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	Engineering and Design WINTER NAVIGATION ON INLAND WATERWAYS	
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US Army Corps of Engineers

ENGINEERING AND DESIGN

Winter Navigation on Inland Waterways

ENGINEER MANUAL

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

EM 1110-8-l(FR)

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Engineer Manual
1110-8-l(FR)

31 December 1990

Engineering and Design
WINTER NAVIGATION ON INLAND WATERWAYS

1. Purpose. This manual provides current guidance and engineering and operational solutions to ice problems on rivers used for navigation.

2. Applicability. This manual applies to all HQUSACE/OCE elements, major subordinate commands, districts, laboratories, and field operating activities (FOA) having responsibility for design, construction, and operation of inland waterways, including navigation and flood control structures that experience winter ice conditions.

3. General. Subjects covered are pertinent to planning, design, construction, and operation of water resource projects that are, or could be, affected by ice conditions. The guidance presented in this manual brings together the technical transfer results of the five-year, $12,000,000 River Ice Management Program and other related efforts that were included in the Ice Engineering Research Program. The purpose of this guidance is to reduce the risk to personnel and equipment operating in severe weather conditions and to minimize the repair costs incurred from damages experienced during ice events.

FOR THE COMMANDER:

ROBERT L. HERNDON
Colonel, Corps of Engineers
Chief of Staff

DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
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CECW-EH

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CHAPTER 1
INTRODUCTION

1-1. Purpose and Scope. This manual presents structural and operational solutions to ice problems on rivers that are used for navigation throughout the winter. These solutions will contribute to efficient, cost-effective, reliable, and safe navigation during ice periods. This manual also presents guidance for developing River Ice Management Plans for specific rivers or river systems. The information used in preparation of this manual largely derives from experience and knowledge gained during the five-year River Ice Management (RIM) Program (1984-88) conducted by the U.S. Army Corps of Engineers.

1-2. Applicability. This manual is applicable to major subordinate commands, districts, laboratories, and field operating activities having civil works design, construction, or operations responsibilities with respect to navigation projects or flood control projects experiencing ice problems.

1-3. References.

a. EM 1110-2-1611. Layout and Design of Shallow-Draft Waterways

b. EM 1110-2-1612. Ice Engineering

c. EP 70-l-l. Remote Sensing Applications Guide

d. ER 1110-2-248. Requirements for Water Data Transmission Using GOES/DCS

e. ER 1110-2-249. Management of Water Control Data Systems

f. ER 1110-2-1458. Hydraulic Design of Shallow-Draft Navigation Projects

g. ER 1125-2-308. Radio Frequency and Call Sign Assignments

1-4. Bibliography and Definitions. A bibliography is provided in Appendix A that lists additional references cited in the text, plus other references that supplement several of the topics covered in this manual. These may be consulted for further study of topics related both to winter navigation on inland waterways and to river ice management. A list of specialized terms and definitions is included as Appendix B.

1-5. Background. Ice-prone rivers in the United States 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). When ice causes navigation to stop or to become significantly curtailed on these rivers, the river-dependent portions of the local, regional, and national economies may be adversely affected.

a. Ice Interference with Lock and Dam Onerations. Corps of Engineers navigation projects cannot operate properly when ice accumulates at locks, dams, and related facilities. Ice interferes with the movement of lock and dam gates, 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. 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. Passing ice at dams, while at the same time maintaining navigation pool levels and avoiding downstream scour, is often difficult or impossible. These 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, and, most importantly, reductions in waterway readiness and capability, leading to lower levels of service to waterway users.

b. 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 unable 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. A related factor is that ice restrictions on usable lock widths dictate narrower tows (e.g., two-barge-wide tows at 70 ft, rather than three-barge-wide tows at 105 ft). 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 delays at locks. Ice can increase actual lockage times for several reasons. Broken ice may need to be locked separately through the chamber before a tow can enter. Double lockages (i.e., breaking up a tow into two parts) may be required because of length or width restrictions in the chamber from ice on the lock walls, gates, or barges. And, where two lock chambers exist, frequently only one of them will be available during ice periods because the other is needed to pass ice. Longer lockage times with heavy traffic mean that tows collect while awaiting their turns to lock through. All these limitations may increase operating costs and decrease operating efficiencies.

c. 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.

d. Ice-Related Shore and Structure Damage; Ice-Jam Flooding. Damage caused by normal ice conditions in ice-prone rivers is generally 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. Public and private river-edge structures can be weakened, distorted, or even destroyed. Once heavy accumulations of ice start to move downstream in the spring, people are at the mercy of the elements. River ice jams may contribute to winter and early spring flood damage. 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. The factors and relationships that determine the probability of ice jams and ice-jam flooding are more complex than those related to open-water flooding. This means that the extensive statistical analysis methods applied to normal flooding phenomena are not readily applicable to ice-related occurrences.

CHAPTER 2
RIVER ICE MANAGEMENT STUDY

Section I. Study Concept

2-1. 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 Plan that is unique for the waterway in question. This manual does not cover the environmental impacts of winter navigation.

2-2. 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.

2-3. 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

2-4. 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 by-passed by locks and canals are also of major interest. It is necessary to know what percent 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.

2-5. Ice Problem Identification. Proper implementation of a winter navigation plan requires that problems be identified, along with their locations and sources (see Chap. 3).

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 underside 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.

2-6. 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 4. 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.

2-7. Structural Solutions. Structural solutions are covered in detail in Chapter 6. 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, seals, etc., 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.

2-8. Operational Solutions. There are numerous operational techniques to control or mitigate ice problems at navigation projects. They are explained in detail in Chapter 7. Additionally, when lock and dam personnel apply the structural solutions as mentioned above or described in Chapter 6, 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.

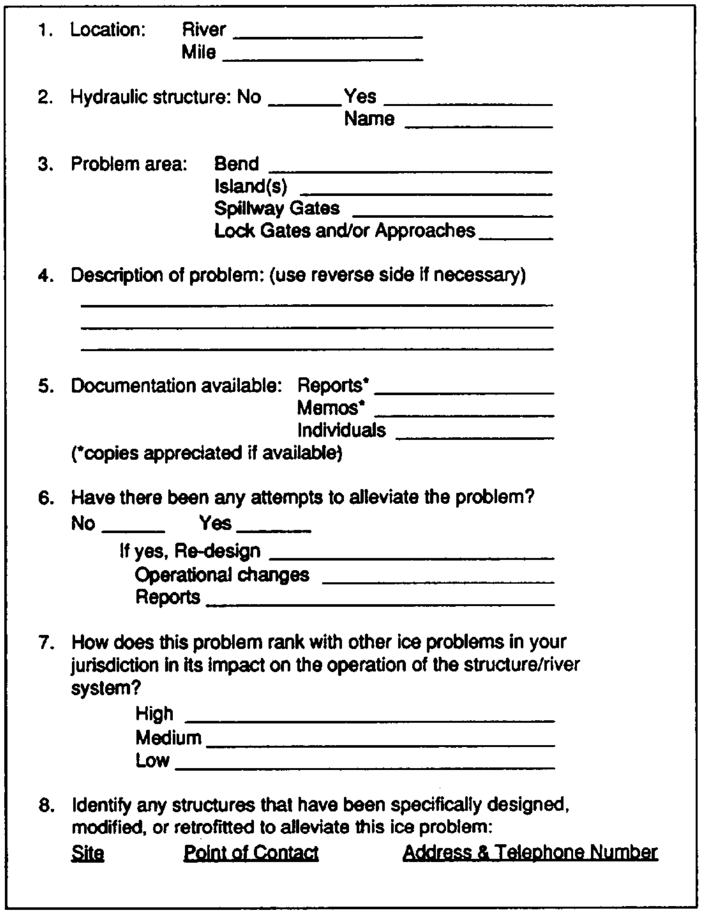
d. Energy from unconventional sources, such as heat from groundwater, solar heating, or wind energy, has been thought to offer promise for ice control at navigation projects. However, analyses show that this would be likely only in a very few restricted cases. Nonetheless, electrical heating appears 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.

2-9. 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 3
RIVER ICE PROBLEM IDENTIFICATION

3-1. 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 (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.

3-2. Hydrology and Hydraulic Studies. Records should be examined to determine if there have been any previous hydrologic or hydraulic studies ofportions 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 hydrologic 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.



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 3-1. Questionnaire for collecting information on ice problems affecting navigation projects and navigational activities.

3-3. Identification of Ice Problem Locations. 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 3-1. 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.

a. General. 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

Figure 3-2. Ice accumulation in the upper lock approach area.

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.

b. Ice Problems Around Navigation Projects.

(1) 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 (Fig. 3-2). 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

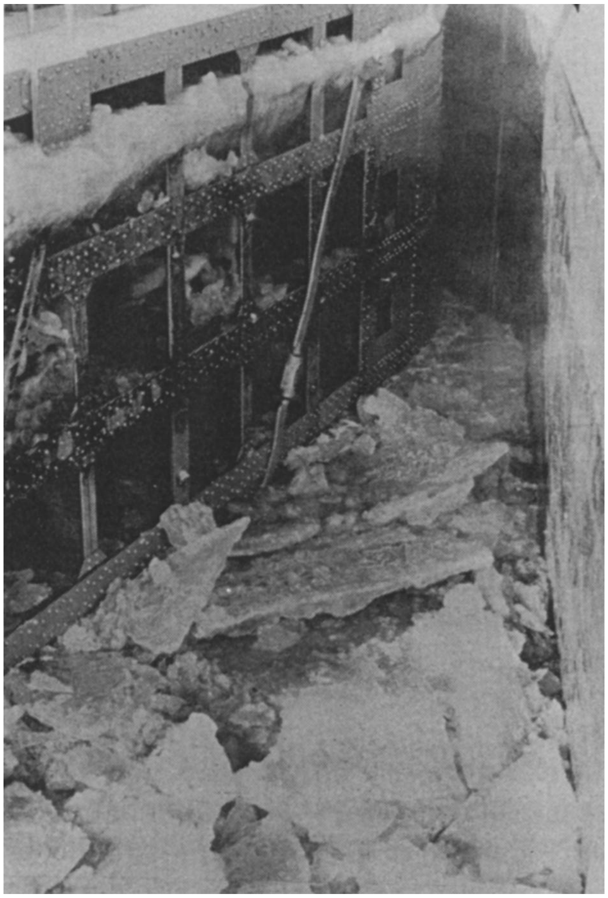


Figure 3-3. Broken ice accumulation between the lower miter gate and the gate recess wail, which hinders full recessing of the gate.

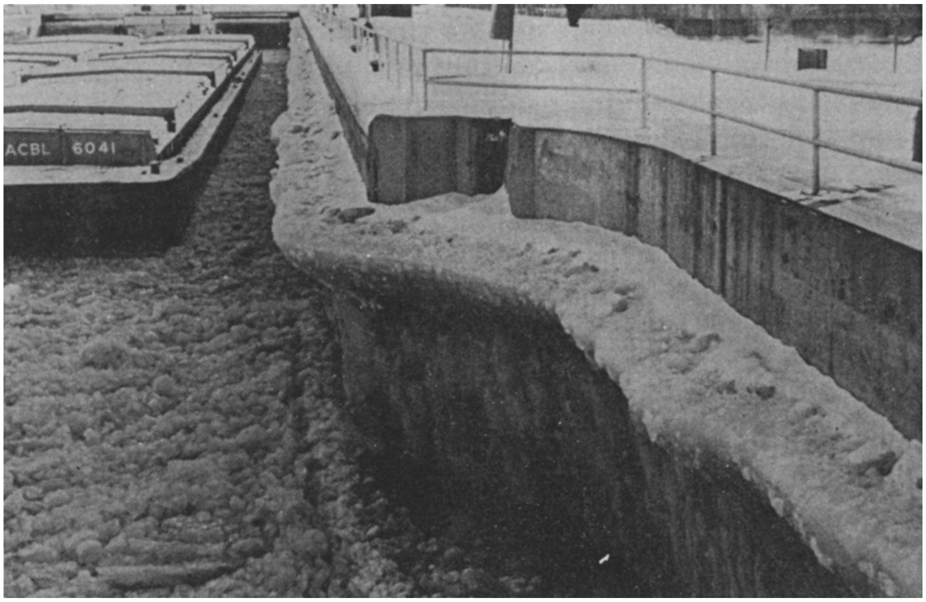


Figure 3-4. Ice collar formation on the gate recess and chamber walls, restricting the full opening of the miter gates and limiting the usable width of the lock.

traffic, ice accumulations sometimes freeze in place, causing further delays and difficulty in operating the upper gates.

(2) 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 (Fig. 3-3). 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.

(3) 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 (Fig. 3-4). 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 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.)

(4) 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 (Fig. 3-5), causing the bitt to freeze in place; the bitt can then dangerously and

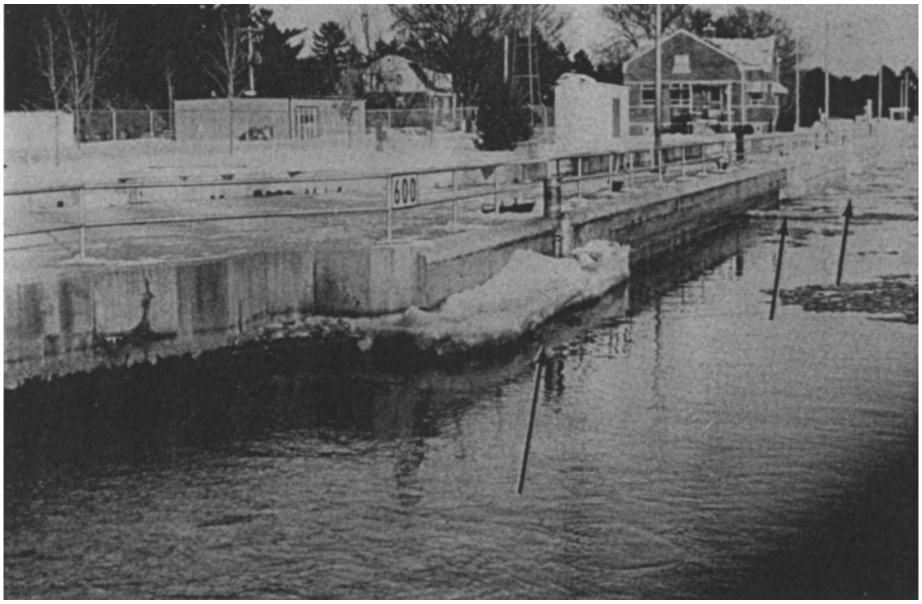


Figure 3-5. Ice collar ference with floating mooring bitts (arrows) in a lock chamber wall.

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.

(5) 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.

(6) 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.

(7) Dam Spillway Gates. Broken ice carrieddownstream usually accumulates at thedam (Fig. 3-6). 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 (usuallydone 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

Figure 3-6. Ice accumulation upstream of the gates of a navigation dam.

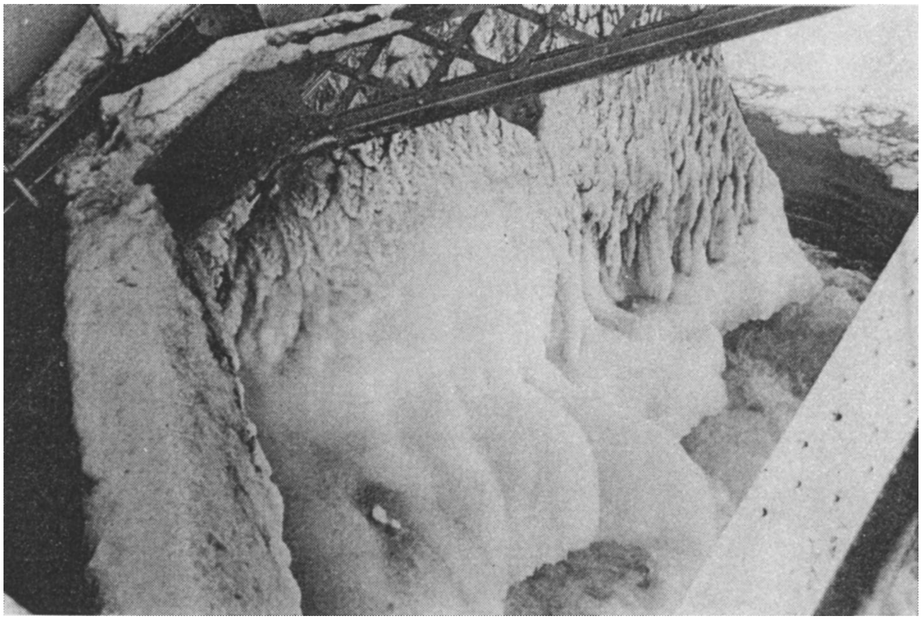


Figure 3-7. Tainter gate structure and gate pier wall with icing that has accumulated through spray and splashing in the course of winter operation.

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.

(8) 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 (Fig. 3-7). 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.

(9) 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 (Fig. 3-8). 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.

(10) 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.

c. Ice Problems Occurring Between Navigation Projects. The channels around islands, bends, and other constrictions tend to accumulate thick deposits of ice (Fig. 3-9). During periods of significant ice, these accumulations may form jams, which can cause scouring and eroding of bed

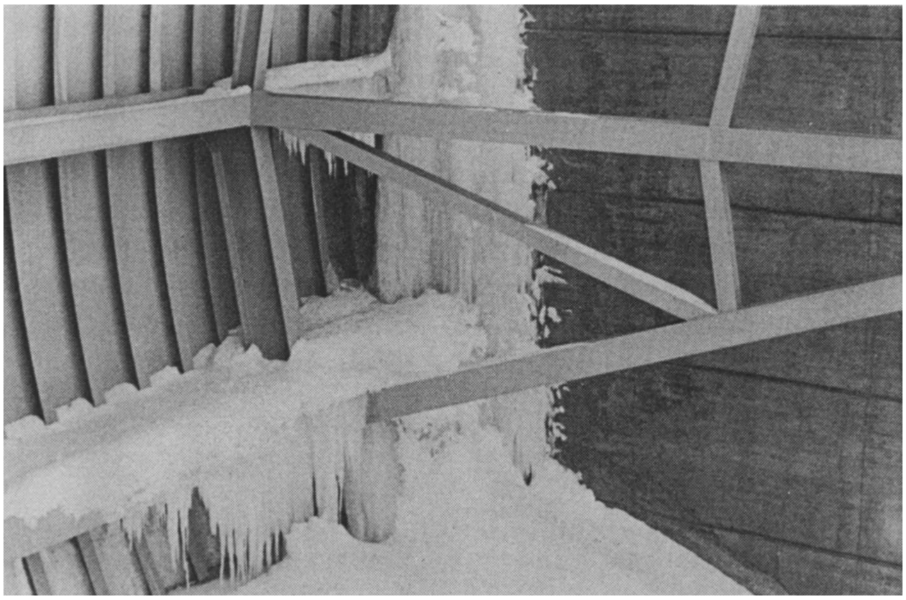


Figure 3-8. Tainter gate frozen in place by ice formed by leakage past the gate's side seals.

Figure 3-9. Heavy accumulations of ice floes and brash ice.

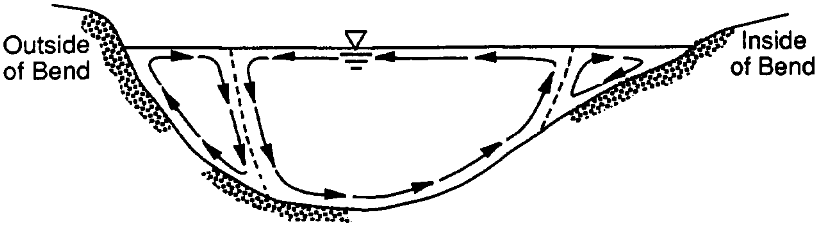


Figure 3-10. Transverse velocities forming secondary circulation cells in river bends.

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.

