coatings Corporation 237 West Main St Wakefield VA 23888 Phone: (757) 899-3807
C-200a	A coal tar epoxy formulation commonly used on U.S. Army Corps of Engineers hydraulic structures exposed to brackish or salt waters. Tested coating was "Bitumastic 300M" and was produced by: Carboline Company

Material	Composition
	350 Hanley Industrial Court St Louis MO 63144 Phone: (314) 644-1000
MIL-P-24441C Type III	A polyamide epoxy formulation commonly used on U.S. Army Corps of Engineers hydraulic structures where VOC-compliance is mandatory. Tested coating was produced by: Indmar Coatings Corporation 237 West Main St. Wakefield VA 23888 Phone: (757) 899-3807
Materials	
Teflon™	Polytetrafluoroethylene (PTFE) thermoplastic
Polyethylene	Ultra-high-molecular-weight polyethylene thermoplastic
Acetal	Acetal copolymer thermoplastic
Titanium	ASTM B348 - Grade 5 (6% aluminum, 4% vanadium)
Dupont Delrin™	Polyoxymethylene homopolymer thermoplastic
Carbon Steel	Cold-rolled 1018
Stainless Steel	Type 410
Aluminum	Type 7075

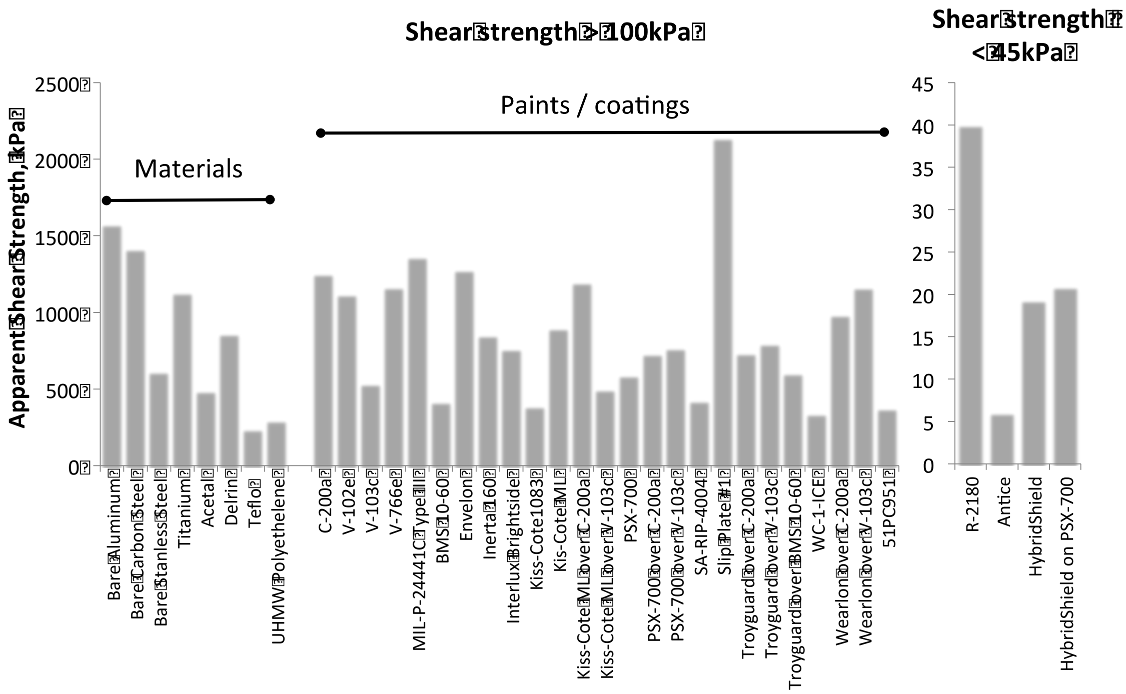

Figure 20-14. Ice adhesion test results for construction materials and commercial coatings. Column heights represent average ice adhesion strength.

(5) The results of these weathering evaluations are presented in Figure 20-15. Most of the materials did not exhibit a statistically significant change in their ice adhesion performance during these weathering tests. Some of the coatings exhibited an increase in adhesion strength from weathering, while some coatings and claddings showed a decrease in adhesion strength. This suggests that some of materials may perform better with time, while for some coatings their performance will degrade over time and require regular reapplication to restore the surface to pristine performance.