(1) 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 (Fig. 3-10). 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 trouble tracking around bends under ice conditions, particularly severe bends as on the upper Monongahela River. Figure 3-11 shows a vessel track

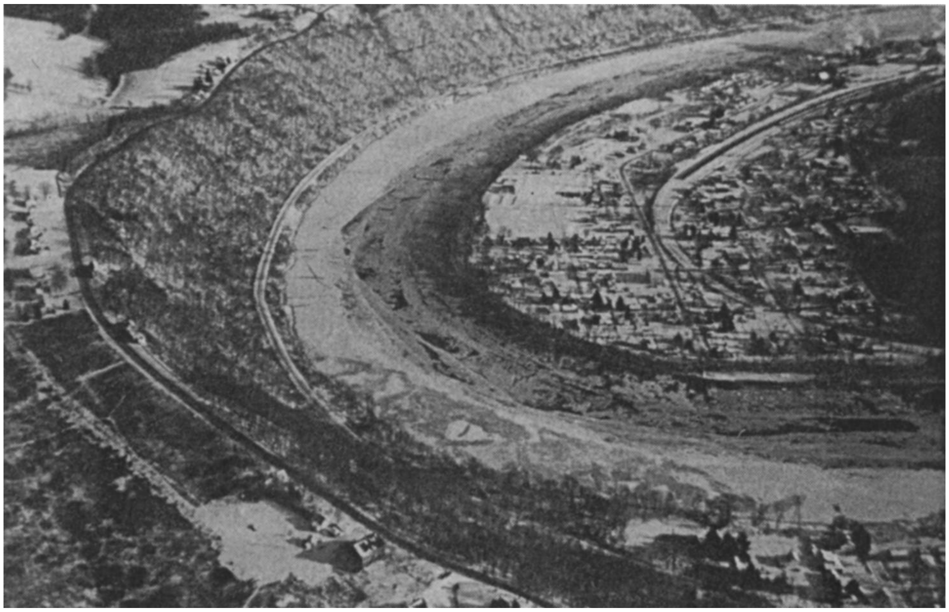


Figure 3-11. Broken, irregular vessel track around a sharp river bend, indicating difficulties in navigating through the ice.

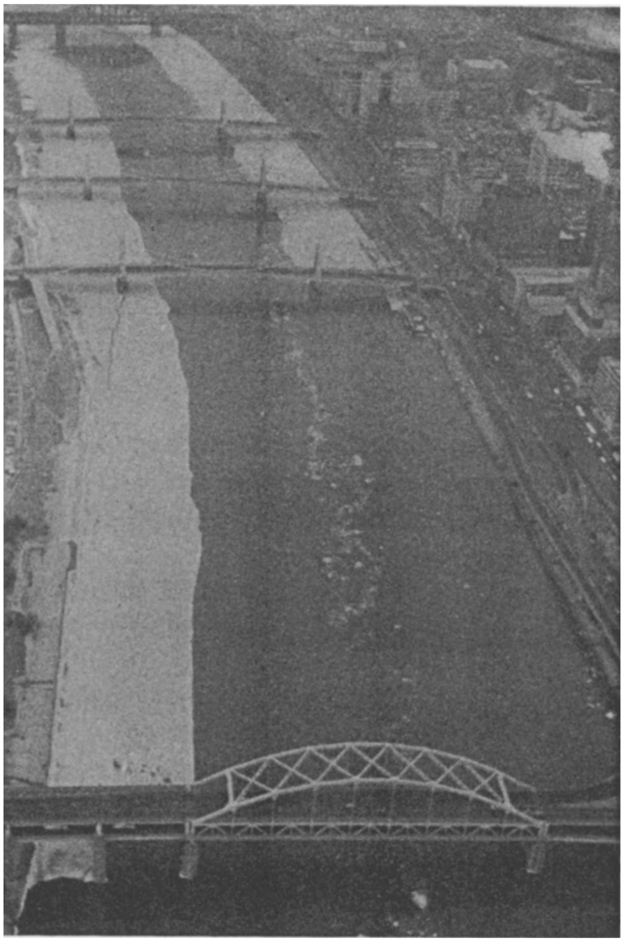


Figure 3-12. Shore ice formation, with bridge piers providing added stability to the shore ice.

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.

(2) 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 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 3-12 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

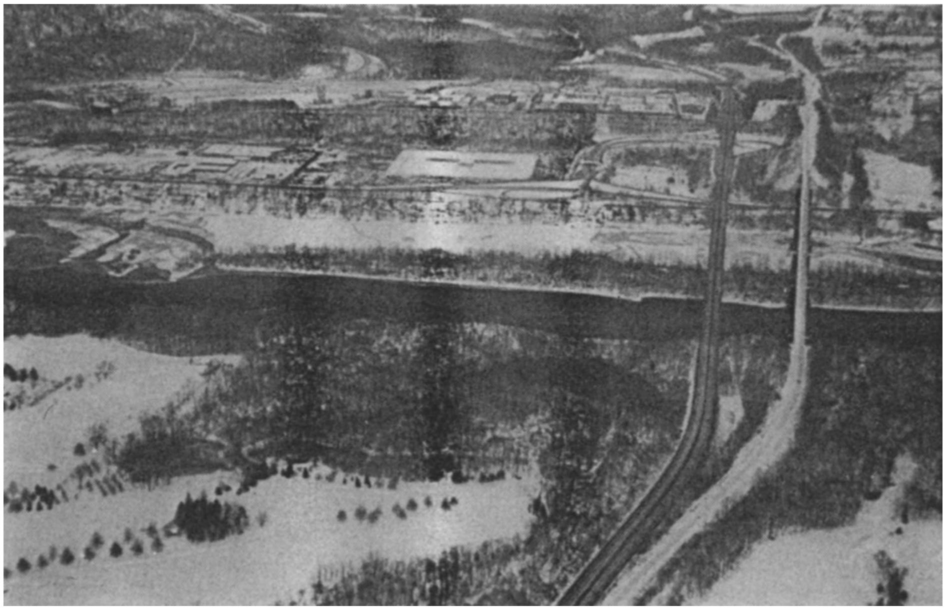


Figure 3-13. River divided into two channels by an island; the main channel is open while the secondary or back channel is ice-covered.

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 3-13 shows an island with one of the channels frozen over.

(3) 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 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 channe1) 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 6 ft and lengths of l/2 mile. It is not unusual for towboats to spend 10 to 18 hours to navigate through this 1/2-mile section.

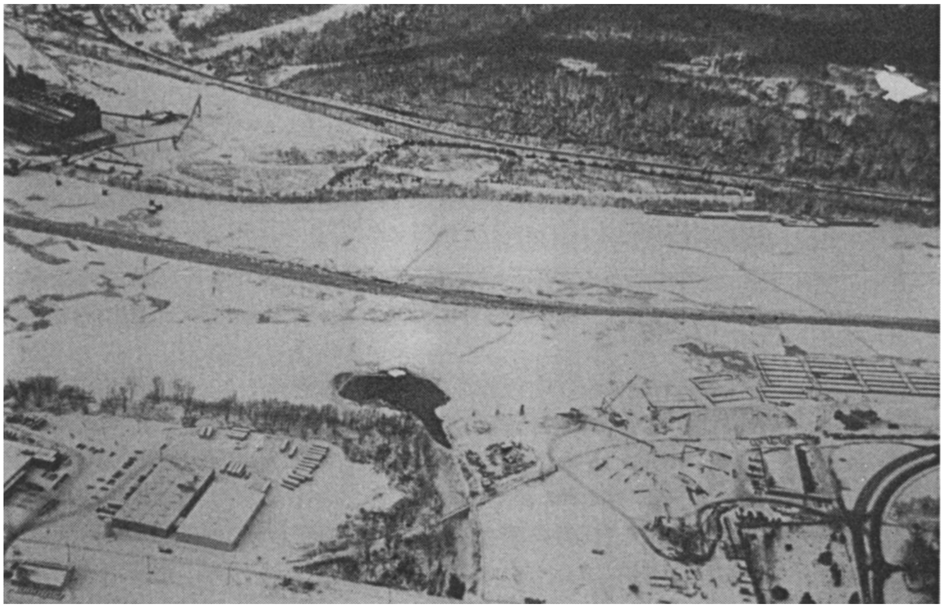


Figure 3-14. Navigation track in the middle of the channel, with a fleeting area at the near bank. Traffic using the fleeting area can breakfree large floes that can move out to block the track.

(4) Fleeting and Mooring Areas. Under mid-winter 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 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 3-14 shows a fleeting area near shore and an established navigation track following the shipping channel.

CHAPTER 4
ICE FORECASTING

4-1. 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 five to seven 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

4-2. Objective. Predictions of water temperature are made primarily to estimate when the water temperature will be at or near the freezing temperature, 32°F. 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.

4-3. 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 convectiondiffusion 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 f is made based on the formula

$$\phi = h_{wa}(T_w - T_a) + q \tag{4-1}$$

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

$$\frac{DT_w}{Dt} = -\frac{\phi}{\rho C_p D} \tag{4-2}$$

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

$$T_a = \bar{T} + a \sin\left(\frac{2\pi t}{T} + \theta\right) + T_{\delta_j} \tag{4-3}$$

where

t = Julian date
T = number of days in year (365 or 366)
θ = phase angle
$\bar{T}$ = 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 $\bar{T}$, 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 4-1. 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 4-1. 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* $\bar{T}$ (°C)	*Amplitude* a	*Phase angle* θ	*Period of record*
Pittsburgh, Pennsylvania	10.16	12.64	-1.9085	1965-1982
Huntington, West Virginia	12.63	11.66	-1.8734	1965-1982
Covington, Kentucky	11.80	12.84	-1.8866	1965-1982
Louisville, Kentucky	13.39	12.43	-1.8769	1965-1982

d. Model Parameters. By substituting Equations 4-l and 4-3 into Equation 4-2 and integrating to solve for T_w, an equation describing water temperature is derived.* 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 $j(T_{w\,j})$ is based on information known from the previous day, j-1. The forecast is made in one-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. † The results of calculating the response coefficient and equivalent temperature for six stations on the Ohio River are shown in Table 4-2. In this case separate coefficients have been calculated for two three-month periods: October through December, and January through March. These two periods cover the entire winter season.

4-4. 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

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*The general equation for T_w, for a specific day j, is given by:

$$T_{w_j} = \overline{T} + a\cos\alpha\,\sin\left(\frac{2\pi t}{T} + \theta - \alpha\right)$$
$$+ \left[T_{w_{j-1}} - \overline{T} - a\cos\alpha\,\sin\left(\frac{2\pi(t-1)}{T} + \theta - \alpha\right)\right] e^{-K_r}$$
$$+ T_{\delta_j}\left(1 - e^{-K_r}\right) + T_q\left(1 - e^{-K_r}\right)$$

where $\alpha = \tan^{-1}(2\pi/K_r T)$.

---

† The coefficients are estimated 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_{δ_j}, and $\overline{T}$.

Table 4-2. 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* T_a	
Location	*Oct-Dec*	*Jan-Mar*	*Oct-Dec*	*Jan-Mar*
Emsworth L&D*	0.1737	0.0725	1.35	3.45
South Heights, Pennsylvania (ORSANCO)	0.0637	0.0697	1.35	3.45
Montgomery L&D	0.1087	0.0706	1.27	3.52
Hannibal L&D	0.0998	0.0700	0.20	2.95
Racine L&D	0.1000	0.0633	0.20	1.80
Meldahl L&D	0.0596	0.0594	0.20	1.79

*Lock and Dam.

deviations from the normal air temperature as described by Equation 4-3. A diagram of the model is shown in Figure 4-l. Generally, the model is run to estimate the period when ice formation is possible, that is, when the water temperature is 32°F. However, this would not be a conservative estimate because unforecasted deviations in air temperature may cause the water to reach 32°F

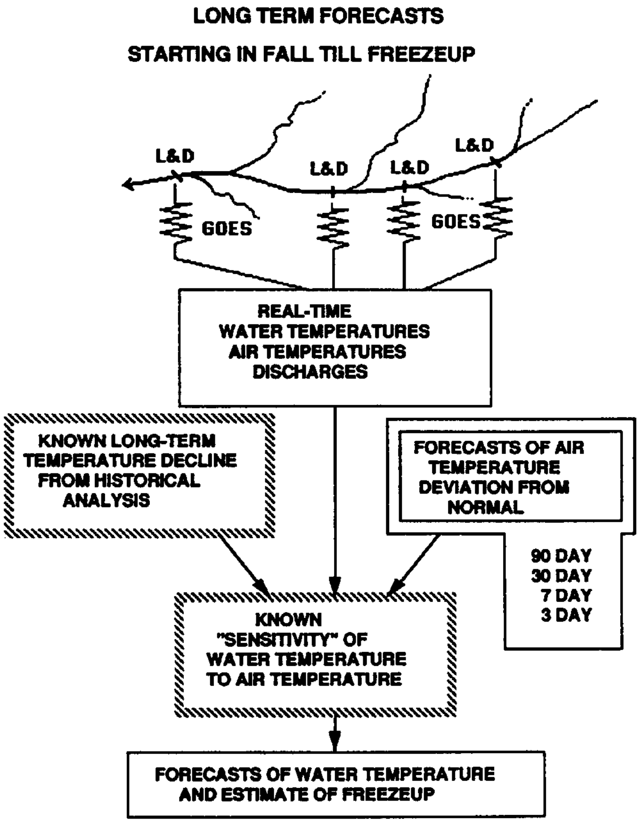

Figure 4-1. Flowchart of Long-Term Water Temperature Forecast model.

sometime before the actual forecasted date, and often, for a given winter season, 32°F 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 34.7°F (1.5°C) or less. The term *ice watch* is used to describe the time when the water temperature is forecasted to be 32.9°F (0.5°C) or less.

4-5. Model Results. An example of a sample water temperature forecast is shown in Figure 4-2. 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 4-3 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:    59.0°F  (15.0°C)

Air  Temperature  Forecasts:          3 Day: NORMAL
                                      7 Day: NORMAL
                                     30 Day: NORMAL


                         FORECASTED
                     WATER  TEMPERATURE
DATE                     °F        “C

01 Nov  87              50.4      10.2
01  Dec  87             39.6       4.2
15 Dec  87              35.4       1.9
01  Jan  88             32.4       0.2
15 Jan  88              33.4       0.8
01  Feb  88             33.8       1.0
15 Feb  88              34.7       1.5

MOST LIKELY ICE PERIOD: 19 Dec 87 - 15 Feb 87

ICE WATCH: 27 Dec 87 - 5 Jan 88
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Figure 4-2.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.*

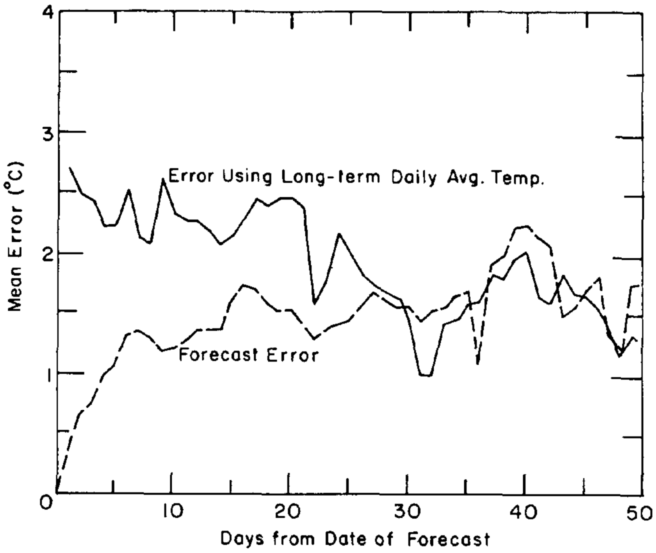

Figure 4-3. Forecast-model accuracy illustrated by plot of error as a function of days since forecast was made. Forecast naturally has its greatest accuracy immediately following the date of forecast, after which error generally increases with time. For comparison, error resulting from simple long-term 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.

4-6. 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 4-3. 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.

Section II. Mid-Winter Ice Forecasts

4-7. 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 ice cover, 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.

4-8. Forecast Model Description. The Mid-Winter Ice Forecast model 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 4-4. 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.

4-9. 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

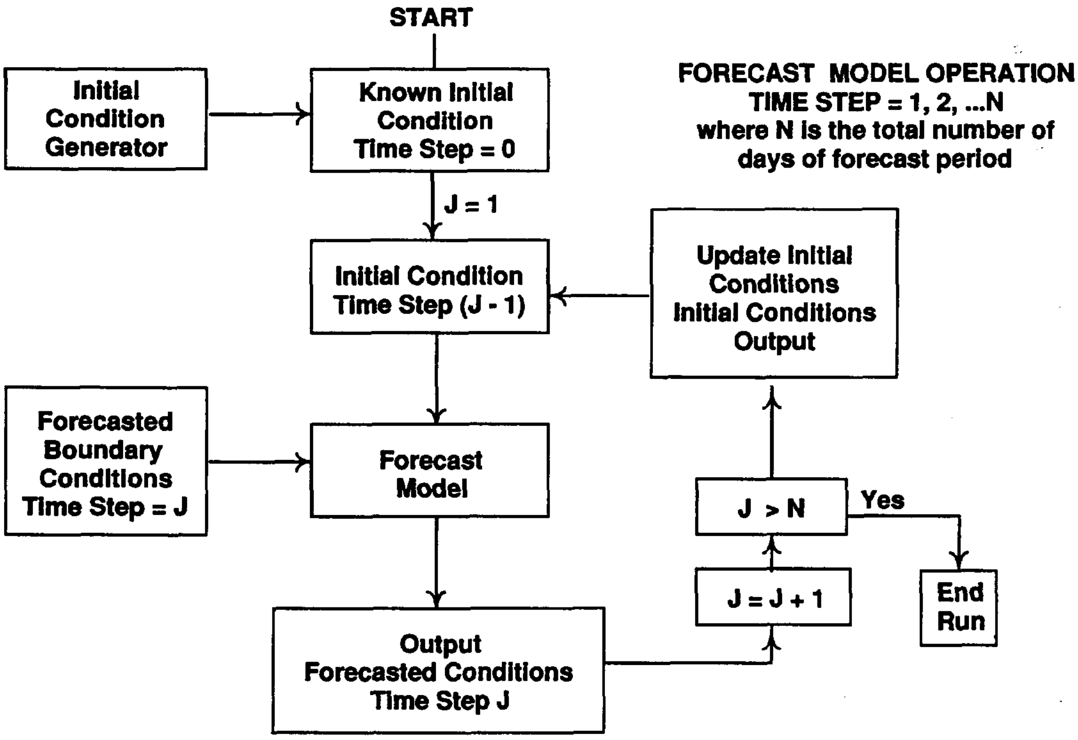

Figure 4-4. Flowchart of Mid-Winter Ice Forecast model.

flood plain. 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 (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 4-5.

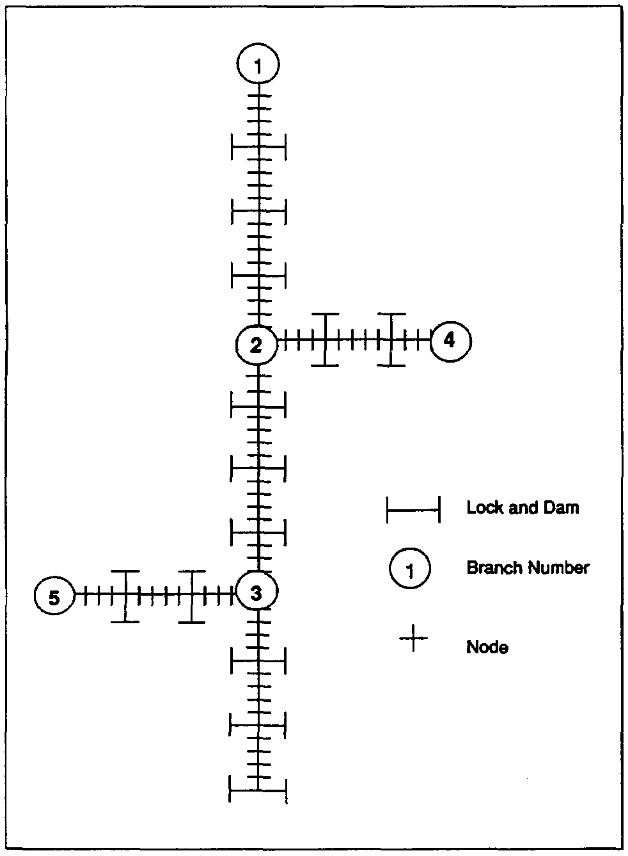

Figure 4-5. A river system represented by nodes and branches, for use in the Hydraulic Model. Note that nodes exist not only at lock and dam projects and at tributary junctions, but also wherever hydraulic and channel information is known or desired.

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.

4-10. 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 32°F. 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 2 in. 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 a formula of the type

$$\phi = h\left(T_w - T_a\right)$$

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 4-1. The difference is that here we are considering a specific area or reach of the river, while Equation 4-1 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 Para. 4-11). 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 32°F, 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.

4-11. 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 4-6. 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

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 ice

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*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.”

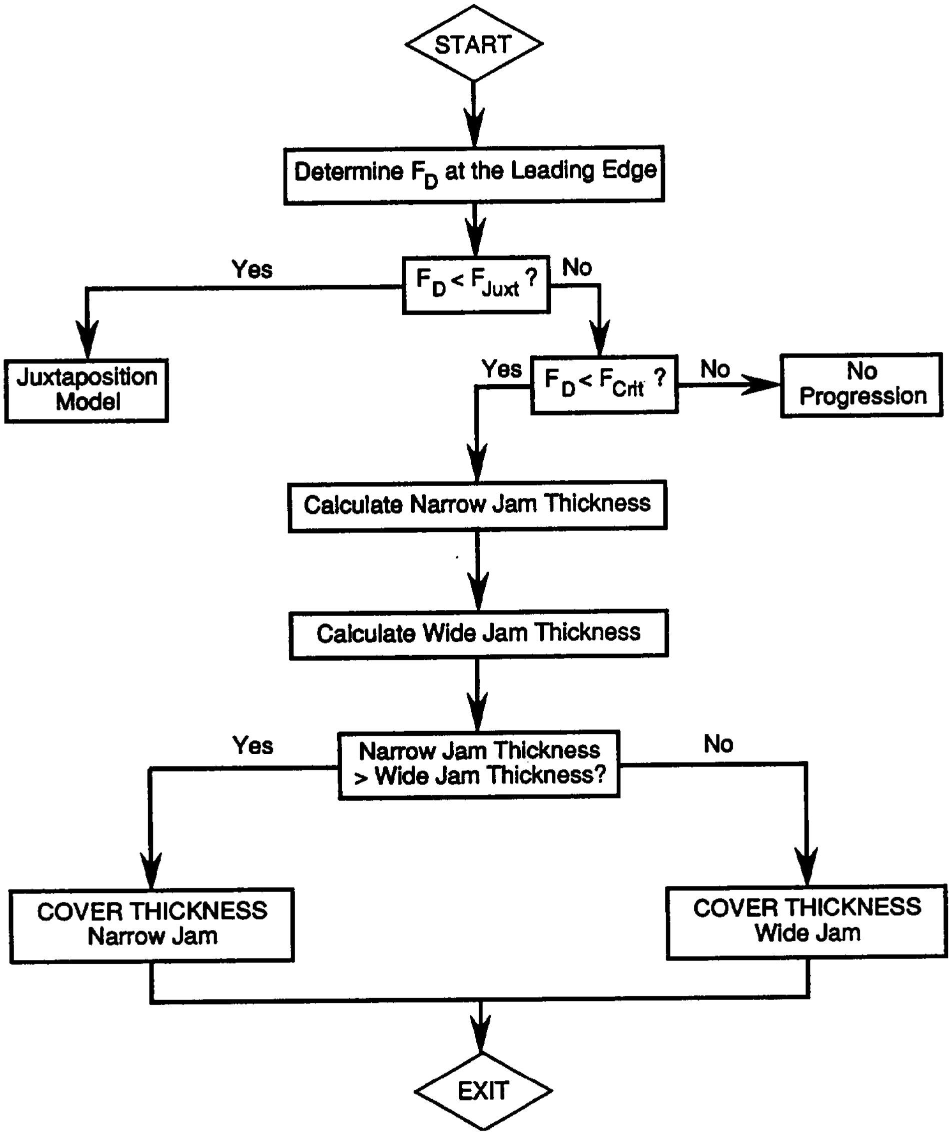

Figure 4-6. Flowchart of the logic used in the Ice Model for determining whether the upstream ice cover progression is by juxtaposition or by jamming (with the associated narrow-jam or wide-jam thicknesses), or whether there is no progression of the ice cover.

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 nor 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 the ability of the cover 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.

4-12. 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.

4-13. 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.
—Flood plain 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) Physical Principles and Parameters Determined from Model Calibration. As noted in Paragraph 4-11, the Ice Model does not have Physical Parameters based on physical principles nor determined by means of model calibration.

4-14. 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.

4-15. 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.

4-16. 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.

4-17. 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 (Para. 4-13d 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.

4-18. Model Operation. A general overview of the operational setup of the Ice Forecasting System is shown in Figure 4-7. 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 (DCP's) 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 5. Thermistors, which change resistance in response to temperature change, are used to measure temperature. As DCP’s 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

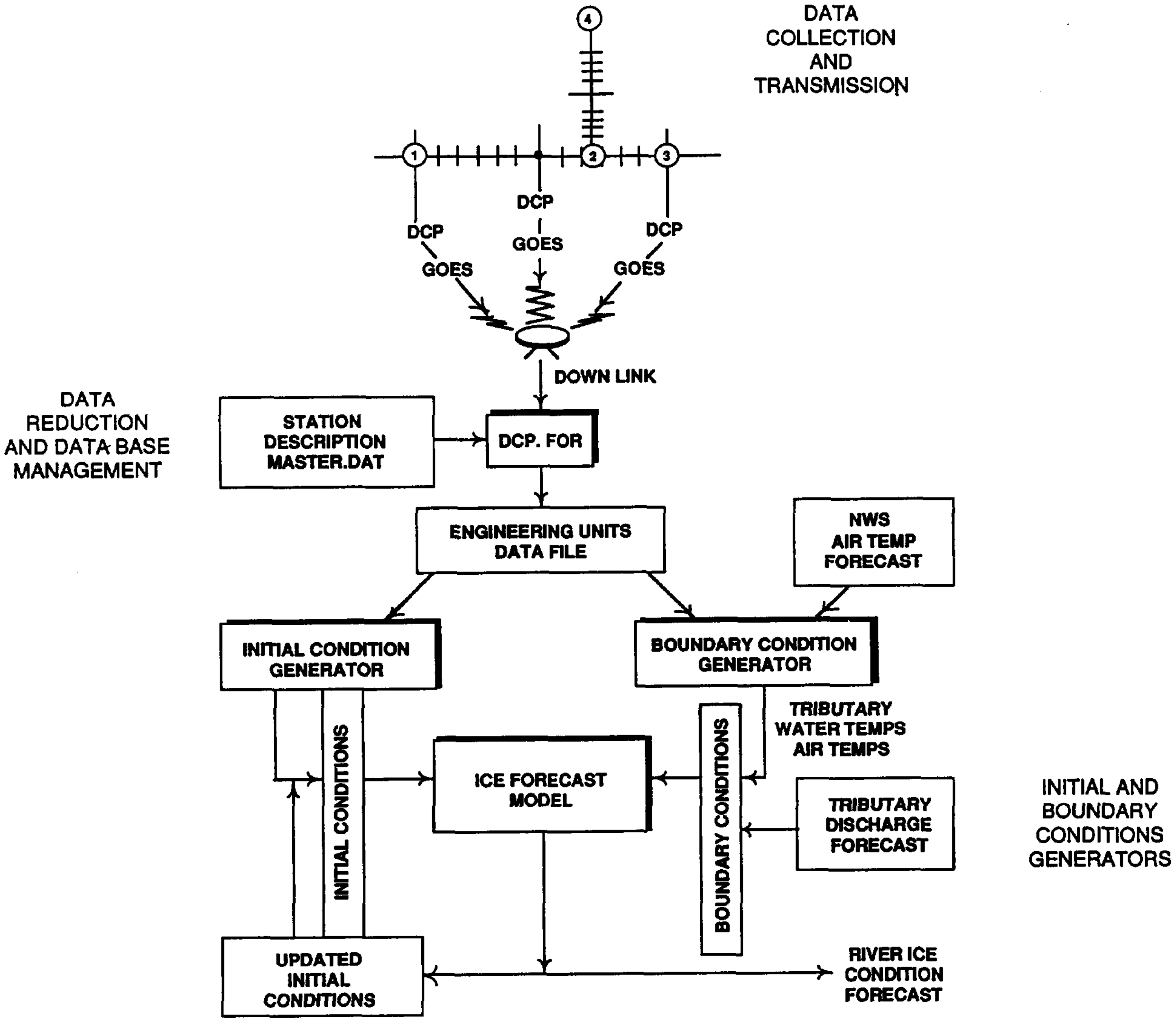

Figure 4-7. Overall flowchart of the Ice Forecasting System, within which the Mid-Winter Ice Forecast model operates under the support of Data Collection and Transmission, Data Reduction and Data Base Management, and Initial Conditions and Boundary Conditions Generators (DCP.FOR and MASTER.DAT are computer program names).

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 DCP's 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. Currently, the output file of DCP.FOR is being 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 4-20 and 4-21.

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 Conditions and Boundary Conditions Generators) prepares the forecast of predicted ice conditions. Two different modes of operation will be described: the Update Mode and the Forecast Mode (see Para. 4-22).

4-19. 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 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.

4-20. Initial Conditions Generator. The Initial Conditions required in the model are listed in Paragraph 4-14.

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, it has been found that 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 5. 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).

4-21. Boundary Conditions Generator. The Boundary Conditions required are listed in Paragraph 4-15. 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.

4-22. 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.

4-23. Model Results. A sample of the Model Output over an entire winter season is shown graphically in Figure 4-8. 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 4-8 is from 22 December 1985 through 12 February 1986, and the presence of ice is shown as determined by the model. In Figure 4-9, 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 made.

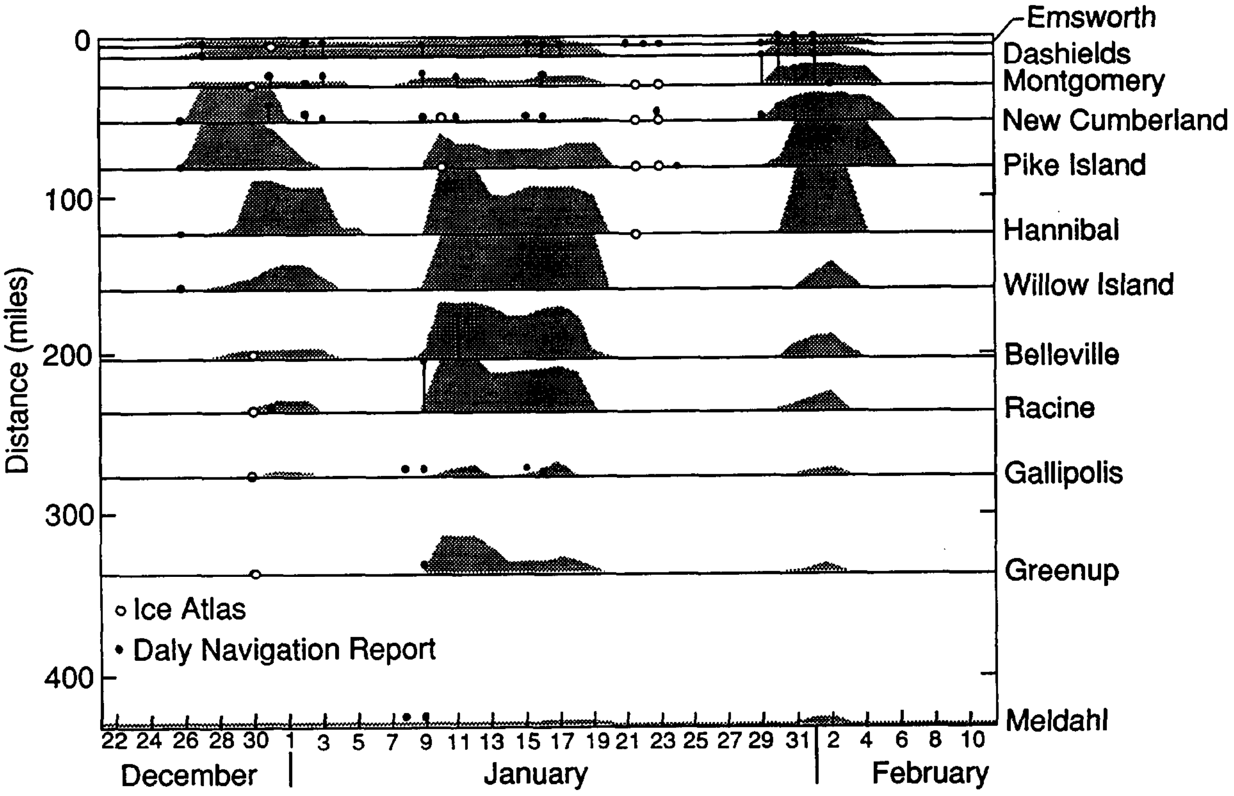

Figure 4-8. Portrayal of the output of the Ice Forecasting System for the upper Ohio River during the 1985-86 winter. The shaded areas indicate forecasted ice cover on the river; elsewhere the river was forecasted to be open. Choosing a river location on the diagram and moving across the diagram horizontally 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. 1987b) based on aerial videotapes.

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ICE  COVER  CONDITIONS  ON  12-20-89