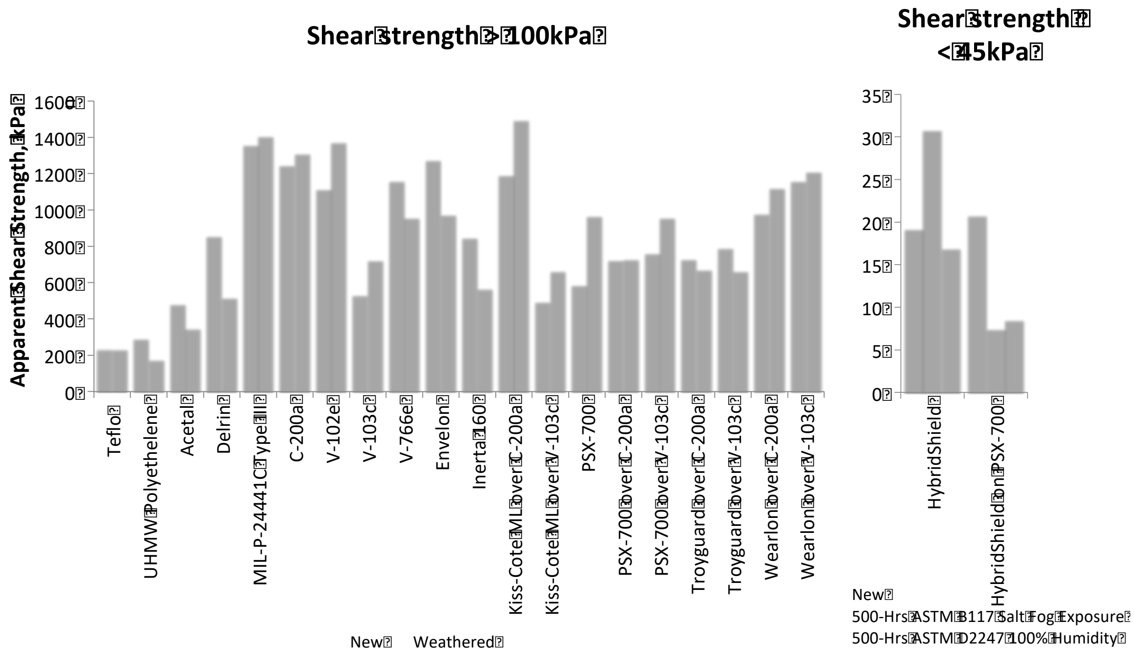

Figure 20-15. Ice adhesion test results for potential low-adhesion coatings and materials. Column heights represent average adhesion values. Samples on left were tested before and after being placed below water level in a Mississippi River navigation lock for a 4-month-long winter to spring period where they were subjected to repeated draining and flooding associated with normal lock operations. The coatings on the right were evaluated according to ASTM standard tests as noted in the legend.

(6) All of the tests conducted to date have shown that the adhesive shear strength of ice bonded to a variety of materials and coatings can vary over two orders of magnitude. For the pristine plastic samples, the variation in adhesion strength between Teflon^{TM} (lowest bond strength) to Delrin^{TM} (highest bond strength) is less than a factor of four. Similarly, the bond strength of ice to carbon steel painted with V-103c is approximately three times lower than that of bare carbon steel. The most significant reduction in ice strength is that exhibited by Antice^{TM} coated over aluminum; the reduction in ice strength of this coating, in comparison to bare aluminum is over a factor of 200.

b. Claddings. In a demonstration at Starved Rock Lock in Illinois, a 1.2- × 2.4-m × 1.2-cm-thick (4- × 8-ft × ½-in.-thick) sheet of high-density polyethylene was fastened to the curved part of the gate recess wall at the quoin end, at the ice-collar level. Hilti studs, 0.5 m (20 in.) on center, were used for attaching the sheets. Ice formed on the polyethylene surface and the concrete surface equally, but far less effort was needed by lock personnel to manually remove the ice from the plastic material, because of the lower adhesion forces between the polyethylene and the ice. Problems were noted with ice being more difficult to dislodge where the studs protruded, but a redesigned fastening technique could overcome that problem. The polyethylene is not highly durable when pike poles or ice chippers have to be used extensively, though. The use of steam to dislodge the ice collars would eliminate the risk of this damage. The panels are easily and economically replaced, since their 1988 cost was only about $75/m^2 ($7/ft^2).

20-5. Mechanical Removal of Ice. A number of mechanical methods have been used with varying degrees of success to remove ice from lock walls, dam gates, intakes, and other critical locations. Some of the mechanical methods used are described below.

a. Mechanical Contact Tools for Ice Removal. Two hand tools that can reliably be used to remove ice from concrete or steel surfaces are the pike pole and the ice chipper. Both of these tools are widely used by lock personnel at sites that experience winter icing problems. Figure 20-17 is a sketch of an ice chipper that has been refined over many years by its users. Large mechanical equipment used to scrape ice collars from lock walls have been used on a limited basis. Backhoes scrape the wall vertically by drawing the bucket teeth up the face of the concrete. With a light machine, this may require more than one pass to scrape through to the concrete, and frequent repositioning of the machine is necessary. With a heavier track-mounted machine, a single pass is usually sufficient. It is easy to move the machine along and there are no spuds to be set. However, with forceful operation, damage to the lock wall is inevitable, and the concrete on grooved or paneled walls could be seriously spalled.

b. Ice Removal with Non-contact Tools. Two techniques for ice removal using non-contacting tools are steam and water jets. Steam, when available at the desired locations, has always been used, often via lances or pipe probes placed and maneuvered by hand. But using steam is slow and time-consuming. The use of high-pressure water jets is rare because of the high horsepower required and the bulkiness of the typical systems. Advances in the design of such systems could make them more attractive.

c. Ice Control at Intakes. One solution for controlling frazil ice accumulation on intakes is to manually clean the trash racks during the periods when frazil ice is in the river, using special built trash rack rakes. These rakes have long handles that allow drawing the rake up across the full length of the trash rack and the tines on the rake are spaced so they fit between each of the bars on the trash rack. If this method is to be employed, it is recommended that a deck with railings be installed above the intake that extends out over the wall. Also, there needs to be a slot in the deck to allow the rake to pass between the wall and deck to access the front of the trash racks. This deck will allow personnel to reach out over the wall while they are pulling the rake up without putting them at risk of falling in the water. As it is so frequent that frazil ice problems occur at night, provision will need to be made to bring on a crew at short notice to rake the trash racks. The crew will likely need to work all night long. To accommodate this, a warming shelter near the intakes should be installed to give a place for personnel to rest and get out of the weather during breaks.