   DAM       LENGTH    ICE  THICKNESS  PER CENT OF POOL   WATER  TEMP   AIR  TEMP
              MILES        FEET          WITH ICE           DEG  F       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    ICE  THICKNESS  PER CENT OF POOL   WATER  TEMP   AIR  TEMP
              MILES        FEET          WITH ICE           DEG  F       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    ICE  THICKNESS  PER CENT OF POOL   WATER  TEMP   AIR  TEMP
              MILES        FEET          WITH ICE           DEG  F       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
GREEN-UP      60.80      0.31             100               32.00         5.22
MELDAHL        0.00      0.00               0               32.76         6.01
```

Figure 4-9. Typical output information from the Mid-Winter Ice Forecast model, covering a five-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 4-9 (Continued).

CHAPTER 5
ICE-RELATED HYDROMETEOROLOGICAL DATA COLLECTION AND MONITORING

5-1. Introduction. Effective regulation of Corps water control and navigation projects requires the collection of a wide variety of real-time hydrometeorological data from field sites. There are reporting stations at each lock and dam. The data can be manually obtained by the lock and dam staff, or can be obtained using Data Collection Platforms (DCP's) via the GOES (Geostationary Observational Environmental Satellite) near real-time data collection system. (GOES is operated by the National Oceanic and Atmospheric Administration [NOAA].) Downlinks are in operation throughout the northern latitudes at New England Division, Ohio River Division, Rock Island District, Missouri River Division, and North Pacific Division. These downlinks enable each Division and District to collect data from field sites at intervals of 4 to 24 hours. The data are checked for completeness before they are stored in dedicated water control computers and are available for analysis by all Corps personnel. Two Engineer Regulations that provide for Corps policy when using the GOES data collection system are ER 1110-2-248 and ER 1125-2-308. Ice conditions can also be monitored using aircraft and satellites; video and still photographs are often used to track ice conditions along navigable waterways. A schematic of a systems approach to data collection and distribution is shown in Figure 5-l.

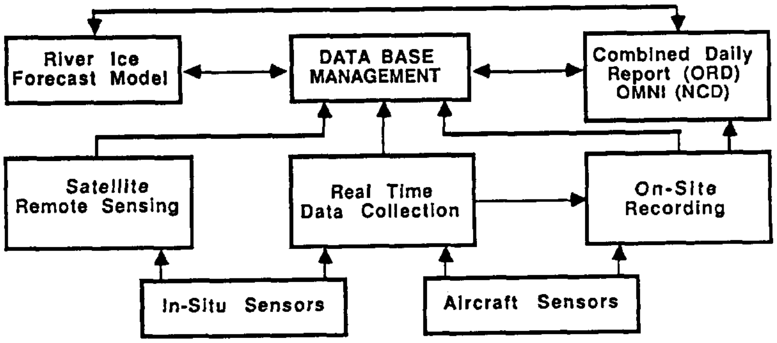


Figure 5-1. Schematic of data collection system for ice information.

Section I. Numerical Data

5-2. Near Real-Time Data Collection. Ice information can be obtained in near real-time using the GOES data collection system. Each Corps office, per ER 1110-2-249, has a Water Control Data System (WCDS) that meets the requirements of automated near real-time data collection, processing, and dissemination for making near real-time water control decisions. A GOES data collection system is made up of four parts: the DCP with related sensors, the GOES satellite, the direct ground readout station, and the WCDS. Authorization to use the GOES system is required, and software for processing and dissemination of ice information is necessary for the use of this system in a river ice management scheme.

5-3. DCP with Ice-Related Sensors.

a. DCP System. The instrumentation requirements for ice monitoring, as in any engineering study, are defined by the kind and accuracy of measurements required and the frequency of data collection necessary. Existing ice forecasting models use the temperature-index approach to predict the onset and breakup of river ice.

(1) The temperature-index approach requires water temperature and air temperature data. These are the minimum requirements for an ice monitoring station. This information, in the absence of a forecast model, could be used by the lockmaster to determine operating criteria. The other extreme would be using an energy-balance model to forecast ice conditions. The energy-balance approach would require other hydrometeorological data in addition to water and air temperatures, such as wind speed and direction, solar radiation, and river stage. Table 5-l shows the parameters to be measured at both the temperature-index and energy-balance types of stations, as well as their resolution and accuracy requirements. The DCP and sensors selected should have the capability to supply the given resolution and accuracy. The need for high resolution and accuracy in water temperature measurement cannot be overemphasized, particularly when such data are inputs to an Ice Forecasting System.

(2) Normally, for the temperature-index approach to ice forecasting, a daily average air temperature and a daily average water temperature are used. To best calculate a daily average of these values, data should be collected every hour. This also holds for the energy-balance approach. Based on the amount of data to be transmitted, a 4-hour transmission interval is best.

Table 5-l. Parameters for ice-monitoring DCP sites.

Parameter	*Resolution*	*Accuracy*
Water temperature	0.2°F (0.1°C)	±0.2°F (±0.1°C)
Air temperature	1°F (0.5°C)	±l°F (±0.5°C)
Wind speed	1 ft/s (0.3 m/s)	±5%
Wind direction	10°	±5°
Solar radiation	1 W/ft^2 (10 W/m^2)	±1 W/ft^2 (±10 W/m^2)
Barometric pressure	0.1 in. Hg (3 mb)	±0.1 in. Hg (±3 mb)
Relative humidity	5%	±5%
Precipitation	0.01 in. (0.2 mm)	±0.01 in. (±0.2 mm)
River stage	0.01 ft (0.003 m)	±0.01 ft (±0.003 m)
Dam gate setting	0.5 ft (0.15 m)	±0.5 ft (±0.15 m)
Ice thickness	0.1 ft (0.03 m)	±0.1 ft (±0.03 m)

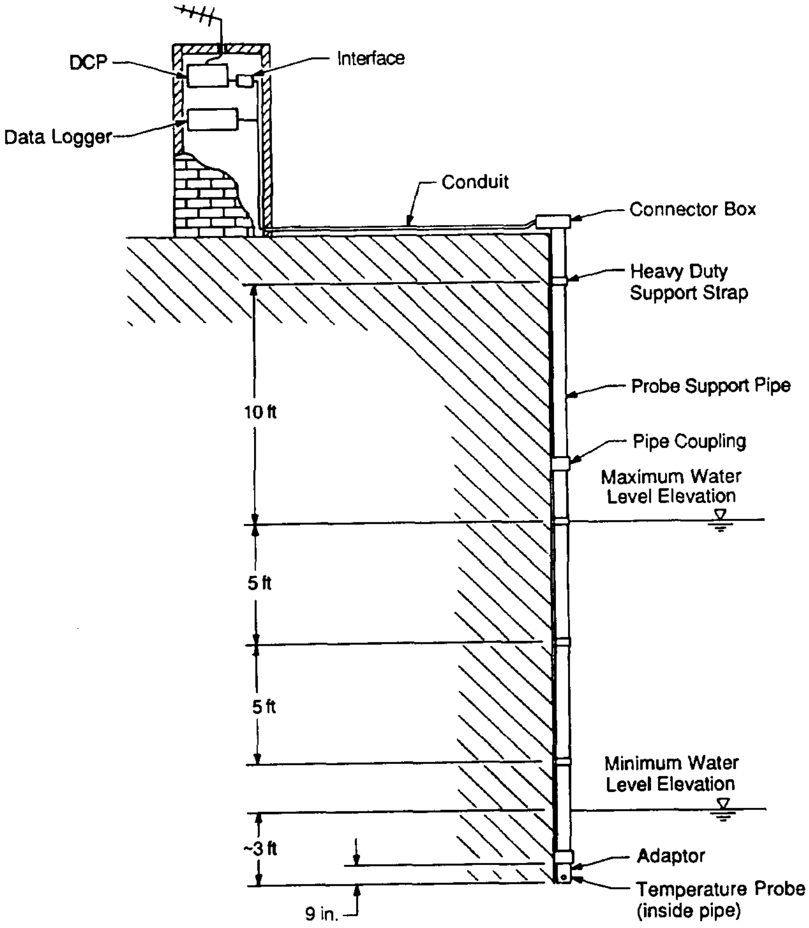


Figure 5-2. Water-temperature measurement system.

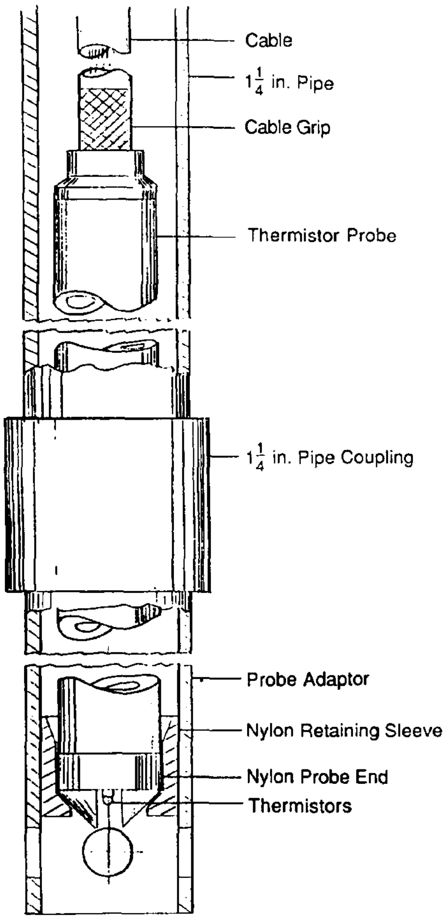


Figure 5-3. Water-temperature probe within the probe adaptor.

b. Water Temperature Measurements. A system developed for remote, accurate river water temperature measurements can be installed at any facility where a water-temperature probe can be properly mounted in contact with the flowing river water. The data can be recorded on a data logger or transmitted by a DCP through the GOES system. Described below are the water temperature measurement system itself and the method of installing it, interfacing the system with a DCP or data logger for recording the water temperature measurements, and reducing the information to engineering units.

(1) Description. This water temperature measurement system consists of a water-temperature probe, a probe support pipe with probe adaptor, connecting cable, and a data logger or DCP (Fig. 5-2). If a DCP is used, a special interface is needed for the probe.

(2) Water-Temperature Probe. The water-temperature probe is a 3-ft length of stainless steel tube with an 1-in. outside diameter (Fig. 5-3). The lower tip of the probe is nylon and contains three thermistors. A cable grip attaches the water-temperature probe to the cable at its upper end. The

water-temperature probe is deployed by dropping it down the probe support pipe and seating it in the probe adaptor. The probe is designed both to protect the thermistors from being hit by debris while allowing them to directly contact the water, and to be conveniently removable for repair or replacement. The cable connected to the water-temperature probe does two jobs: it provides electrical connection to the thermistor, and it is used to place or remove the probe by hand.

(3) Thermistors. The thermistors in the probe are typically of the bead-in-glass type and are suitable for immersion in water. The thermistors are individually spliced into the cable. Each splice must be individually tested for electrical and mechanical integrity and to make sure that it is waterproof. A strain relief device attached to the nylon tip prevents any strain from being applied directly to the thermistors. Depending on the application, the thermistors can be calibrated individually or as a group.

(4) Probe Support Pipe and Probe Adaptor. The probe support pipe protects the probe from debris or ice, holds the probe, and provides an easy way for the probe to be installed and removed. At the lower end of the probe support pipe is the probe adaptor (Fig. 5-2). The adaptor has one Teflon or nylon ring that cradles the probe and holds it in position (Fig. 5-3). The probe support pipe is 1-1/4-in. schedule 80 galvanized steel pipe with couplings. Installation of the probe support pipe and adaptor is discussed in Subparagraph 5-3b(9)(c) below.

(5) Connector Box. At the upper end of the probe support pipe is a connector box (Fig. 5-4) that provides easy access for placing or removing the water-temperature probe. A water-resistant electrical connector attaches the cable to the water-temperature probe and the cable to the data

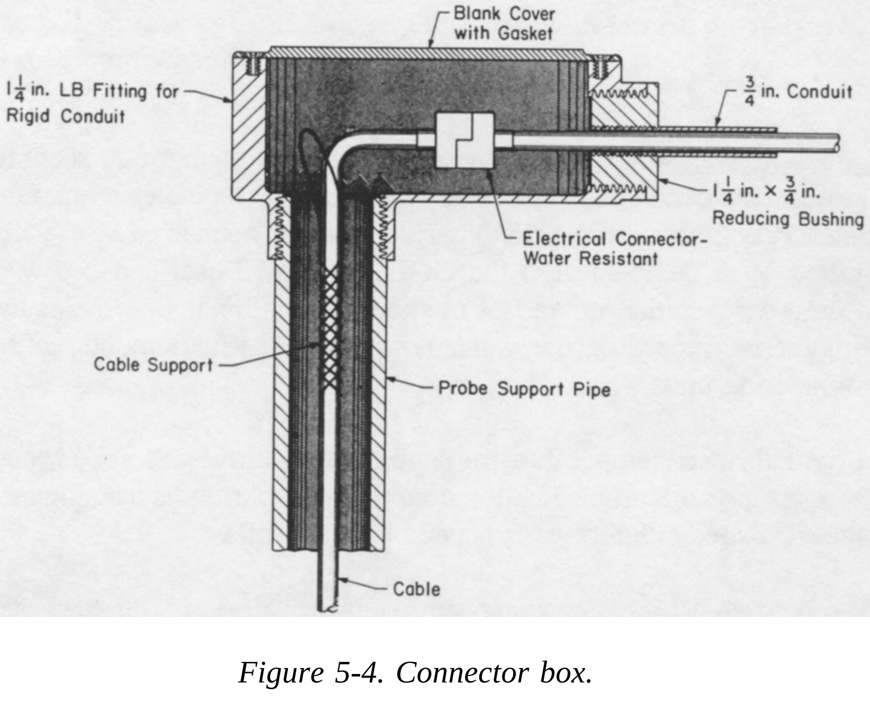


Figure 5-4. Connector box.

logger or DCP. The connector box is typically a 1-1/4-in. Line Back (LB) conduit box (zinc electroplate with aluminum lacquer), with a water-resistant neoprene-gasketed cover, and bushings to connect with the probe support pipe and conduit.

(6) Conduit. A 3/4-in. conduit protects the cable running from the connector box to the location of the DCP or data logger. In many instances existing cableways can be used. If new conduit is installed, provision for pull boxes at appropriate intervals must be made.

(7) Cable. The cable used to connect the temperature probe and the electrical connector in the connector box must be rugged. A petrolatum-polyethylene gel-filled cable with a polyethylene jacket is recommended. The cable should have a solid copper tape shield with three-pair 19-AWG conductors. This type of cable is relatively inexpensive and will provide long life. The cable is stiff and can be used only for straight runs or wide sweeps. A wire cable support grip may be attached to the upper end of the cable to assist in placing or removing the water-temperature probe. To hook up the electrical connectors in the connector box and the interface box, a cable with three 18-AWG, twisted, shielded pairs with drain wire is recommended. The cable should have a polyvinyl chloride (PVC) outer jacket. This type of cable is more flexible than the gel-filled cable and can easily be pulled through the recommended conduit. This cable has also been used to connect the temperature probe and the electrical connector in the connector box with success.

(8) DCP Interface. 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, 2-1/4 x 2-1/4 x 5 in., that is typically installed immediately adjacent to the DCP. Figure 5-5 shows a schematic diagram of the wiring of the interface box and the connections to the temperature probe and the DCP. The resistance of a thermistor R_i can be determined by the relation

$$R_i = (10{,}000)\,\frac{V_i}{V_o - V_i}$$

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. The measured voltage across the reference resistor V_f can then be used to calculate each thermistor's resistance by

$$R_i = \frac{(10{,}000)\,V_i}{2V_f - V_i}.$$

As an example, for $V_i = 0.219$ V and $V_f = 0.294$ V, the resistance of the thermistor of the water-temperature probe R_i is calculated by the above equation to be 5935 W. Suppose the calibration

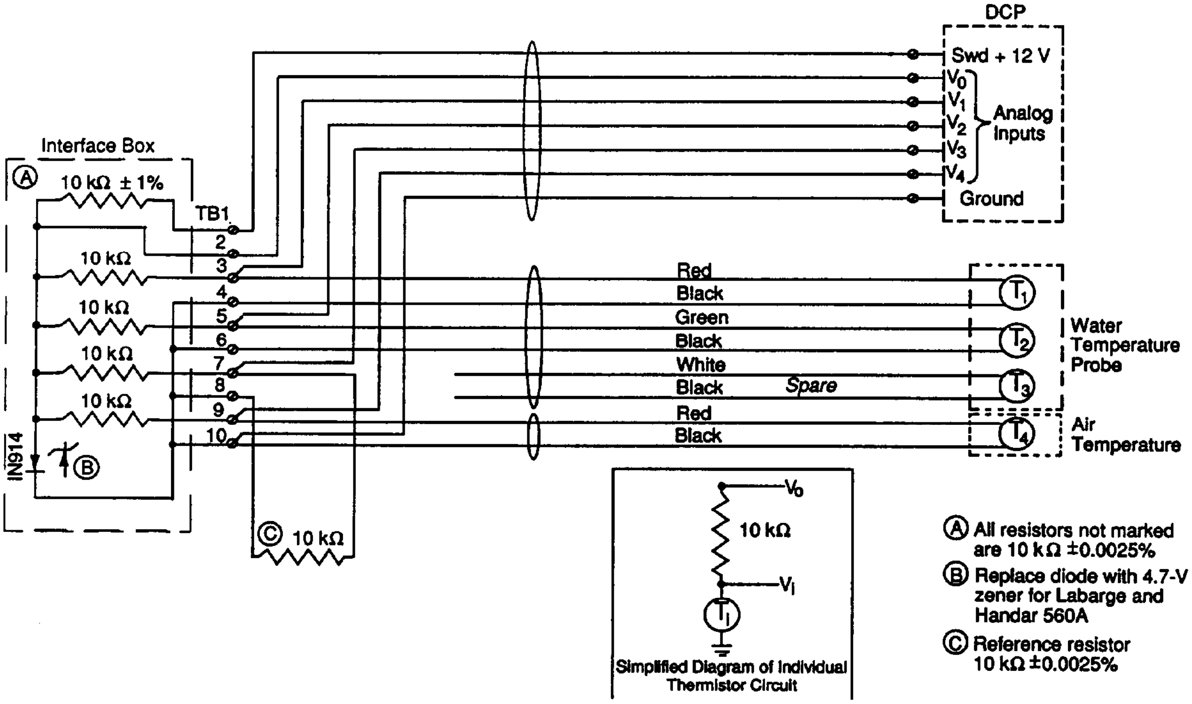


Figure 5-5. Schematic wiring diagram of DCP interface box.

table for this particular thermistor is in degrees Celsius and gives 5951.3 W for 0.1°C and 5919.1 W for 0.2°C. Then by interpolation the water temperature would be determined to be 0.15°C or 32.27°F. The foregoing discussion addresses some of the potential problems in interfacing input parameter signals to a DCP. In all cases 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, thus ensuring a trouble-free overall installation.

(9) Installation. There are five steps in the installation of this water-temperature measurement system: selection of location, determination of minimum water surface elevation, installation of probe support pipe and adaptor, installation of the connector box and conduit, and installation of the data logger or DCP.

(a) Selection of Location. The probe support pipe is typically installed on a wall or pier. The probe support pipe must be installed so that it is in contact with the moving river water. It should not be placed in gage wells, locks, or other areas where the water may stand for long periods. It should be placed in a protected location, if possible, so that it is safe from drift and ice floes. The downstream side of piers, cells, piles, pile dolphins, ladder accessways, and recesses in walls parallel to the river are acceptable.

(b) Determination of Minimum Water Level Elevation. River water level elevations or stages can change rapidly and can vary considerably. The difference between low flow levels and flood levels may be 40 to 60 ft in some locations. The minimum and maximum stage possible at a given site must be taken into account before installation. An estimate of the minimum must be made to ensure that the stage does not fall below the elevation of the water-temperature probe. If this happens, water temperature measurement will obviously not be possible. The bottom of the adaptor must be a minimum of 3 ft below the lowest stage expected. If very thick ice is expected, the adaptor should be placed even lower to keep the water-temperature probe in flowing water. The connector box should be above the normal seasonal high water levels.

(c) Installation of Probe Support Pipe and Adaptor. The probe support pipe must be installed vertically to allow the water-temperature probe to be lowered and removed easily. The length of pipe should be determined as follows: Measure the distance from the top of the wall to a point 3 ft below the low water level elevation at the site. Subtract 6 in. from this distance. This will be the total length of schedule 80 pipe plus couplings that will be required. This will bring the top of the schedule 80 pipe 3 in. above the top of the wall, which is the correct height for the connector box. The required number of sections of the galvanized steel pipe. are fastened together with couplings to form the probe support pipe. The adaptor is fastened on the lower end of the probe support pipe with a coupling. All couplings are tightened using a 24-in. pipe wrench to ensure that the entire probe support pipe and adaptor are securely fastened. The probe support pipe with the adaptor is raised into position by a crane or other means. Heavy-duty stainless steel straps are fastened at regular intervals with 1/2-in. Hilti quick studs or equivalent along the probe support pipe to hold it in position, again, with the bottom of the adaptor 3 ft below the lowest water level expected. The straps should be spaced using a maximum 5-ft interval up to the maximum water level elevation. Above the maximum water level elevation, a maximum spacing of 10 ft is allowable. The plumb of the probe support pipe should be checked continuously to make sure that the pipe remains completely vertical during installation. Otherwise, problems could occur with future probe removal or reinstallation.

(d) Connector Box and Conduit Installation. The connector box is threaded onto the probe support pipe. The connector box should be mounted such that the water-temperature probe can be placed in the probe support pipe through the top of the connector box with the cover plate removed. The connector box should be 3 in. above the wall so that it can be seen during snow removal. A reducing bushing is installed in the end of the connector box to adapt it to 3/4-in. conduit. Conduit is installed from the connector box to the point of data collection, with provisions for pull boxes where required.

(e) Installation of the Data Logger or DCP. The data logger or DCP is connected (Fig. 5-5) to the interface box. Analog inputs to DCP's with scaling resistors should be avoided or the scaling resistors removed. If a data logger is used, a 12-V-dc power supply must be provided. For consistency, the connections with the interface box should be in the order indicated.

5-4. GOES Satellite-WRSC Authorization. ER 1125-2-308 established in September of 1986 specifies that the Water Resources Support Center, Data Collection and Management Division (WRSC-C), has the responsibility and is the focal point for the US. Army Corps of Engineers Civil Works for call sign and radio frequency management.

5-5. Direct Ground Readout Station. The GOES system can only be used to relay environmental data. In-situ data from any sensor that can be interfaced to the data collection platform can be telemetered to District offices. All the data transmitters that use the GOES/DCS must be certified by the National Oceanic and Atmospheric Administration, National Environmental Satellite Service. See ER 1110-2-248 and ER 1125-2-308 for further instructions.

5-6. Water Control Data System (WCDS). The receiving sites at the Corps offices are usually a part of the WCDS. Guidance for the management of dedicated water control data systems (including equipment and software used for the acquisition, transmission, and processing of real-time data for the purpose of regulating water projects that are the Corps' responsibility) can be found in ER 1110-2-249.

Section II. Imagery

5-7. Introduction. A necessary part of an ice management program is having adequate information on ice conditions. Corps Districts generally have one or both of the following objectives when documenting ice conditions as part of their river ice management activities: to analyze past ice conditions as an aid in forecasting future conditions during a given winter, and to monitor current conditions during a winter in sufficient detail so as to plan waterway operations and anticipate navigation problems.

a. The first objective can be accomplished 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, have neither the spatial resolution nor can they routinely be in the hands of District personnel quickly enough to enable decision-making regarding waterway operations or ice emergencies (Gatto et al. 1987a, Gatto 1988a, 1988b). As satellite sensors and image processing systems improve, future images may be provided rapidly enough and may be of sufficient resolution to be useful.

b. Aerial photographs and videotapes can currently provide timely ice information to meet the second objective above, i.e., monitoring current conditions (Gatto et al. 1986, 1987b). The acquisition of ice data from these two sources is the subject of the remainder of this chapter. Taking photographs is the best approach when it is only ice conditions at selected locations that must be documented. When continuous bank-to-bank coverage of ice conditions over large reaches of a waterway is required, vertical (downward-looking) aerial videotapes are most useful. Oblique videotaping can be done through an aircraft window, but this is awkward and uncomfortable for the videographer for extended periods, and complete bank-to-bank coverage is often difficult to obtain over large river reaches. Table 5-2 provides information comparing hand-held aerial photography and aerial videotaping.

Table 5-2. Two methods for monitoring ice conditions on navigable waterways.

	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-$8O/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 1/2 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 (1/2 in.), $5000 (3/4 in.) $1600-$2200 $7/tape $1.50 each $60-$8O/hr	Continuous view of river Immediate availability of tapes Operator sees image during acquisition; could correct problems in flight Low cost No extensive training requited; 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.

5-8. Aerial Photography by Hand-Held Camera. Many photographic formats, film types, and cameras are available for taking aerial photographs. However, one of the least expensive and most useful formats is hand-held 35-mm oblique photography, producing slides or prints taken during low-altitude aircraft flights. The use of 35-mm photos for documenting general ice conditions and evaluating potential problem areas, e.g., ice jam sites, heavy ice, etc., is very appropriate when cartographic precision and photogrammetric quality are not required (Gatto and Daly 1986). Such photographs are simple and inexpensive to acquire and most people are familiar with them, as compared to other more elaborate aerial photographs. The Corps' Remote Sensing Applications Guide (Engineer Pamphlet 70-l-l) discusses these other types of aerial photographs.

a. Crew. The number of people required to get the photographs will vary depending on the complexity of the mission. When a few photographs of a small area are needed, one person can take them, even if that person is the pilot. A more complex mission would require three people including the pilot. One person would act as navigator to check items on the mission plan, direct the pilot to sites, take notes of sites photographed, change film, etc. The photographer would devote full time to taking pictures.

b. Mission Plan.

(1) The photographer and navigator should prepare a general mission plan, and discuss the plan and flight objectives with the pilot before a flight (Shafer and Degler 1986). They should discuss the features to be photographed and devise a way to communicate to let the pilot know when pictures are being taken. The pilot can then make a special effort to minimize motion and provide a good view of the area to be photographed. A professional pilot, with or without remote sensing experience, can contribute significantly by understanding what the flight objectives are.

(2) Mission planning will also permit more accurate estimates of materials needed, flight time, and overall costs for the mission. A mission plan should include a list of prospective targets and film requirements, maps marked with the most economical flight path, and a checklist of equipment, including extra batteries, lens caps, battery chargers, extra film, filters, etc. The maps help to avoid unnecessary circling and the resulting questions regarding whether a particular site has been photographed or not. When maps are used in flight, a lapboard serves as a convenient writing surface.

c. Equipment (Shafer and Degler 1986). A 35-mm camera with a built-in automatic light meter and a standard (50-mm) lens is the minimum equipment needed. Optional but useful equipment includes a zoom lens, motor drive, data and magazine backs, and filters. The configuration of a camera system depends upon budget and photographic requirements.

(1) Either a single lens reflex (SLR) or rangefinder camera can be used effectively. With a rangefinder camera, the photographer must be aware that a clear shot through the rangefinder does not assure that the camera’s field of view will not be partially blocked by part of the aircraft. With an SLR, what is seen is literally what is photographed. In difficult lighting situations where there is glare from aircraft windows, the SLR makes the photographer aware of potential problems so a correction for glare can be made during the flight.

(2) Regardless of what length of lens is used, it should be a relatively “fast” one (i.e, capable of admitting adequate light at higher shutter speeds) to avoid any loss of definition resulting from aircraft vibration. A zoom lens is useful because it allows the photographer to rapidly change for wide-angle and narrow-angle (more detailed) pictures.

(3) A motor drive permits obtaining several good exposures of a site during one pass. By simplifying the operation of the equipment, it also encourages the photographer to focus attention on the sites being evaluated, rather than concentrating on camera operation.

(4) Because of the high cost of aircraft rentals and the relatively low costs of film and processing, it makes sense to take a large number of pictures. However, labeling and sorting them is a chore at best. Data backs are particularly useful in recording the time and date, saving considerable time and effort

later. Magazine backs (for up to 250 pictures) eliminate the need to change film frequently. They provide continuity during a flight and reduce the chance of error in numbering sequential rolls of film. They also permit the photographer to take many pictures with a minimum of costly time spent changing film. However, processing of long rolls (in excess of 36 exposures) must be done by a specialty lab. If a magazine back is not utilized, a second camera is a good investment. The navigator can reload one camera while the photographer is using the other.

(5) Regular true color film for slides (e.g., Ektachrome) and prints (e.g., Kodacolor) works fine for most conditions. A relatively fast film (ASA 100 or higher) with a fine grain is best.

(6) As a matter of course, clear-filters should be on all lenses to protect them from dirt and damage. A polarizing filter may be used successfully with most films; however, the combination of a polarizing filter and the aircraft window may produce a wavy pattern on a picture. Usually, a polarizing filter improves the quality of photographs taken where reflections from water produce glare.