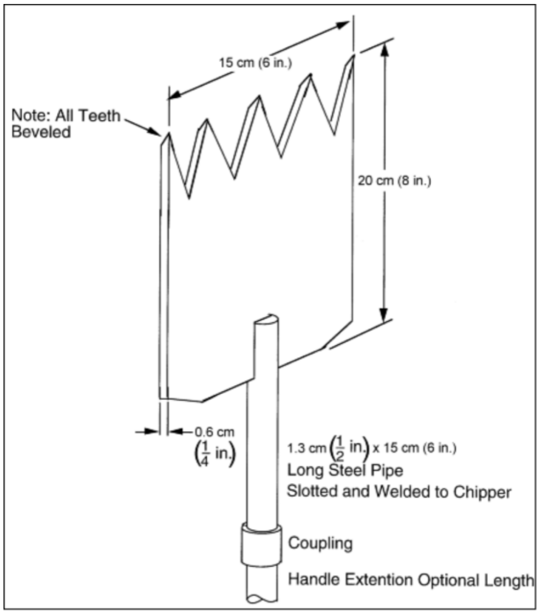

Figure 20-17. Effective design for a manual ice-chipping tool.

20-6. References

a. Required Publications.

(1) None.

b. Related Publications.

(1) *Army Publications*.

(a) EM 1110-2-2002. Maintenance and Repair of Concrete and Concrete Structures. https://www.publications.usace.army.mil/Portals/76/Publications/EngineerManuals/EM_1110-2-2002.pdf

(2) *Other Publications*.

(a) Billfalk, L. (1987). Ice Problems in Hydro Power Plants. Report U(L) 1987/15, Vattenfall Alvkarlebylboratoriet, Alvarkarleby, Sweden.

(b) Bockerman, R.W. and Wagner, P.A. (1998). Solutions to Gavins Point Tainter Gate Icing Problems. In Proceedings of the Engineering Technology Transfer & Training Conference, Kansas City, MO, 2–4 June.

(c) Daly, S.F., Haynes, F.D., Garfield, D.E., and Clark, C.H. (1992). Field tests of a surface-heated trash rack to prevent frazil ice blockage. In Proceedings, 11th International Symposium on Ice, IAHR, 15–19 June, Banff, Alberta, Canada. Vol. 1, p. 71–78.

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(f) Haehnel, R.B. and Clark, C.H. (1998). Maintaining operation of bypass tainter gates during frazil ice conditions at the Heywood Generating Station. Contract Report prepared for St. Catharines Hydroelectric Commission, St. Catharines, Ontario. Hanover, NH: U.S. Army Cold Regions Research and Engineering Laboratory.

(g) Haynes, D., Haehnel, R., Clark, C., and Zabilansky, L. (1997). Ice control techniques for Corps projects. REMR-HY-14. Vicksburg, MS: Waterways Experiment Station.

(h) Logan, T.H. (1974). Prevention of frazil ice clogging of water intakes by application of heat, REC-ERC-74-15, U.S. Department of Interior, Bureau of Reclamation, Engineering and Research Center, Denver, CO.

(i) Reid, C.R. (1928). Electric heating of rack-bars in hydroelectric plants. The Engineering Journal, April, p. 263–265.

(j) Ruths, A. (1924). Ice troubles in Norwegian power plants. In Transactions, First World Power Conference, London, p. 771–787.

(k) Samsioe, A.F. (1924). Measures taken in Sweden against ice troubles at water power plants. In Transactions, First World Power Conference, London, p. 806–811.

Appendix A
Glossary

Agglomerate	An ice cover floe formed by the freezing together of various forms of ice.
Anchor ice	Submerged ice attached or anchored to the bottom, irrespective of the nature of its formation.
Anchor ice dam	An accumulation of anchor ice that acts as a dam and raises the water level.
Beginning of breakup	Rivers: Date of definite breaking or movement of ice attributable to melting, currents, or rise of water level. Lakes: Date of visual evidence of initial deterioration along shoreline, such as the appearance of shore leads.
Beginning of freezeup	Date on which ice forms a stable winter ice cover.
Black ice	Transparent ice formed in rivers and lakes.
Border ice	Ice sheet in the form of a long border attached to the bank or shore; *shore ice*.
Brackish ice	Ice formed from brackish water.
Brash ice	Accumulations of floating ice made up of fragments not more than about 2 meters (6 feet) across; the wreckage of other forms of ice.
Breakup	Disintegration of ice cover.
Breakup date	Date on which a body of water is first observed to be entirely clear of ice and remains clear thereafter.
Breakup jam	Ice jam that occurs as a result of the accumulation of broken ice pieces.
Breakup period	Period of disintegration of an ice cover.
Candle ice	Rotten columnar-grained ice.
Channel lead	Elongated opening in the ice cover caused by a water current.
Channelization	Modification of a natural river channel; may include deepening, widening, or straightening.
Columnar ice	Ice consisting of columnar-shaped grains. The ordinary black ice is usually columnar-grained.
Concentration	The ratio (in eighths or tenths) of the water surface actually covered by ice to the total area of surface, both ice-covered and ice-free, at a specific location or over a defined area.

Conveyance	A measure of the carrying capacity of a river channel.
CRREL	U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.
Degree-day	Also termed *freezing degree-day*, a measure of the departure of the mean daily temperature *below* a given standard, usually 0°C (32°F). For example, a day with an average temperature of –5°C (23°F) represents 9 freezing degree-days by the Fahrenheit scale (5 freezing degree-days by the Celsius scale). Accumulated freezing degree-days (AFDD) are simply the sum of any number of degree-days. For example, the AFDD of a week with mean daily temperature of –5, 0, +5, 0, –5, –10, and –5°C are 20 freezing degree-days by the Celsius scale (23, 32, 41, 32, 23, 14, and 23°F) 36 freezing degree-days by the Fahrenheit scale.
Drifting ice	Pieces of floating ice moving under the action of wind or currents.
Dry crack	Crack visible at the surface but not extending through the ice cover, and therefore dry.
Duration of ice cover	The time from freezeup to breakup of an ice cover.
Dynamic ice pressure	Pressure attributable to a moving ice cover or drifting ice. Pressure occurring at moment of first contact termed ice impact pressure.
Floating ice	Any form of ice floating in water.
Floc	A cluster of frazil particles.
Floe	See *Ice floe*.
Flooded ice	Ice that has been flooded by melt water or river water and is heavily loaded by water and wet snow.
Floodplain	Land area adjoining a water body that is not normally submerged but may be submerged during flood conditions.
Fracture	Any break or rupture formed in an ice cover or floe by deformation.
Fracture zone	An area that has a great number of fractures.
Fracturing	Deformation process where fracture occurs and the ice is permanently deformed.
Frazil	Fine spicules, plates, or discoids of ice suspended in water. In rivers and lakes it is formed in supercooled, turbulent waters.
Frazil slush	An agglomerate of loosely packed frazil that floats or accumulates under the ice cover.
Freezeup date	The date on which the water body is first observed to be completely frozen over.