d. Taking Photographs (Evans and Mata 1984). Aerial 35-mm pictures may be taken nearly vertically or obliquely out the window of a small, fixed-wing aircraft or helicopter. Shutter speeds should be 1/500th of a second or faster. An altitude of 1500 ft above the ground is recommended, but any altitude must be consistent with local Federal Aviation Administration regulations. If possible, shoot with the window open. This eliminates glare and reflection caused by the glass. If you have to shoot through the window, use an 81A filter, or an equivalent haze filter, to compensate for the slight blue-green tint inherent in the acrylic glass used in most light airplane windows. Also, wear a long-sleeved dark shirt or jacket to reduce the chance of creating unwanted window reflections. Always use a lens shade. Window glare can often be eliminated by moving the lens slightly closer to the window or by draping the photographer and camera with a jacket or blanket to stop light passing over the photographer's shoulder. With a high-wing aircraft, the best shooting angles are in front of and behind the wing-struts. The front angle is best for tracking a subject, if care is taken to avoid getting the propeller in the frame. With a mid- or low-wing plane, pictures may have to be taken in a steep turn to avoid photographing the wing.

(1) A hand-held camera can take stereo pairs by photographing two successive images framed to get the same location. The movement of the aircraft between exposures will produce the parallax necessary for stereo viewing. The stereo effect will show the surface roughness of the ice, and this three-dimensional view is more realistic and easier to relate to actual visual observation. Panoramic mosaics of reaches of a river can also be made by taking as many successive photographs as required to cover the area of interest. Be sure to overlap successive photos enough to get complete coverage of the area. Note that the overlap areas will be in stereo.

(2) If repetitive photographs are going to be taken during different flights over periods of days, weeks, or months, the comparison of photos from the several flights will be easier if the same camera, focal length lens, filters, etc., are used each time. Taking photos from the same general position, and showing the same ground area, will also expedite comparisons of repetitive photos. Such repetitive photos give a visual time series of ice conditions, and are useful for determining how conditions are changing.

e. Photointerpretation. An advantage of using hand-held aerial photographs is that almost everyone has taken them and looked at, i.e., "interpreted," them. No special equipment is required to study the photos. The most important element for interpreting photos of ice conditions is to have a person familiar with river ice involved in the interpretation. Engineer Pamphlet 70-1-1 addresses photointerpretation techniques in depth.

5-9. Aerial Videotapes. 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 9 x 9-in. aerial photographs. Such continuous coverage can be acquired with a video camera mounted to look through the nose or out the side door of a helicopter, or through a belly port of a fixed-wing aircraft.

a. Crew. Since videotaping will generally be used to get continuous coverage, a pilot and videographer are all that is required. A navigator is not required because all of a waterway is going to be covered and site selection and spotting are not done. The pilot should be familiar with techniques for maintaining a flight course so as to get complete coverage while keeping the video camera in a vertical or near-vertical position. The videographer will have to use a zoom lens and tell the pilot when altitude adjustments are required to maintain bank-to-bank coverage.

b. Mission Plan (Maggio and Baker 1988). Just as when acquiring hand-held aerial photographs, careful mission planning must be done to get useful videotapes. It is important to keep in mind that bank-to-bank coverage should be maintained while videotapes are being taken. This will allow easy locating later by comparing features on the tapes with those on maps. 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 5-3).

c. Equipment (Meisner and Lindstrom 1985, Meisner 1986). The type and setup of videotaping equipment (Fig. 5-6) used to get vertical videotapes from an aircraft will depend on cost and requirements. Numerouscameras and recorders exist, and technology is improving constantly, but whatever kind of system is used it should be professional-grade, compact, and built to take abuse, and should provide high quality video. Camcorders combine video cameras and recorders in one unit and also provide high quality tapes.

(1) The audio track of the airborne Video Cassette Recorder (VCR) may be connected to a "press to talk" microphone, allowing oral comments to augment written notes during flight. In particular, landmarks and locations should be called out. A soundproof headphone intercom system used in the aircraft can be directly connected to the VCR audio input.

(2) Video monitors display the video image. Portable monitors generally have a 5-in. diagonal screen, providing a 3 x 4-in. image, although color monitors as small as 2.6 in. (screen size of 1.6 x 2.1 in.) are available and may be useful for airplane cockpit mounting. The video monitor must be located within the pilot's view to provide feedback for positioning and control

Table 5-3. Aerial video coverage versus pixel (picture element) size, altitude, and aircraft speed (based on 2/3-in. video format).

Coverage		*Effective pixel size**	*Altitude (feet above ground) requiredfor various lens focal lengths*					*Maximum aircraft speed** (mph)*
Width	*Length*							
(ft)		*(ft)*	*6.0 mm*	*8.5 mm*	*12.5 mm*	*16.0 mm*	*25.0 mm*	
500	375	2	341	483	710	909	1,420	63
1,000	750	4	682	966	1,420	1,818	2,841	126
1,500	1,125	6	1,023	1,449	2,131	2,727	4,261	189
2,000	1,500	8	1,364	1,932	2,841	3,636	5,682	252
2,500	1,875	10	1,705	2,415	3,551	4,545	7,102	315
3,000	2,250	12	2,045	2,898	4,261	5,455	8,523	379
3,500	2,625	14	2,386	3,381	4,972	6,364	9,943	442
4,000	3,000	16	2,727	3,864	5,682	7,273	11,364	505
4,500	3,375	18	3,068	4,347	6,392	8,182	12,784	568
5,000	3,750	20	3,409	4,830	7,102	9,091	14,205	631
5,500	4,125	21	3,750	5,313	7,813	10,000	15,625	694
6,000	4,500	23	4,091	5,795	8,523	10,909	17,045	757
6,500	4,875	25	4,432	6,278	9,233	11,818	18,466	820
7,000	5,250	27	4,773	6,761	9,943	12,727	19,886	883
7,500	5,625	29	5,114	7,244	10,653	13,636	21,307	946
8,000	6,000	31	5,455	7,727	11,364	14,545	22,727	1,009
8,500	6,375	33	5,795	8,210	12,074	15,455	24,148	1,073
9,000	6,750	35	6,136	8,693	12,784	16,364	25,568	1,136
9,500	7,125	37	6,477	9,176	13,494	17,273	26,989	1,199
10,000	7,500	39	6,818	9,659	14,205	18,182	28,409	1,262
10,500	7,875	41	7,159	10,142	14,915	19,091	29,830	1,325
11,000	8,250	43	7,500	10,265	15,625	20,000	31,250	1,388
11,500	8,625	45	7,841	11,108	16,335	20,909	32,670	1,451
12,000	9,000	47	8,182	11,591	17,045	21,818	34,091	1,514
12,500	9,375	49	8,523	12,074	17,756	22,727	35,511	1,577

* 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.

of the aircraft. A sun shield on the monitor screen is essential for in-aircraft use. Interpretation in the office can be done with the portable monitor, but a larger screen is preferable.

(3) Power supply should be taken from the aircraft if possible. Airplanes operating on 12 V should be able to power the system directly through the cigarette lighter outlet. Larger planes operate on 24-V systems, requiring a dc adaptor to directly power the video system. Alternatively, power can be obtained from built-in, rechargeable battery packs or a rechargeable, sealed, lead-acid battery (gel cell).

(4) The playback video system used for interpretation in the office following the flight should have fast-motion, slow-motion, and still-frame capabilities. Of these, the still-frame (or freeze-

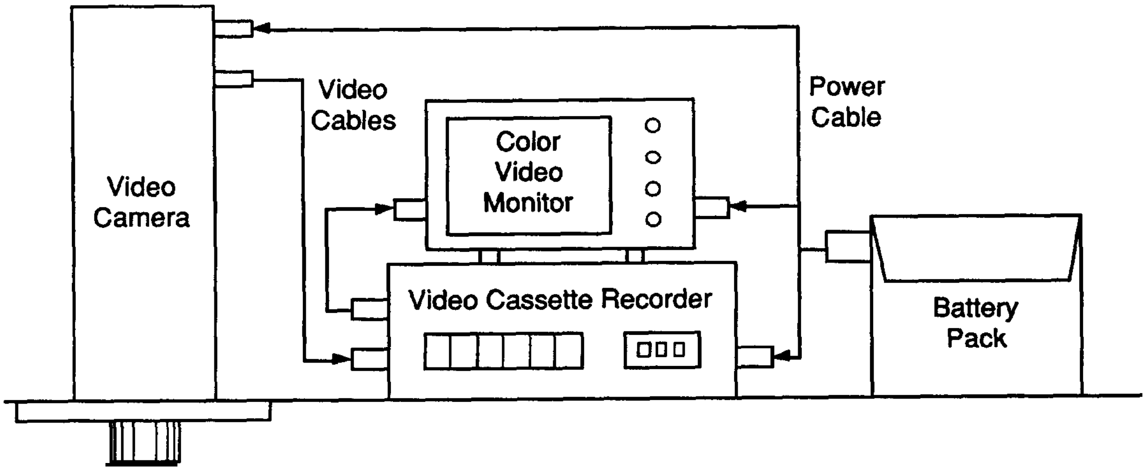
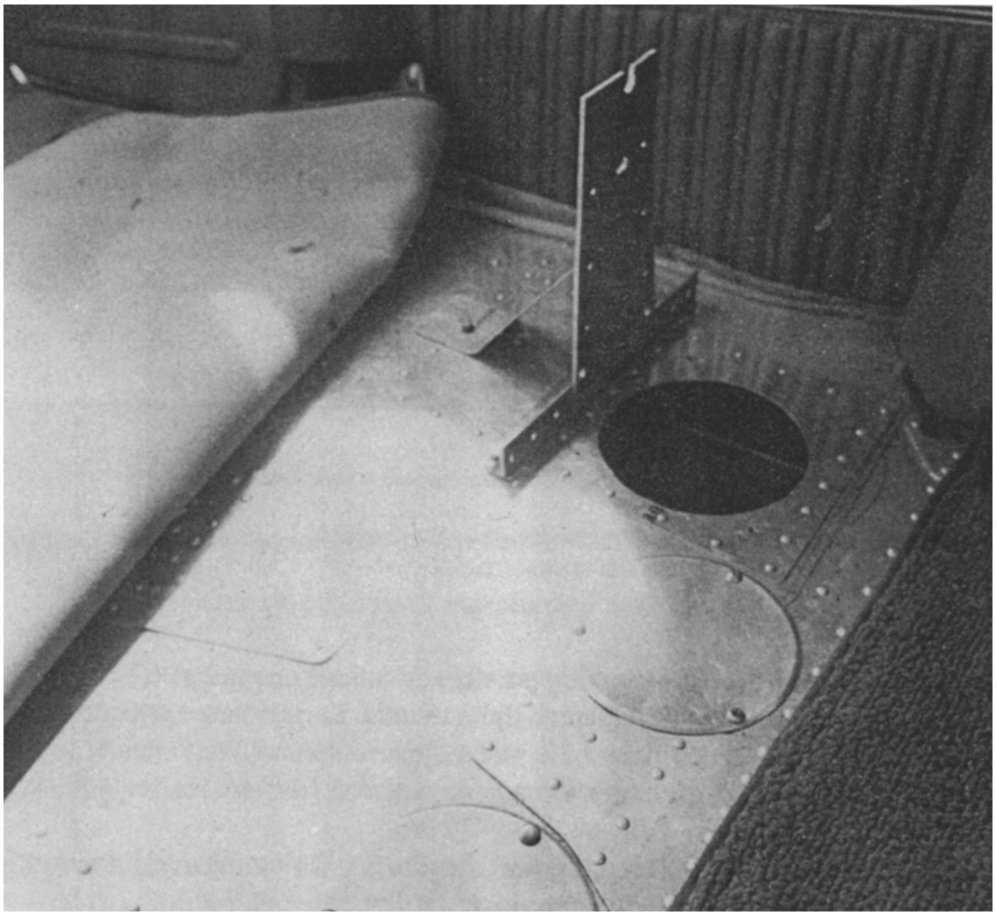


Figure 5-6. Generalized video equipment setup in an aircraft for vertical aerial videotaping (after Meisner 1986).



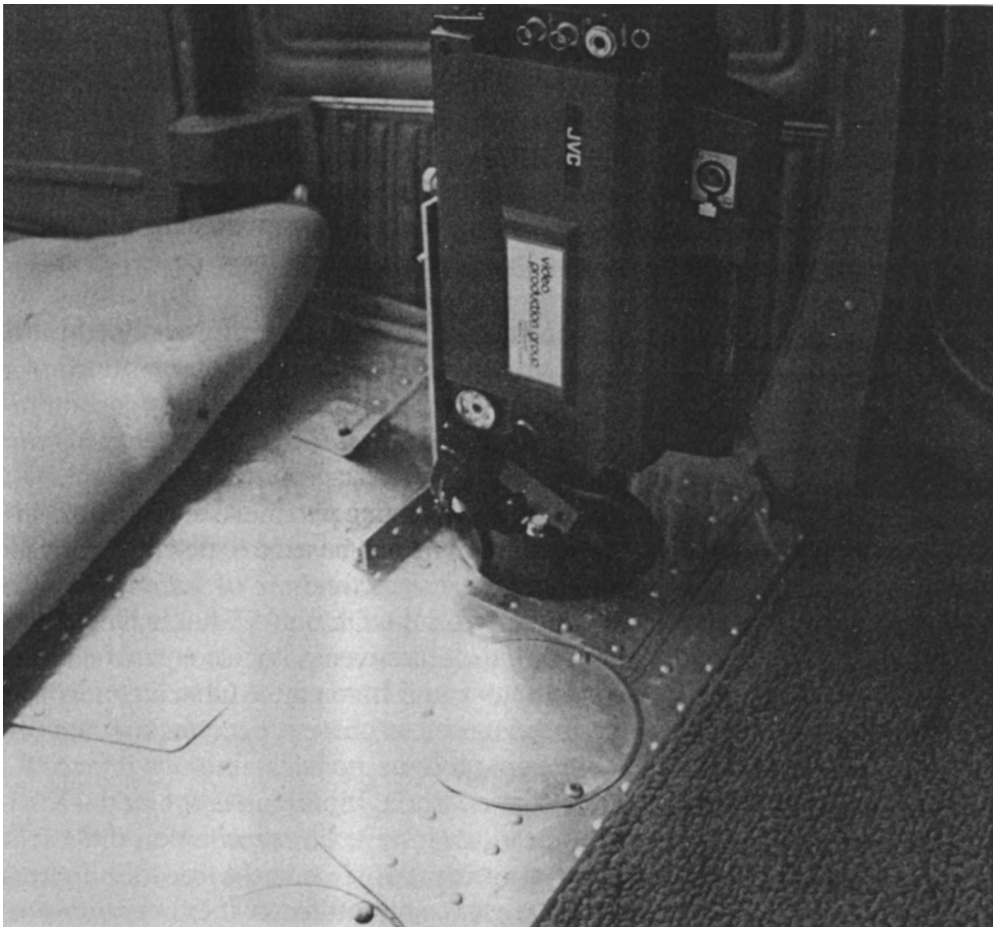
a. Camera mount and viewing port.

Figure 5-7. Simple video camera mount in the floor of an aircraft for through-a-port videotaping.

frame) is the most important, since a single frame must be displayed if actual mapping is done during interpretation. The still-frame must be free from noise bars and hold steady on the screen. A playback VCR with stereo audio tracks is useful. This allows one track to be used for in-flight annotation, the other track for later interpretation comments.

d. Taking Videotapes (Maggio and Baker 1988, Meisner 1986). The blur problem caused by aircraft vibration can be solved by properly mounting a video camera on the floor of an aircraft for taping through a port (Fig. 5-7). Districts should be sure that contractors taking vertical videotapes have a mount that has been tested and proven to work. Forward-looking mounts would be useful for providing improved navigational assistance to the pilot. Forward-looking video also improves the ability to locate the imagery during interpretation. The background of each frame will show a wide area, giving more landmarks, while the foreground will provide larger scale for interpretation. Since whatever appears at one time in the background will later appear in the foreground, the continuous coverage nature of video imagery helps in this case. Even in applications requiring vertical coverage, a selectable forward inclination would be very useful for navigating up to the start of a flight line. The camera could be tilted forward on the approach to the line, and returned to the vertical position at the start of the line.

b. Camera in place for vertical videotaping.



e. Tape Interpretation. In addition to the portable equipment used during tape acquisition in an aircraft, and a monitor for office use, some additional hardware can be useful when viewing the tapes in the office. The importance of a high quality still-frame capability has already been mentioned. High quality, four-head VCR's can provide a more steady image than compact portable units, and may be worth obtaining for interpretation use. The best still-frame images are provided by a digital freeze-frame unit, also called a frame-grabber. Such a device converts a frame of imagery to digital data, stores it in computer memory, and regenerates a video image from the stored data. Unfortunately, these devices are quite expensive. Good quality prints, slides, and film negatives can be made directly from videotapes with a Polaroid Frame Grabber. As with 35-mm photographs, almost everyone has looked at videotapes, and the most important element in interpretation is to have a person who knows river ice, and has observed and studied it, be involved in the video image interpretation.

5-10. Ground-Based Video.

a. Normal Speed. Video systems consisting of battery operated portable cameras and recorders, or combined camcorders, can be used to document ice conditions and other problems along a river. Rock Island District has supplied the lockmasters with these devices and is using them to document both wintertime and summertime problems. Such problems may be ones calling for special maintenance attention, ones suggesting operational or structural modifications, or ones that can potentially lead to litigation. These video systems are attractive because of the instant documentation that is available and the low cost of operation. When using a video camera for documentation, it is helpful to remember the following points. Known problem areas should be regularly documented, preferably from the same vantage point. A tripod should be used whenever possible to minimize motion in the picture. And finally, deliberate movement of the camera or lens (panning and zooming) should be minimized, and if done, done slowly.

b. Time-Lapse. When a River Ice Management Plan is being developed and a problem area has been identified, it is desirable to obtain a complete record of observations of ice problems at that problem location throughout the winter. These problems are often concentrated at the upstream approaches of the locks, where broken ice becomes lodged, adversely affecting the operation of lock gates and the movement of tow traffic. Time-lapse videography permits the collection of an extensive record of these conditions without having personnel occupying the site continuously for the entire ice season. Time-lapse videography can be used to determine the causes of specific ice problems at a location, or to monitor the effectiveness of ice control solutions. Time-lapse videography has been used successfully on the Ohio and Illinois Rivers both to determine the causes of ice problems and to monitor the effectiveness of ice control measures at locks, such as high-flow air systems. At Emsworth Lock and Dam on the Ohio River near Pittsburgh, Pennsylvania, time-lapse videography has been used to observe the effects of winds, currents, and large tow traffic on ice movement into the upper lock approach since the winter of 1984-85. At Peoria Lock and Dam on the Illinois River near Peoria, Illinois, and at Starved Rock Lock and Dam on the Illinois River near Ottawa, Illinois, data have been recorded on the effects of winds, river currents, and large tow traffic on the movement of ice in the upper lock approaches. In addition, the effectiveness of high-flow air screens was monitored at the latter two sites. The time-lapse videographic records at Peoria have been taken annually since the winter of 1984-85, while records from Starved Rock are available since 1985-86. In addition to wintertime uses, various Corps facilities—e.g., Starved Rock Lock and Dam in Illinois and Lower Granite Lock and Dam on the Snake River in Washington-are using video cameras to monitor recreational boating, commercial navigation, debris control, and general facility security.

(1) Equipment. There are two general types of time-lapse setups that are available today, time-lapse photographic film cameras, and time-lapse VCR's, Of the two, the VCR system is preferable (it is easier to work). While the initial cost of both systems is comparable, the VCR system is substantially cheaper to operate. The minimum equipment required for an ice monitoring time-lapse videographic system consists of the following:

—Time-lapse recorder with recording time ranges of 2 to 240 hours and monitor.
—Solid state imaging video-camera and zoom lens with a focal length range of 10-100 mm.
—Environmental camera housing capable of maintaining an interior temperature of 40°F while the ambient air temperature can be as low as -60°F. The camera housing should be mounted on a remotely controlled pan and tilt mount.
—Remote controllers for the pan-tilt mount and the zoom lens.
—Miscellaneous equipment such as mounting brackets, cables, relay boxes, etc., that may be required for a specific site.

(2) Installation. The camera is best installed in a high location, such as an antenna mast or the crane-way over the dam gates. The VCR and various controllers should be located in a protected shelter where it is convenient to monitor the video and to change tapes. At a lock facility, this can be the lockmaster's office or one of the machinery buildings. The main requirements here are that the humidity be low enough that condensation does not form, and the temperature be kept between 40 and 100°F. Figure 5-8 is a schematic of a typical installation. The problems encountered in placing cables for the controllers and the video signal may influence the choices for placing the equipment.

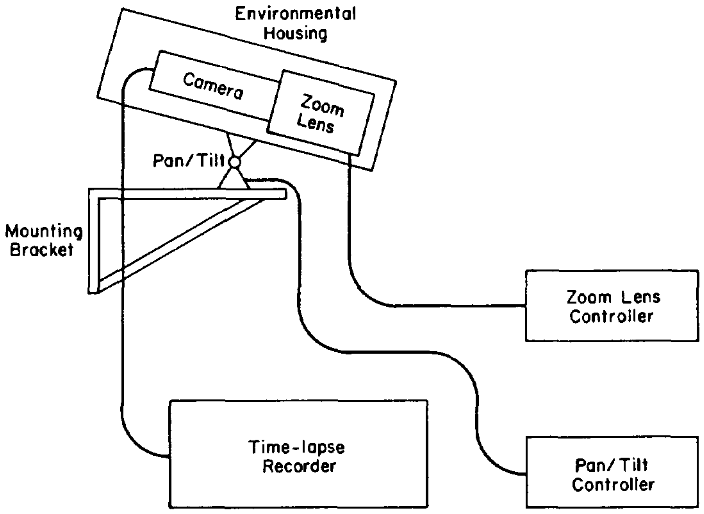


Figure 5-8. Schematic diagram of a ground-based time-lapse video system.

CHAPTER 6
STRUCTURAL SOLUTIONS

Section I. Ice Retention Methods

6-l. Introduction. An example of river ice management by ice control structures is found on the St. Marys River at Sault Ste. Marie, Michigan. The harbor there, called Soo Harbor, covers a large area, and immediately downstream from the harbor is a 600-ft-wide, man-made navigation channel, called Little Rapids Cut. Below the cut lies Lake Nicolet with its low velocity flows. The channel is dredged to a minimum depth of 27 ft, and ocean-going vessels and lake carriers of various sizes up to 1000 ft long use it. Ice broken from Soo Harbor by passing ships would accumulate in Little Rapids Cut so much that at times the river discharge was retarded and unacceptably high water levels would develop in the harbor. Also ferry traffic to an island community was frequently disrupted.

a. An ice-hydraulic-navigation model was made of this locale and tests were conducted. The tests showed the optimum location, orientation, and size for an ice control structure that acted mainly on the water surface. An ice boom with a 250-ft-wide navigation opening was designed, built, and installed in 1975 at the harbor end of Little Rapids Cut. Later, two gravity structures were set in the harbor upstream of the boom to inhibit some troublesome lateral movement that would develop in the 1-3/4-mile-long ice sheet that was retained by the boom. The booms and the structures were removed in the spring and reinstalled in the fall. Artificial islands eventually replaced the gravity structures. This work was done as part of a demonstration program that has been completed; the booms, however, continue to be used because they provide stability to the ice cover during storms and intermittent ship transits (Perham 1985).

b. The above situation is unusual for a river system because of the size of the harbor and the depth of the navigation channel. Most rivers have a 9-ft navigation depth and handle barge traffic almost exclusively (Perham 1988a). Harbors and fleeting areas for most navigable rivers are not found exclusively in bays and inlets, as are coastal seaports, but are instead found in almost any type of river reach, including the inside and outside of bends, at confluences, and in straight reaches. Structural ice control measures would most likely have to be located outside of the harbors and fleeting areas to permit free access of barge tows to moorings and wharfs and to accommodate cross-stream traffic (Perham 1988b).

6-2. Flexible Structures. The primary flexible ice control structures applicable to navigable rivers are ice booms. Another supplemental device with promise is called the line array, but it has only undergone experimental testing. A common characteristic of flexible structures is that they are installed, removed, and maintained using common maritime equipment, such as barges, cranes, winches, and tugs.

a. Ice Booms. Ice booms are the most widely used type of sheet ice retention structure. The first such structures were long booms of logs chained or wired end-to-end into a long line across a water

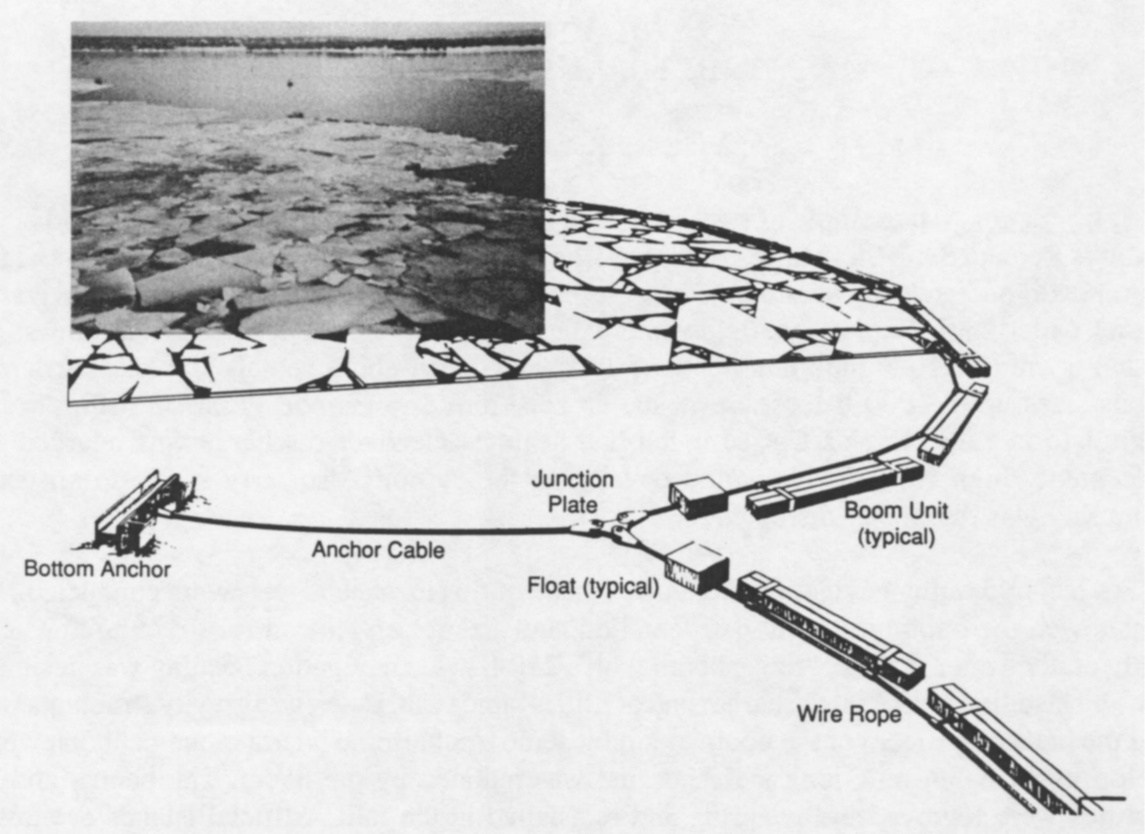


Figure 6-1. Typical ice boom arrangement.

body. The logs provided flotation as well as structural strength. Sometimes, several logs were bolted side by side to obtain sufficient flotation. The booms were anchored onshore and to boom docks (rock-filled timber cribs) in midstream. The trash booms used at hydroelectric plants to keep floating debris from power canals are similar and may have been the first to use a continuous wire rope for structural strength. The most common type of ice boom consists of large floating timbers held in place by a wire rope structure and buried anchors (Fig. 6-l). The weight of the wire rope connectors, anchor rope, and junction plates is carried by supplemental floats.

(1) Boom structures can be installed across a portion of a river or across the entire width, according to the amount of control needed. To be effective, an ice boom must restrain an ice cover at the surface without restricting water flow, and it must move up and down with the ice cover. The floating timbers intercept moving ice floes, frazil slush, and brash ice to form an unconsolidated ice cover upstream of the boom. In early winter the ice cover usually becomes consolidated within 10 days. An unconsolidated ice cover develops most rapidly and reliably when the water velocity (bringing ice floes to the boom) is as large as possible without causing appreciable quantities of ice to pass beneath the boom. Field tests show that this velocity for a straight, 9-ft-deep channel is 1.5 ft/s. This value is also optimum for the deeper (35 ft) but somewhat irregular Beauharnois Canal (a power and navigation canal in Canada). During the freezeup period, the flow on the

Beauharnois is reduced to approximately 1.6 ft/s to allow a smooth ice cover to develop. As the ice cover becomes solid, the canal flow is gradually increased until the flow velocity is returned to 2.2 ft/s and higher for efficient power generation. In several major boom installations the mean velocities vary from 0.95-2.75 ft/s, but during freezeup, attempts are made to keep velocities no greater than 1.5-1.6 ft/s.

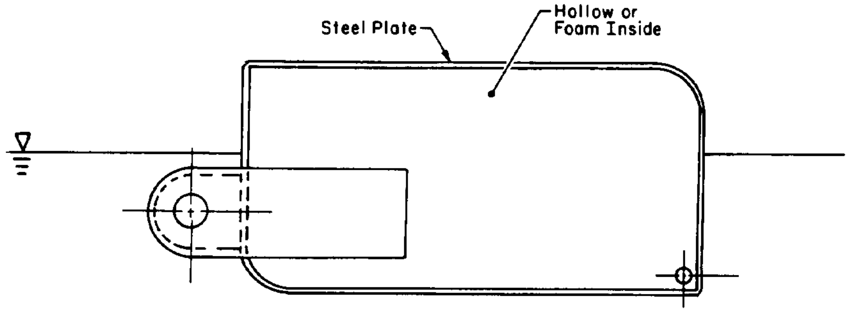
(2) Although ice booms vary in function and appearance, their wire rope structures are similar. The wire ropes to which the timbers or pontoons are connected are somewhat longer than the spacing between the anchors and anchor ropes, giving a boom its scalloped appearance. In existing booms these lateral ropes are longer than the span by values ranging from 6 to 25 percent; the greater length lowers the tension in the lateral rope. Individual wire ropes are connected by steel junction plates that are supported by buoys or floats. Galvanized wire ropes are often used for longer life, although the strength of the galvanized wire is 10 percent less than that of uncoated wire when new. However, for the Allegheny River Ice Boom at Oil City, Pennsylvania (discussed later), the Pittsburgh District chose stainless steel wire rope for long life. District personnel determined that the earlier anticipated replacement of galvanized wire rope, due to abrasion and subsequent corrosion, would exceed the higher initial cost of stainless steel.

(3) Figure 6-2 shows a variety of ice boom designs, The designs shown in Figures 6-2h, i, and k have been used as shear booms for waterborne trash and logs; the floating material is expected to slide along the upstream face of the boom. The proper combination of buoyancy and stability can be determined through tests and analysis. Wooden timbers can lose effectiveness with time by becoming waterlogged.

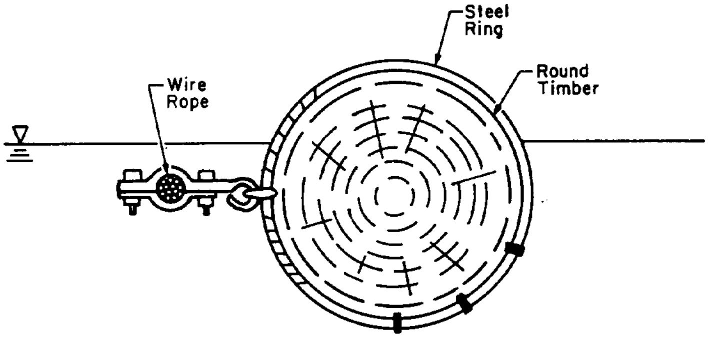
(4) Anchor types may vary on any one boom and from one boom to the next. They rely on the strength of the riverbed and bank materials. A structure that reaches from shore to shore will have anchors onshore and sometimes along the river bottom, depending on the expected loading. The length of the anchor lines from the river bottom to the floating parts is generally about 12 times greater than the water depth. Typical anchors are shown in Figure 6-3. The cell structure (Fig. 6-3c) is sometimes used at the midstream end of a spur boom, i.e., one that reaches only partway across a river.

(5) A representative list of flexible ice booms is given in EM 1110-2-1612. The largest boom to be installed in recent times is in Lake St. Francis on the St. Lawrence River, upstream of the Beauharnois Canal in Canada (Fig. 6-4). It was designed to accommodate ship navigation and was extensively tested as a model.

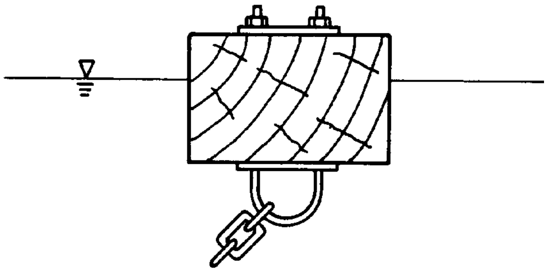
(6) Though not a navigation application, a similar design was used for the boom built by the Corps of Engineers in 1982 on the Allegheny River upstream of its confluence with Oil Creek at Oil City, Pennsylvania (Fig. 6-5). Oil City has along history of ice jams and floods that were caused by large deposits of frazil ice downstream of the confluence in a deep section of the river. The accumulations especially restrict flows from ice breakup on Oil Creek, which precedes ice breakup on the Allegheny River. The ice cover upstream of the boom stabilizes in early winter and eliminates the primary source of frazil ice. A boom of this type could be utilized to control ice from a tributary stream that otherwise would enter a navigable river.



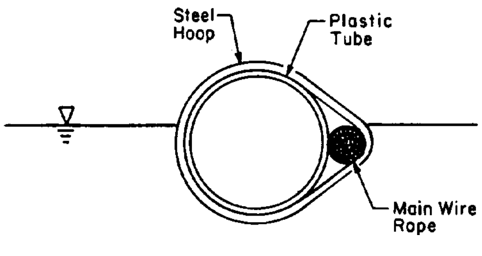
a. Rectangular pontoon boom.



b. Round timber boom.

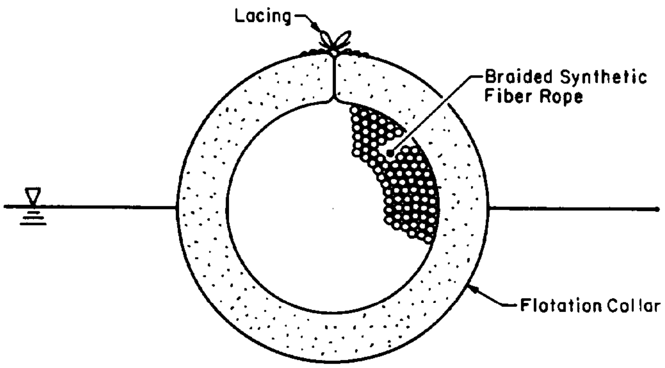


c. Single rectangular timber boom.

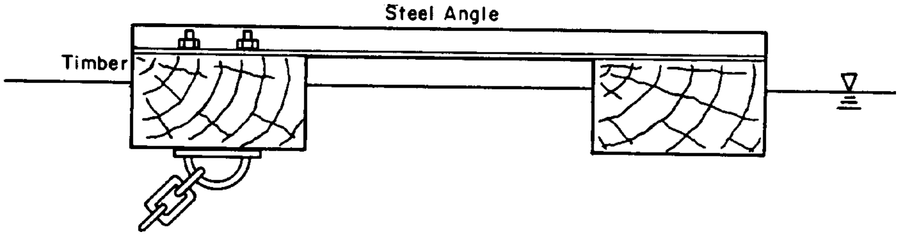


d. Plastic tube boom.

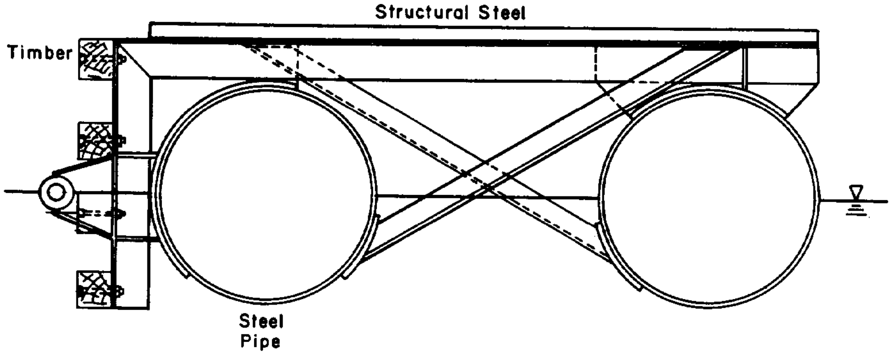
Figure 6-2. Cross sections of ice boom timbers and pontoons for a variety of ice boom designs.



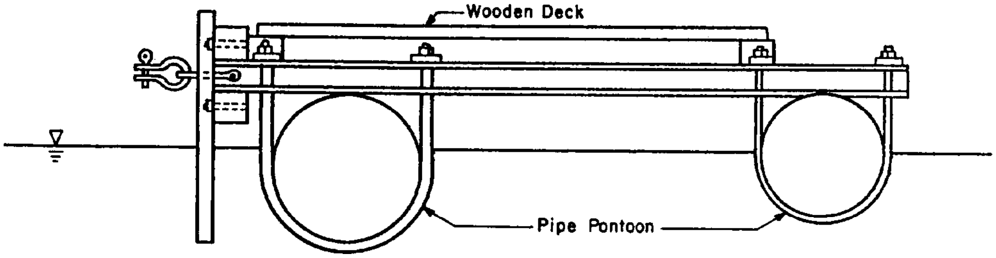
e. Synthetic fiber rope boom.



f. Double rectangular timber boom.

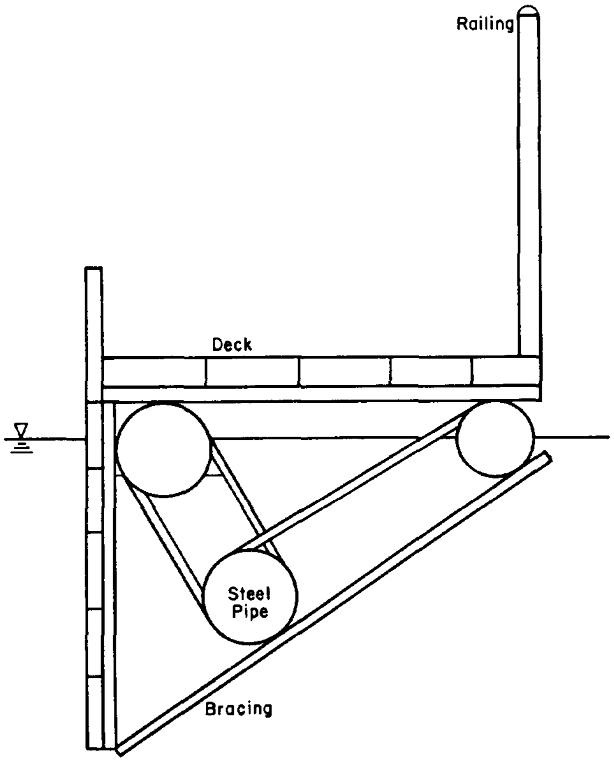


g. Double steel pontoon boom.

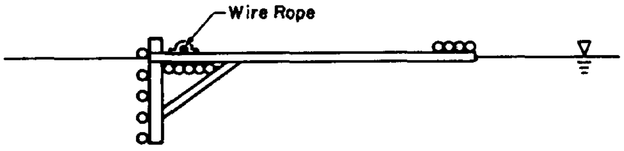