Freezeup jam	Ice jam formed as frazil ice accumulates and thickens.
Freezeup period	Period of initial formation of an ice cover.
Frost smoke	Fog-like clouds caused by contact of cold air with relatively warm water that can appear over openings in the ice or leeward of the ice edge and may persist while ice is forming.
Froude number	$F_R = V\sqrt{gH}$ where V = mean velocity, g = gravitational acceleration, and H = water depth.
Frozen frazil slush	Accumulation of slush that has completely frozen.
Glare ice	Ice cover with a highly reflective surface.
Gorge	An archaic or localized term for an ice jam; see *ice gorge*.
Grounded ice	Ice that has run aground or is in contact with ground underneath it.
Hanging dam	A mass of ice composed mainly of frazil or broken ice deposited under an ice cover in a region of low flow velocity.
Hinge crack	Crack caused by significant changes in water level.
Hummock	A hillock of fractured ice that has been forced upward by pressure.
Hummocked ice	Ice piled haphazardly, one piece over another, to form an uneven surface.
Hummocking	The pressure process by which ice is forced into hummocks.
Hydraulic radius	$R = A/p$, where A = cross-sectional flow area, p = wetted perimeter.
Ice arch	Frazil or fragmented ice that has stopped moving and bridges across a river channel; also called an *ice bridge*.
Ice boom	Floating structure designed to retain ice.
Ice bridge	A continuous ice cover of limited size extending from shore to shore like a bridge.
Ice cover	A significant expanse of ice of any form on the surface of a body of water.
Ice crossing	Man-made ice bridge.
Ice floe	Free-floating piece of ice greater than about 1 meter (3 feet) in extent.
Ice foot	A narrow fringe of thickened ice attached to the shore and unmoved by changes in water level.

Ice free	No floating ice present.
Ice gorge	A local term for ice jams, used primarily on the central U.S. rivers. This term is subject to regional variations in meaning.
Ice jam	A stationary accumulation of fragmented ice or frazil, which restricts or blocks a stream channel. This term is subject to regional variations in meaning.
Ice jamming	Process of ice accumulation to form an ice jam.
Ice ledge	Narrow fringe of ice that remains along the shores of a river after breakup. Also termed *shear wall*.
Ice push	Compression of an ice cover, particularly at the front of a moving section of ice cover.
Ice run	Flow of ice in a river. An ice run may be light or heavy, and may consist of frazil, anchor, slush, or sheet ice.
Ice sheet	A smooth, continuous ice cover.
Ice shove	On-shore ice push caused by wind and currents, changes in temperature, etc.
Ice twitch	Downstream movement of a small section of an ice cover. Ice twitches occur suddenly and often appear successively.
In situ breakup	Melting in place.
Lake ice	Ice formed on a lake, regardless of observed location.
Lead	Long, narrow opening in the ice.
Manning equation	$V = 1.486\ R^{2/3}S^{1/2}/n$ in English units ($V = R^{2/3}S^{1/2}/n$ in SI units) where V = mean flow velocity, R = hydraulic radius, and S = hydraulic slope; n is a coefficient of roughness.
Mush ice	Floating accumulation of very fine ice fragments (around 0.25 centimeters [0.1 inch] in size) that is somewhat cohesive.
New ice	A general term for recently formed ice, which includes frazil ice, slush, shuga (sludge), and other types of ice.
Overbank flow	Flow that exceeds the level of a river's banks and extends into the floodplain.
Pancake ice	Circular flat pieces of ice with raised rims; the shape and rim are caused by repeated collisions.
Polynya	Any nonlinear-shaped opening enclosed by ice. Polynyas may contain brash ice or be covered with new ice.

Pressure ridge	Line or wall of broken ice forced up by pressure.
Puddle	Accumulation of melt water on ice, mainly from melting snow but in the more advanced stages also from the melting of ice. Initial stage consists of patches of melted snow.
Rafted ice	Type of deformed ice formed by one piece of ice overriding another.
Rafting	Pressure processes whereby one piece of ice overrides another. Most common in new ice.
Ridge	A line or wall of broken ice forced up by pressure. May be fresh or weathered.
Ridged ice	Ice piled haphazardly, one piece over another in the form of ridges or walls.
Riprap	Rocks strategically placed against riverbanks or beds to prevent erosion of underlying material.
Rotten ice	Ice in an advanced stage of disintegration.
Rough ice	General term for ice covers with rough surfaces.
Sea ice	Any form of ice originating from the freezing of seawater.
Shear crack	Crack formed by movement parallel to the surface of the crack.
Shear wall	Ice accumulation having a vertical wall or face and remaining along the shores of a river after an ice jam has released. The height of the vertical face provides an estimate of the thickness of the ice jam.
Shearing	Motion of an ice cover because of horizontal shear stresses.
Sheet ice	A smooth, continuous ice cover formed by in situ freezing (lake ice) or by the arrest and juxtaposition of ice floes in a single layer.
Shore depression	Depression in the ice cover along the shore often caused by a change in water level.
Shore ice	See *border ice*.
Shore lead	A water opening along the shore.
Skim ice	Initial thin layer of ice on a water surface.
Sludge	An accumulation of spongy ice lumps formed from compressed frazil, slush, snow slush, or anchor ice.
Slush ball	Result of extremely compact accretion of snow, frazil, and ice particles. This is produced by wind and wave action along the shore of lakes or in long stretches of turbulent flow in rivers.

Slush-ice run	Ice run composed mainly of slush ice.
Snow ice	Ice that forms when snow slush freezes on an ice cover. The presence of air bubbles makes it appear white.
Snow slush	Snow that is saturated with water on ice surfaces, or as a viscous mass floating in water after a heavy snowfall.
Static ice pressure	Pressure developed by a static ice cover.
Stranded ice	Ice that has been floating and has been deposited on the shore by a lowering of the water level.
Supercooled water	Water whose temperature is slightly below the freezing point (0°C or 32°F).
Surface crack	Crack visible at the surface.
Thalweg	Deepest portion of the river channel; the line of major flow.
Thaw holes	Vertical holes in ice formed when surface puddles melt through to the underlying water.
Thermal crack	Crack caused by contraction of ice caused by a change in temperature.
Through crack	Crack extending through the ice cover. Sometimes called a wet crack.
Tide crack	Crack caused by rise and fall of tides. A special kind of hinge crack.
Unconsolidated ice cover	Loose mass of floating ice.
Water slope	Change in water surface elevation per unit distance.
Water stage	The water surface elevation above the bottom of the river channel or above some arbitrary datum.
Weir	Barrier placed in a river to raise water elevation.
White ice	See *snow ice*.

Appendix B
Ice Jam Mitigation Case Studies

B-1. Kankakee River, Illinois—Thermal Control

a. The upstream end of the backwater from the Dresden Island Lock and Dam on the Illinois River extends to about River Mile 3.5 on the Kankakee River near Wilmington, Illinois. Frazil ice floes form a stable ice cover on the pool, which thickens as frazil ice then deposits beneath the ice cover. The thick frazil ice deposit requires more force to break up than the thinner upstream ice and provides an obstruction to the passage of upstream river ice, which breaks up prior to this thick ice deposit. An ice jam often forms at the upper end of the deposit and progresses upstream, flooding the city of Wilmington and surrounding areas. The ice jam flood in 1982, which caused more than $8 million in damages, was followed by other ice jam events in 1984 ($500,000) and 1985 ($1 million). Several alternative ice jam mitigation measures were considered. Because of the proximity of the cooling pond for the Dresden nuclear power plant, thermal ice control appeared feasible. The intent of the thermal control was to thin or melt the thick frazil deposits that resist breakup, thus allowing the fragmented ice from upstream to pass unobstructed.

b. In a demonstration project, 20°C (68°F) water from the cooling ponds adjacent to the Kankakee River near Wilmington was siphoned in three 0.76-m-diameter (30-inch-diameter) pipes into the river upstream of the ice cover for 2 weeks prior to the anticipated breakup in 1988 (Figure B-1). The maximum siphon flow is 4.25 m^3/s (150 ft^3/s) compared with the expected river flow of approximately 113 m^3/s (4000 ft^3/s). The measured rise in water temperature was less than 0.56°C (1°F). The warm water input melted the existing ice so that ice floes passed unhindered during the natural breakup period and flooding was averted (Figure B-2).

c. This $450,000 system worked successfully for 2 consecutive years. There were no reported negative environmental impacts.

B-2. Hardwick, Vermont—Improved Natural Storage, Ice Retention, Mechanical Removal

a. Relatively frequent breakup ice jams have caused serious damage in this small Vermont town. A combination of techniques is used to reduce flooding impacts.

b. To slow the movement of broken ice, two booms were constructed (Figure B-3). The vertically oriented tire booms, which are suspended from shore, collect broken ice during breakup, some of which is stored on the overbanks. The booms delay the downstream passage of ice while ice removal is performed in town. Since the winter of 1983–84, these booms have been placed upstream from town annually. Although the booms occasionally fail, they do provide ice retention.

c. An ice storage area downstream of the town accommodates some of the ice that jams and thereby provides added protection. In addition, when local officials first begin to notice serious ice jams developing, the town road crew mechanically breaks up and removes the ice to keep the river open.

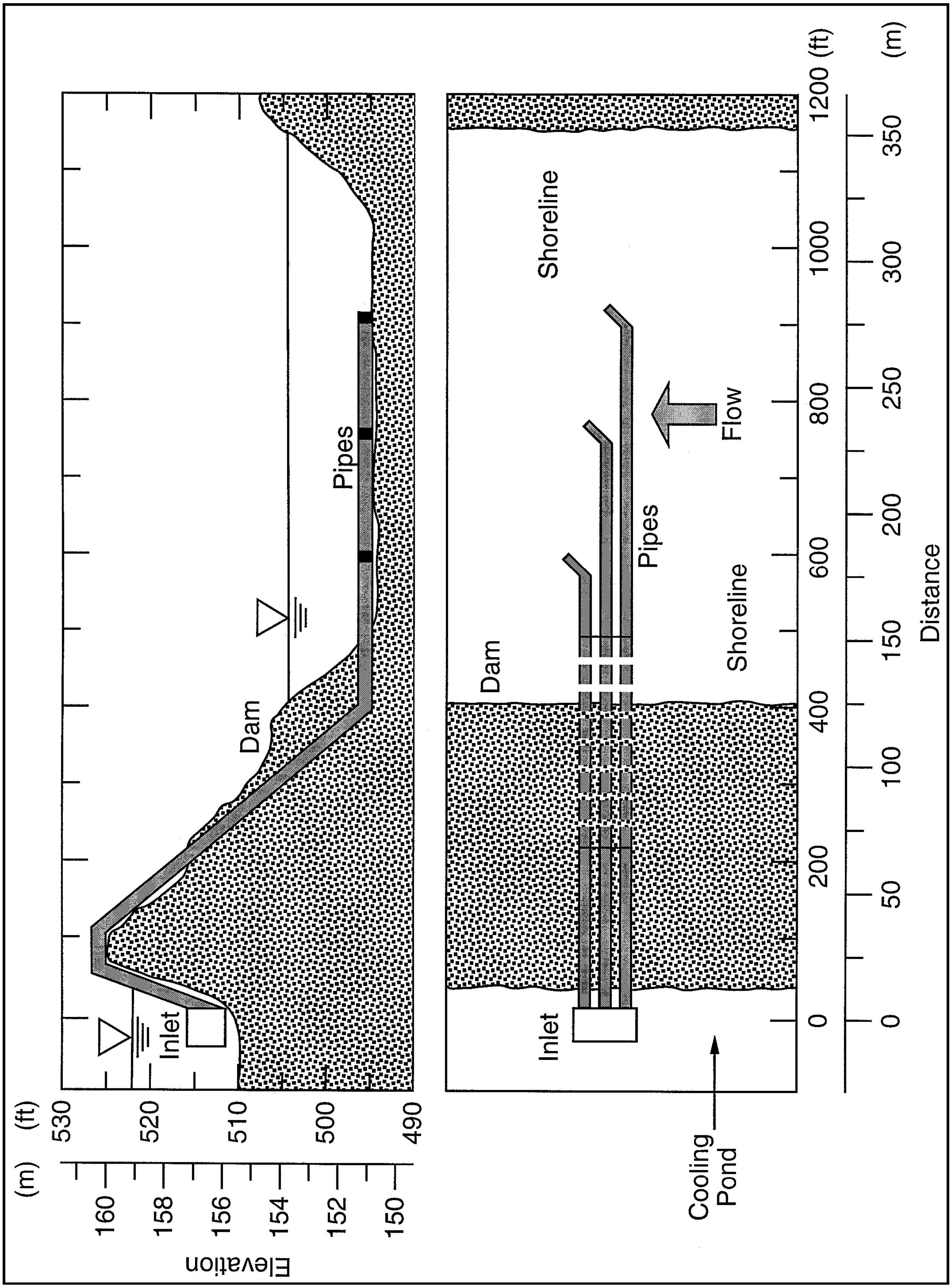

Figure B-1. Schematic of siphon system, Kankakee River, Illinois

Figure B-2. Map of meltout, Kankakee River, Illinois

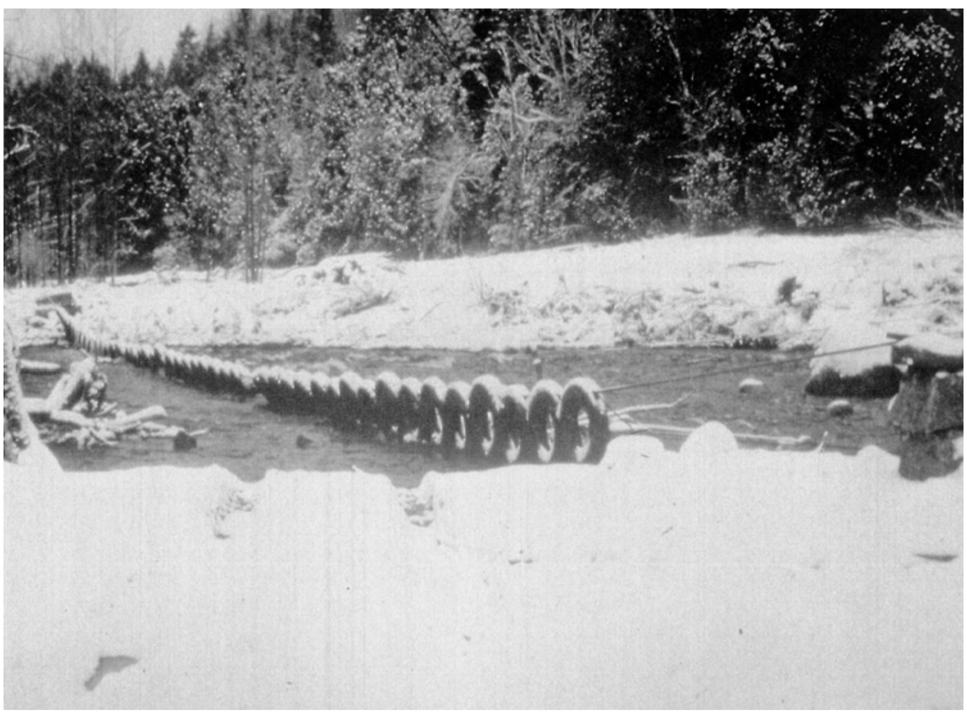

Figure B-3. Tire boom at Hardwick, Vermont

B-3. Oil City, Pennsylvania—Floating Ice Boom, Revised Operational Procedures, Ice Control Dam

a. Oil City is located in northwestern Pennsylvania. The city suffered chronic ice jam flooding from the mid-1880s to the mid-1980s. In February 1982, ice jam flooding caused more than $4 million in damages in downtown Oil City.

b. Research indicates that the ice jam flooding was caused in part by a massive deposit of frazil ice naturally occurring in a long, deep pool in the Allegheny River downstream of Oil City and extending upstream past the confluence with Oil Creek. Large quantities of frazil generated in the creek were also deposited in the river and backwater at the mouth of the creek. The ice on Oil Creek typically broke up and moved downstream before the ice cover on the Allegheny River. The tributary ice ran unimpeded to the river until it met the stable ice at the confluence with the Allegheny River and formed an ice jam.

c. An environmentally and economically beneficial floating structure (Figure B-4) was designed and installed upstream of the city on the Allegheny River to quickly form a stable ice cover to suppress further frazil generation and minimize excessive deposition in the trouble area. Discharge at an upstream dam was decreased during freezeup to allow the rapid formation of a stable ice cover at the boom. The floating boom was installed during the 1982–83 winter at a cost of $900,000. Since its installation, the boom has been fully effective and the river has remained relatively ice-free downstream from the boom in spite of extremely cold winters (Deck 1984).

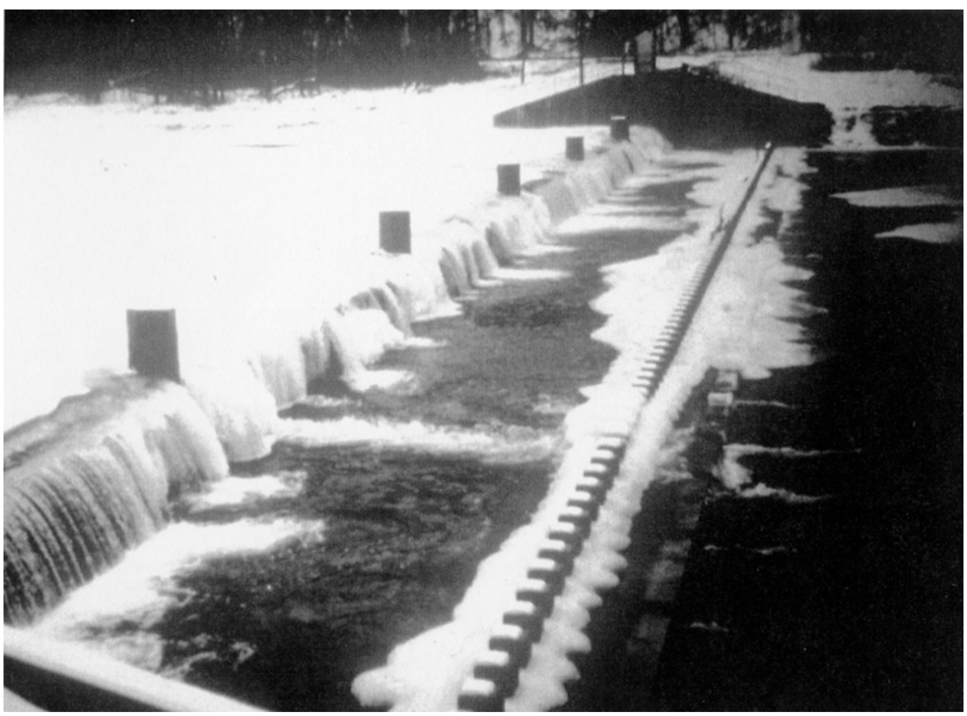

Figure B-4. Oil Creek ice-control structure, Oil City, Pennsylvania

d. A permanent ice-control structure was also constructed on Oil Creek by the Pittsburgh District of the Corps of Engineers in 1989. The structure is 1.5 meters (5 feet high), 107 meters (351 feet) long, and includes a 13.7-meter-wide (45-foot-wide) leaf gate, which allows for sediment and fish passage, as well as recreational use by canoeists and fishermen. Two low-flow pipes also provide fish passage. Levees were constructed on both upstream banks to contain the Standard Project Flood. The project cost was

$2.2 million (Wuebben and Gagnon 1995). No damaging ice jam has occurred in Oil City since the Allegheny River ice boom and Oil Creek ice control structure were put into use.

B-4. Lancaster, New Hampshire—Weir, Ice Retention, Storage

a. Lancaster, New Hampshire, experienced ice jams every year because of the breakup of the ice cover on the Israel River. Broken ice passage is impeded by a natural frazil deposit that forms at the change in slope, which occurs at the upper end of the backwater formed by the confluence with the Connecticut River. Few ice jams were reported prior to 1936, probably because four dams then in existence decreased frazil production, provided frazil ice storage, decreased the downstream transport of frazil ice, and delayed the downstream passage of broken ice. The dams have been removed since that time.

b. The Corps' New England Division (now New England District) and CRREL designed and built an ice control project to reduce the production and transport of frazil ice and decrease the volume of ice available to ice jams downstream. Environmental and financial constraints limited the scope of the project, which ideally would have provided the same protection as the four dams. The project consists of two parts: 1) a submarine net to capture surface ice, and 2) a 36.6-meter-long by 2.7-meter-high (120-foot-long) by 9-foot-high permanent weir located several miles downstream (Figure B-5). The submarine net is a form of suspended ice retention structure that allows water to flow through but captures floating ice pieces, which are then stored in overbank floodplains.

c. The ice control weir includes four 1.2-meter-wide by 2.4-meter-deep (4-foot-wide by 8-foot-deep) sluiceways for fish passage. During the winter, stop logs or metal bar racks are placed in the sluiceways to develop an ice retention pool. The pool forms an ice cover, and frazil ice generated upstream deposits beneath the ice cover. After the ice cover has formed, two of the gates are opened, allowing the pool level to drop. This creates additional water storage in the pool area, provides additional discharge capacity through the weir, and slightly delays the breakup and movement of ice through the pool as well. The project, which cost $300,000 was completed in 1982. Although costs constrained the size of the project to less than ideal, no major flooding has occurred since this relatively inexpensive, innovative project was constructed (Axelson 1991).

B-5. Idaho Falls, Idaho—Land Acquisition

In 1982, two hydroelectric dams were removed and rebuilt on the Snake River near Idaho Falls, Idaho. Freezeup ice jam floods on the Snake River affected Bear Island homeowners during the winters of 1982–83 and 1984–85. Ice jam floods also threatened two houses on the west bank of the river. The homeowners associated their flooding problems with the rebuilt dams located 9.7 kilometers (6 miles) downstream. As a result, they requested help from the city of Idaho Falls, the Federal Energy Regulatory Commission, and elected officials. Field data collection and hydraulic analyses indicated that ice jams were caused by frazil produced in turbulent open-water sections of the Snake River. The results showed that the changes in reservoir levels and the dams had no direct effect on ice jam flood levels in one area, although two properties were affected by changes in reservoir levels. Based on CRREL's recommendations, the City of Idaho Falls decided to purchase the two properties affected by the Upper Power Project (Zufelt et al. 1990).

a. Installing racks in sluiceways

Figure B-5. Lancaster, New Hampshire, weir

B-6. Platte River, Nebraska—Dusting

a. In February 1978, disastrous ice jam flooding took place on the Platte River in Nebraska, causing millions of dollars in damages. Record cold in January 1979 produced both extremely thick ice on the Platte River and its tributaries and a consequent threat of similar ice jams during spring breakup. Ice dusting, approximately 3 weeks before breakup, was recommended for alleviating ice jam floods.

b. Ice accumulated behind structure in early spring

Figure B-5. (Concluded)

b. The Nebraska Civil Defense Agency decided to try dusting selected areas with technical assistance from the Corps. The Corps assisted with advance preparation for the ice dusting operation, during the actual dusting procedures to ensure a proper application rate on the test areas, and during subsequent measurements to evaluate the effectiveness of the program. Dusting was performed using coal ash and slag from a local power plant.

c. Two periods of breakup occurred in March 1979. Because the dusted ice had already started to deteriorate, the jams were minor, even following heavy rains. The ice and water flowed smoothly down the channel with no flood damages (U.S. Army 1979).

d. Similar dusting operations were repeated in March 1994, prompted by severe ice jam flooding in the spring of 1993 that threatened the water wells supplying the city of Lincoln, Nebraska (U.S. Army 1994).

B-7. Allagash, Maine—Floodproofing, Relocation

a. Rainfall and 5 to 6 days of mild weather resulted in breakup ice jams and severe flooding on the St. John, Little Black, Allagash, and Aroostook rivers of northern Maine in April 1991. In Allagash, two bridges and 11 homes on the St. John River were destroyed; 22 other homes suffered damages. A 30-meter (1000-foot) section of a state highway was washed away. Ice jam flooding also caused evacuations and damage to 16 homes in neighboring towns. Damages totaled more than $14 million, mostly for rebuilding bridges, roads, and other public works (Federal Emergency Management Agency 1991).

b. Raising the affected buildings was considered. However, it was determined that elevation of the ground floor of homes to meet the requirements of the National Flood Insurance Program and local floodplain regulations might not provide adequate protection from future ice jams. In the town of Dickey, several residents indicated a willingness to relocate outside the floodplain. The following permanent settlement changes were made:

Three new homes were built at higher elevations on the original lots, and one home was repaired and moved to higher ground on the same lot.

Two new homes were constructed on new sites outside the floodplain, three homes were repaired and were moved to higher ground outside the floodplain, and two destroyed homes were replaced with mobile homes on higher sites.

Thirteen wells or septic systems were replaced with mitigation measures, meaning they were floodproofed or moved to higher ground.

B-8. References

a. Required publications.
None.

b. Related publications.

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Appendix C
Typical River Ice Management Study

C-1. General

A River Ice Management Study is conducted for the purpose of developing a River Ice Management Plan for a particular river or river basin. Typically, the River Ice Management Study would identify several options and develop schedules of time and costs for each. Then the chosen option or combination of options would go into the recommended River Ice Management Plan, which would become an operating document at the District level. The typical River Ice Management Study would be composed of the following elements.

C-2. Elements

a. Inventory of river characteristics.

- River reaches delineated and evaluated.
- Major tributaries evaluated.
- Hydraulic and flood control structures identified (including features and operational characteristics).
- Hydraulic and hydrologic data.

b. Description of ice problems.

- Ice and winter histories.
- Winter navigation and traffic characteristics.
- Project operational techniques in winter (site-specific).
- Ice problem identification and description (site-specific).
- Current ice problem mitigation techniques.

c. Ice–hydraulic–meteorological data.

- Existing data summarized (including stations, data types, collection, and processing).
- Data gaps identified.
- Recommendations for additional data collection (site-specific).
- Ice forecasting system (including capabilities, function, operation, and integration with existing hydraulic models).

d. Communications systems.

- Existing ice information reporting systems.
- Recommendations for improvements (including content, frequency, availability, and dissemination of current ice information).

e. Possible structural solutions.

- Techniques available.
- Application of site-specific structural solutions.
- Determination if Environmental Impact Statement is needed.

f. Possible operational solutions.

- Techniques available.
- Application of site-specific operational solutions.

g. Recommended Functional River Ice Management Plan for Subject River or Basin.

- Data collection program.
- Development and integration of ice forecasting methodology.
- Recommended structural ice control measures.
- Recommended operational techniques.
- Operational guide.
- Ice emergency options (including decision “tree” or “matrix” for determining when to close the river to navigation because of extreme ice conditions).
- Implementation plan.
- Schedule of structural improvement costs and annual operating costs.
- Benefit–Cost Analysis for structural measures (done by District even if River Ice Management Study is conducted by non-District entities).