h. Shear boom.

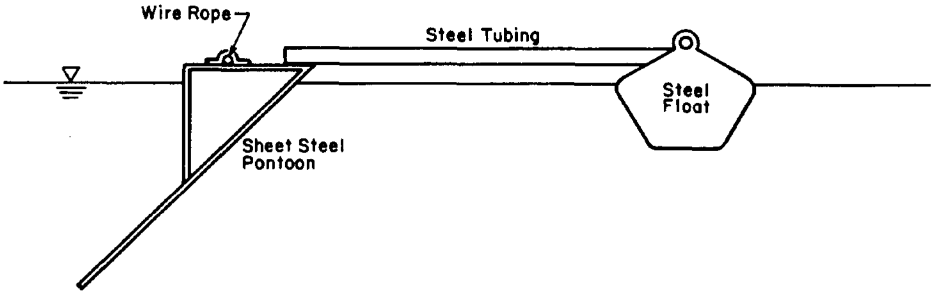
Figure 6-2 (Continued).



i. Shear boom.

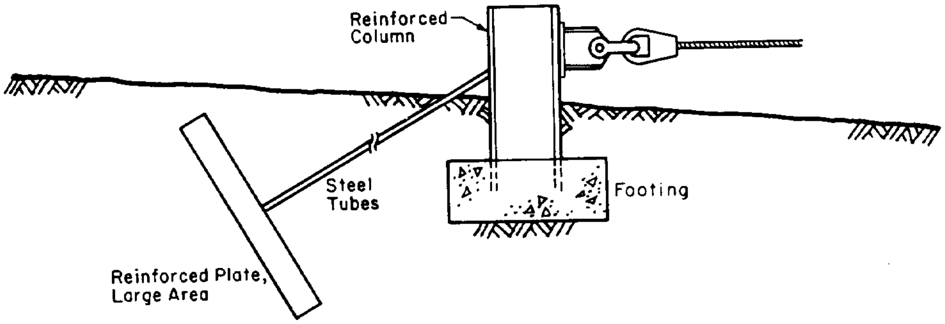


j. Wooden pole boom.

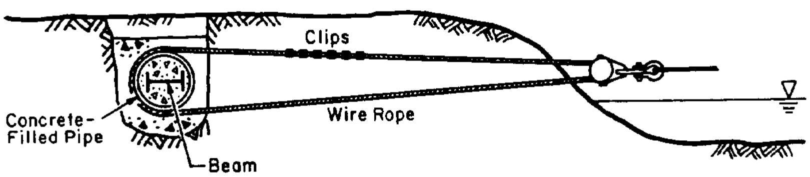


k. Triangular-skirted pontoon boom.

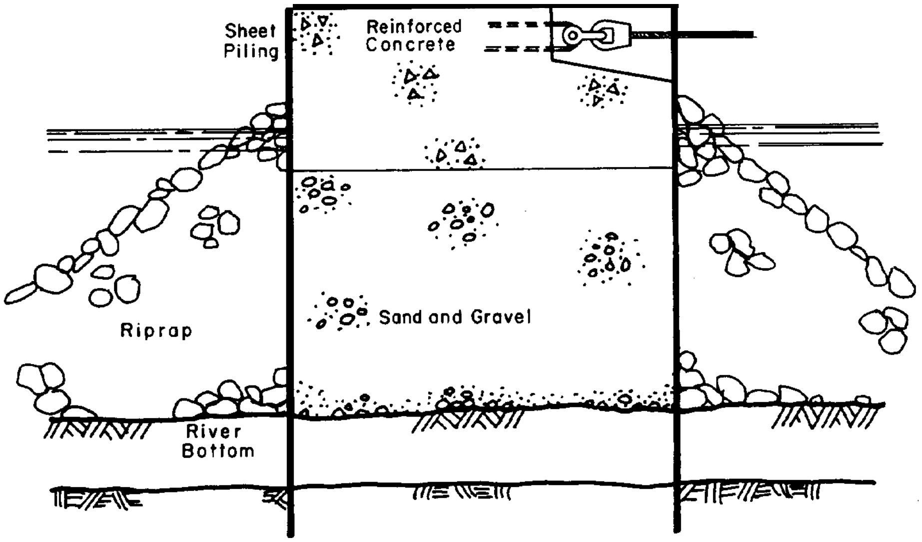
Figure 6-2 (Continued). Cross sections of ice boom timbers and pontoons for a variety of ice boom designs.



a. *Deadman and pedestal (end, land).*

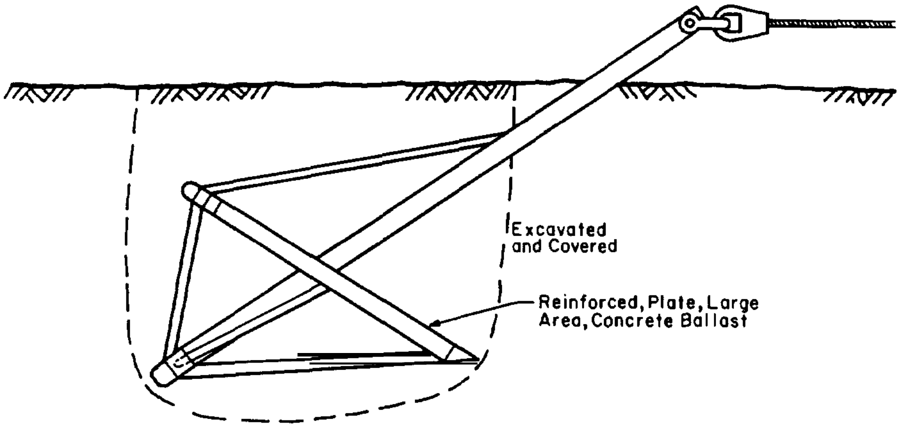


b. *Deadman and wire rope (end, land).*

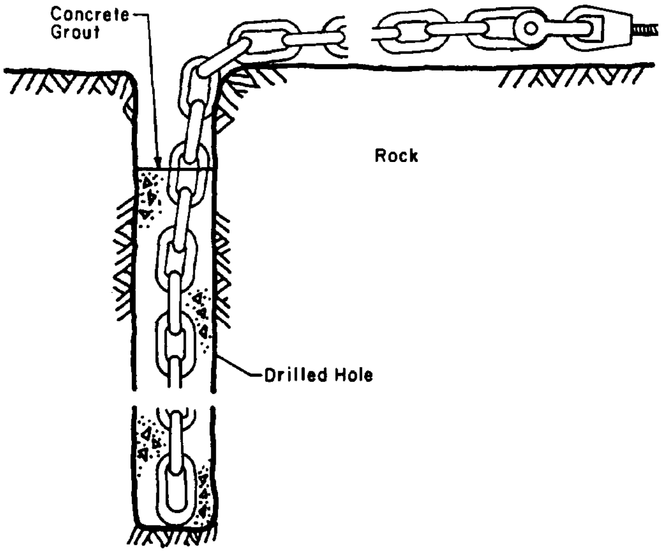


c. *Sheet piling cell (end, in water).*

Figure 6-3. Typical ice boom anchors.

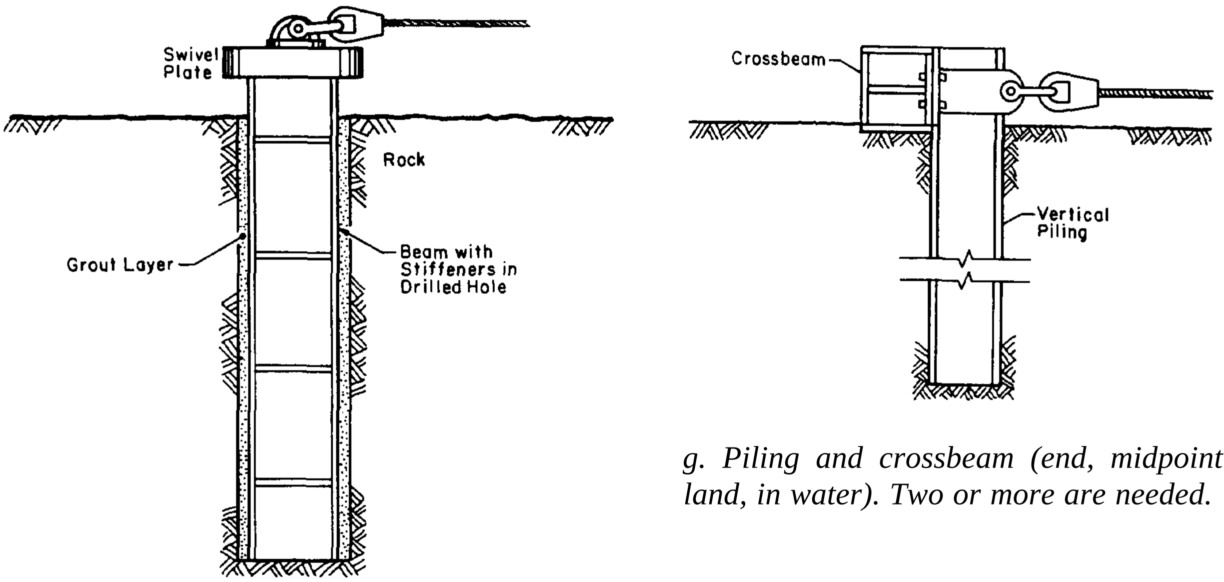


d. Steel anchor (midpoint, in water).



e. Grouted chain (midpoint, in water).

Figure 6-3 (Continued). Typical ice boom anchors.



g. Piling and crossbeam (end, midpoint, land, in water). Two or more are needed.

f. Grouted weldment (midpoint, in water).

Figure 6-3 (Continued).

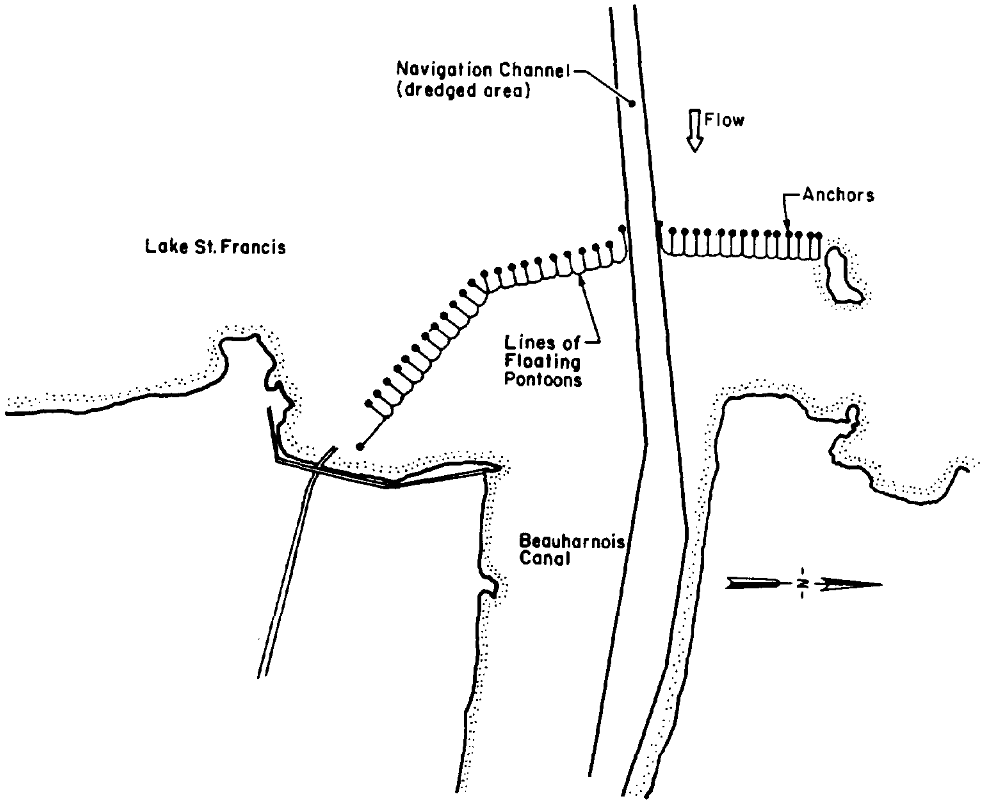


Figure 6-4. Plan view of the Lake St. Francis ice boom built in 1981.

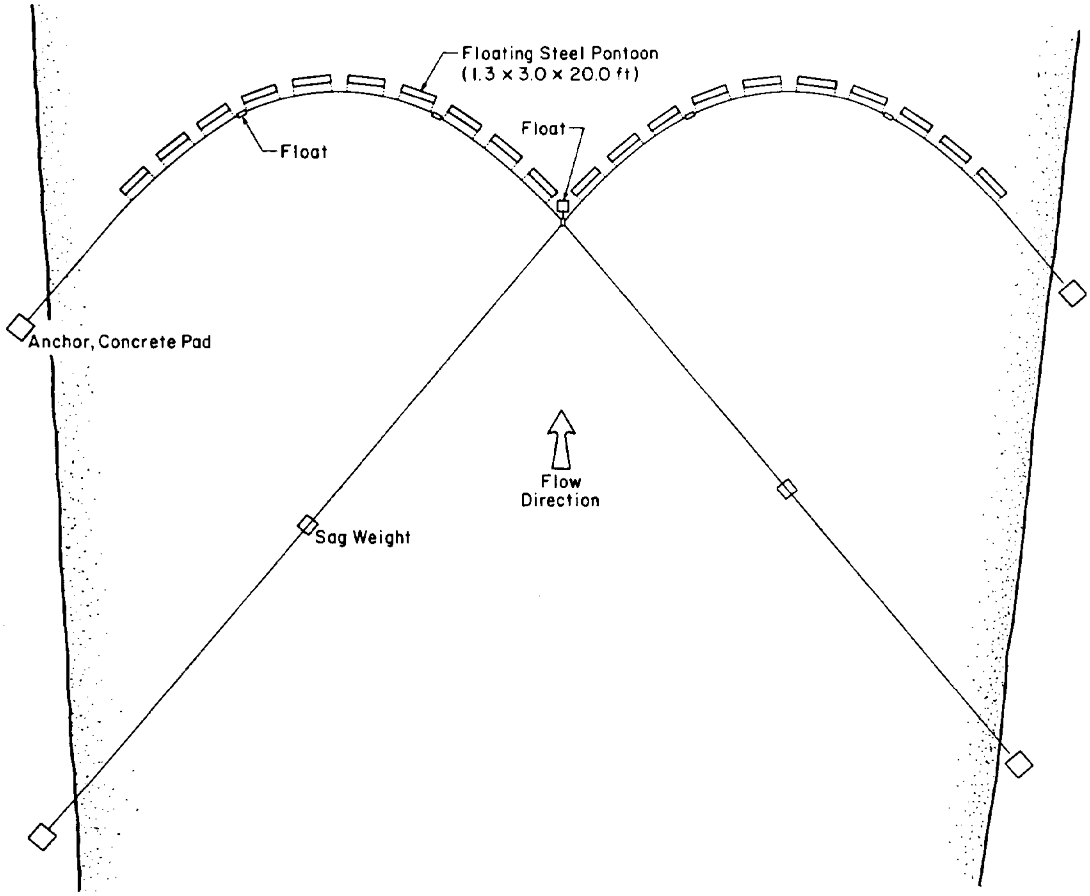


Figure 6-5. Plan view of the Allegheny River ice boom built in 1982.

b. Line Arrays. These devices are still experimental. Arrays are made from nylon, polypropylene, polyester, or wire rope. Arrays of buoyant lines may be used to stabilize existing large ice sheets by holding them in place against flow forces after they crack free from shore. The lines can expand the area that a buoy, or a timber, is expected to reliably influence. An example is shown in Figure 6-6. Such cracks can result from water level changes, ship passages, or warm water discharges. Also, several sets, probably without the shore anchors shown in Figure 6-6, have the potential for delaying spring ice movement on a section of river. The loss of a device like this during ice breakup is always a possibility, and the consequences of this loss must be considered (also see EM 1110-2-1612).

6-3. Rigid or Semi-Rigid Structures. Rigid or semi-rigid structures may or may not have moving parts. They are appreciably more rigid than a typical ice boom, but their deflection in response to the horizontal push of an ice sheet is on the same order as the deflections that develop in the ice sheet itself. Because these structures are generally unyielding, they are particularly susceptible to ice sheet impact and thermal expansion loads. The state of the art in design today is generally based on the conservative values of load and stress developed for dams and bridges. A list of rigid or

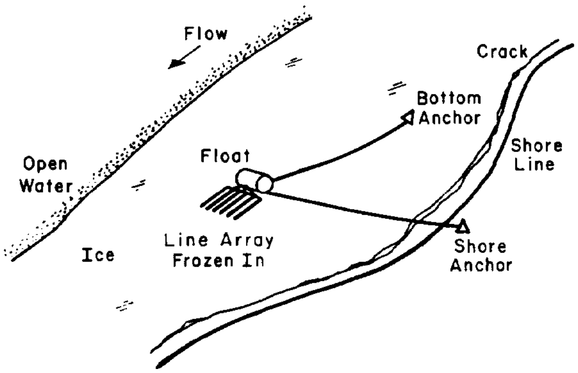


Figure 6-6. Line array anchoring an ice sheet that has cracked free from shore.

semi-rigid structures is given in EM 1110-2-1612. Only the structures in this category that have actually been used for navigation ice control will be discussed in this manual. Several of the others, however, have been seriously considered for navigation purposes.

a. Ice Piers. Ice piers are structures set in the river to protect a fleeting area against moving ice. The piers take the brunt of the impact and pressure forces and either stop the ice or deflect it to move around the ice pier location. Barges and tows are anchored downstream of the ice piers, which have anchoring chains for this purpose. The piers may be rectangular reinforced concrete structures, 16 x 25 x 10 ft high above water, or they may be similar to cylindrical sheet piling cells as in Figure 6-7.

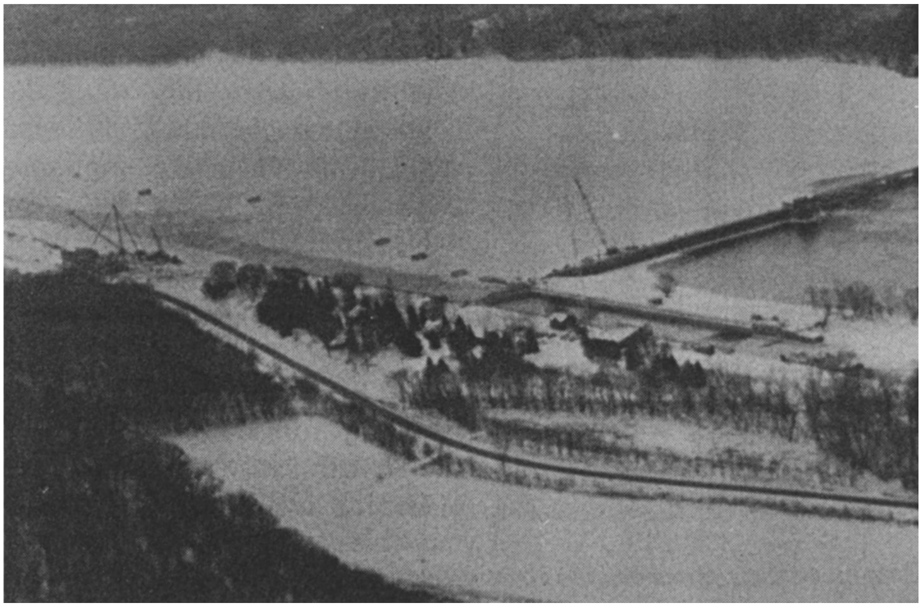


Figure 6-7. Cylindrical sheet piling mooring cells upstream of a navigation dam can help to stabilize the ice cover in winter.

b. Drift Deflectors.

(1) A drift deflector is usually a barge or barges set on a diagonal with one end against the shore to deflect material floating with the currents outwardly away from shore. This method is seen to work well on the inside of bends where the normal water currents have a natural component away from the shore. A fleeting area immediately downstream could be protected by a drift deflector.

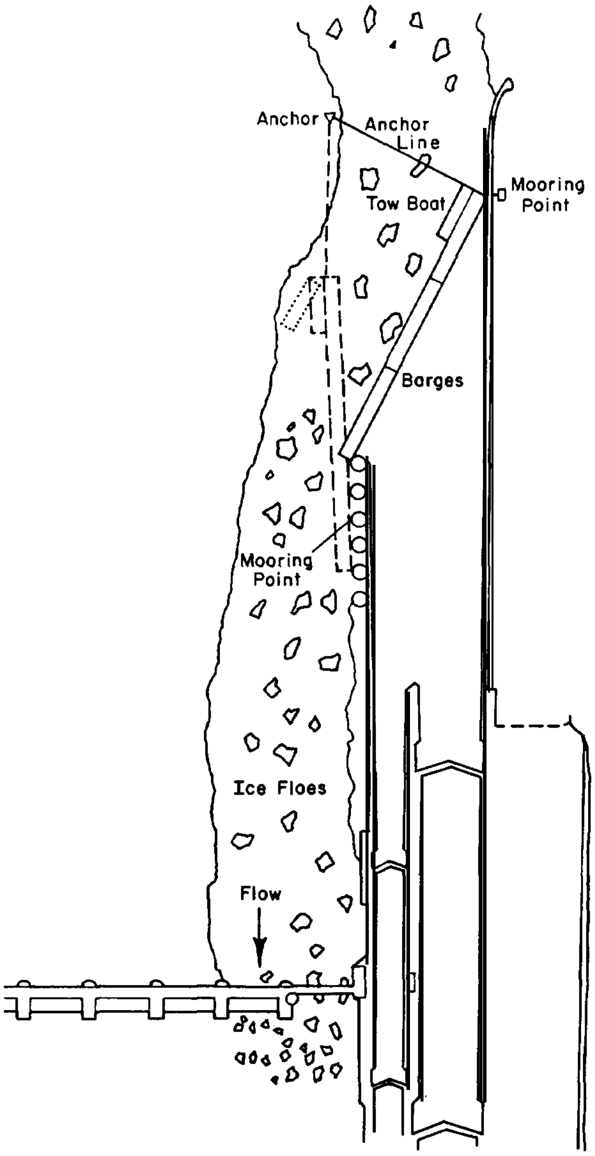


Figure 6-8. Diagram of a proposed movable ice deflector composed of three barges and a towboat, which could be deployed to protect an upper lock entrance from ice accumulation.

(2) A large ice deflector arrangement was proposed for installation (but not built) at Montgomery Locks and Dam, on the Ohio River, to reduce the amount of ice entering the lock during winter navigation. As shown in Figure 6-8, three barges and a mechanical linkage type of anchoring were proposed. A towboat was to move it between its open and closed positions and also break ice. A similar function is sometimes provided by barge tows on the Mississippi River waiting for lockages at Chain of Rocks Canal and at Lock and Dam No. 17. Ice passage at these sites is no problem.

c. Artificial Islands. In the same manner that natural islands help hold ice in place, artificial islands can be used to help form, stabilize, and retain an ice cover in certain locations. One example is the Lake St. Peter section of the St. Lawrence River, about 50 miles downstream of Montreal, Canada (Fig. 6-9). Lake St. Peter is about 8 miles wide and 20 miles long and has an average depth of 10 ft. Passing through the middle of the lake is a 800-ft-wide navigation channel dredged to a depth of 35 ft. The water flow velocity in most of the lake averages about 1.0 ft/s, while in the channel it is 1.6 ft/s.

(1) To prevent floods in Montreal Harbor, a passageway for ice floes, slush, and frazil ice is maintained by icebreakers from Montreal Harbor to Quebec City. At times, however, ice sheets would break free and be moved by wind and water to clog the passageway. Occasionally, a strong northeast wind would move the floating ice back upstream. Some light-tower bases helped hold the ice, but more stabilization was needed.

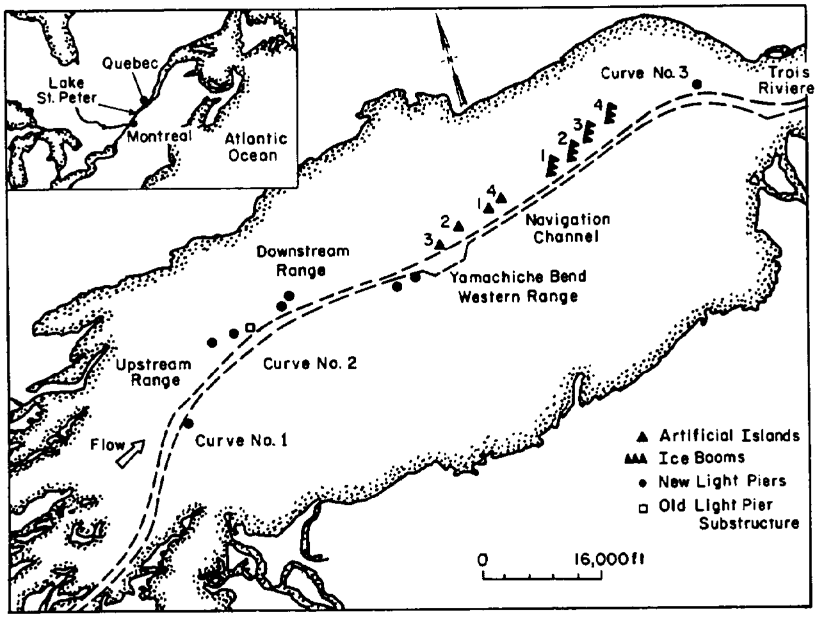
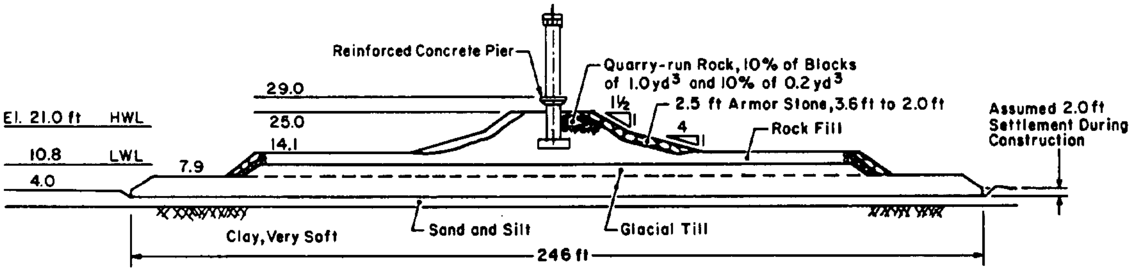
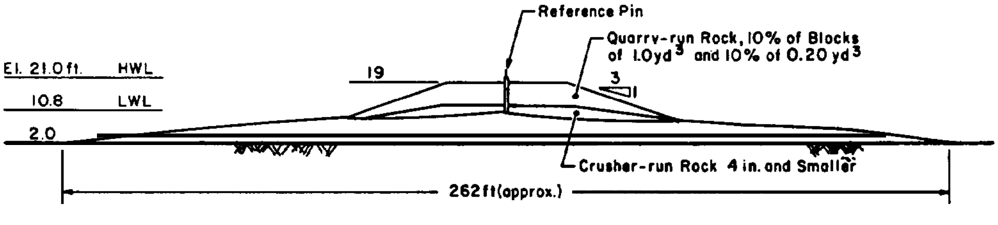


Figure 6-9. General plan and location of artificial islands, ice booms, and light piers in Lake St. Peter, St. Lawrence River.

(2) Several ice control structures were evaluated in various parts of Lake St. Peter and at Lavaltrie upstream in the river. Ice booms were successful but pile clusters did not perform well because the lake bed was probably too weak for the pilings to sustain the high ice forces. Artificial islands of three types were built to anchor the ice cover. The most stable type for the existing conditions is shown in Figure 6-10a. The second type (Fig. 6-10b), which cost much less to build, is only as high as the mean winter high water level. A third type was formed by placing riprap



a. High-type.



b. Low-type.

Figure 6-10. Cross sections of artificial islands in Lake St. Peter.

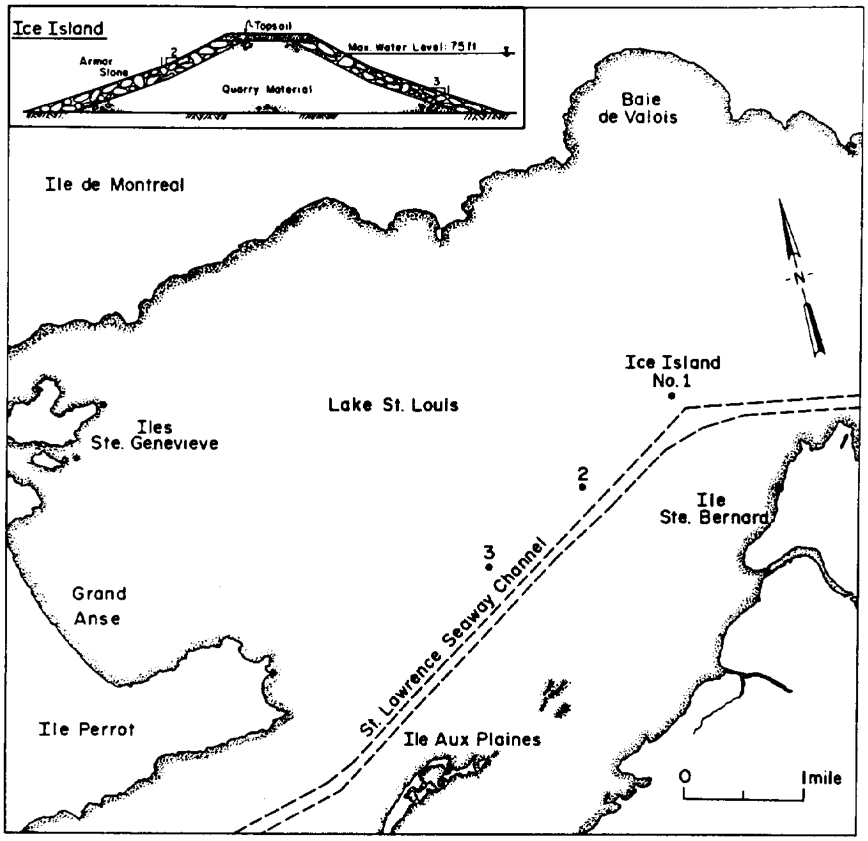


Figure 6-11. Artificial islands in Lake St. Louis, St. Lawrence River.

around the substructures of old light piers. The islands were successful in forming and retaining a stable ice cover, and the winter navigation season was increased by an average of 30 days. The islands, especially the low ones, require maintenance because the foundations have settled and the slopes have been eroded by moving ice.

(3) In 1980 three artificial islands were constructed in Lake St. Louis on the St. Lawrence River, upstream of Montreal. The islands are permanent and located east of Ile Perrot and north of the navigation channel (Fig. 6-l 1). The islands were designed and constructed to help stabilize the ice cover north of the navigation channel, particularly during the spring breakup and the opening of the navigation season, eliminating the problem of large ice floes obstructing navigation. The effectiveness of the artificial islands has not been fully assessed.

(4) Artificial islands have been helpful in some locations, but they were chosen only after the ice movements had been studied. These islands provide good lateral stability to the ice cover, but a small change in water elevation will fracture the ice near the islands. Ice on the lee side may move away from the island, but ice on the windward side will remain in position. Islands armored with stone cost more initially but have lower maintenance costs.

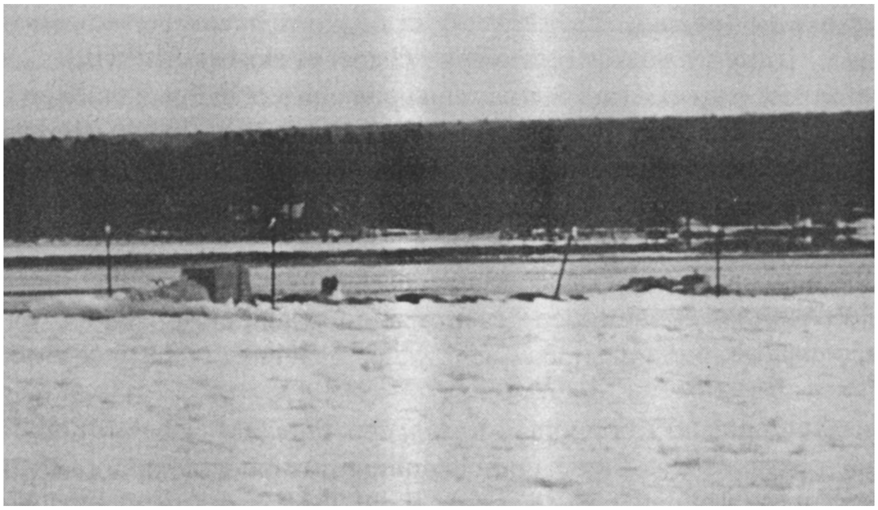


Figure 6-12. Rock-filled scow stabilizing the ice cover in Soo Harbor, Michigan.

d. Removable Gravity Structures. A problem developed with the St. Marys River ice control boom in the harbor at Sault Ste. Marie, Michigan, because the ice cover above the boom would break free from shore and move laterally into the open ship track. Although the loads from the ice sheet were within the expected range, their distribution was different enough to cause damage when the boom timbers were frozen solidly into the ice cover. Damage could be prevented if the ice cover could be kept from rotating. The only method that could be used at that time was a removable gravity structure. The main structure used was a scow, surcharged to a total weight of 270 tons and sunk in shallow water (Fig. 6-12). The scow was also secured with ship anchors. In the spring it was refloated and moved away. The method has worked very well.

(1) Later, observers noticed that sewage plant effluents weakened part of this ice cover on the St. Marys River. Thus, the ice-holding capability of the scow was supplemented by placing a stack of crane weights in the shallow water of Soo Harbor, about halfway between the scow and the ice boom. The reinforced concrete crane weights key together when stacked and are bound into a unit by wire ropes. The six crane weights weigh a total of 95 tons. They helped to reduce the rotating ice sheet problem to a manageable level.

(2) The holding force available from gravity devices depends not only on the weight of the device in water but also on the coefficient of friction between the device and the bottom; a value of 0.3 was used in the Soo Harbor analysis. The force level was estimated from the expected action of water and wind drag on the maximum expected ice sheet. Eventually, all the removable devices in Soo Harbor were replaced by artificial islands.

e. Pilings and Dolphins. Piles that support a wharf or pier can anchor or retain an ice sheet. The effects of the vertical uplifting forces and horizontal forces from ice sheets must be considered for structures using exposed pilings. Piling clusters, or dolphins, have received greater consideration for restraining ice. These are usually formed by a cluster of closely driven piles secured at the top with wire rope. Model tests of a line of individual pile clusters indicate that good ice retention is possible. An installation of several timber clusters in Lake St. Peter in 1962, however, failed early in winter. The cause was attributed mainly to a very weak foundation and large ice forces. Tests show that dolphins have surprisingly little resistance to steady lateral pulls.

(1) A dolphin in the Cap Cod Canal, Massachusetts, resisted ice action for several years but eventually failed from the action of ice floes moving in water currents with velocities up to 10 ft/s. The replacement dolphin in the 33-ft-deep water was made of 21 steel H-piles.

(2) Besides vertical and horizontal forces, the effect of ice abrasion is an important consideration. It is possible for ice to sever timber pilings in a matter of hours. Oak pilings are fairly ice resistant, but timber structures may last only about 20 years, partly as a result of ice abrasion. Timbers can be protected by steel armor. Concrete can also be adversely affected by ice abrasion and by the spalling of material from repetitive freezing and thawing of ice on its surface.

6-4. Structures Built for Other Purposes. The formation and retention of ice covers can be aided by structures that were not built for that purpose. Flows over hydroelectric dams can be manipulated to help an ice cover form. Other structures, such as wicket dams and bridge piers, aid in the formation and retention of ice covers simply by their presence.

a. Hydroelectric Dams. It is possible to aid the formation of an ice cover on a river by increasing flow depths and decreasing flow velocities at strategic times during the early winter. This capability must be accompanied by a comprehensive understanding of the hydraulics and ice conditions on the river, and how the river responds to various meteorological influences. Usually, ice-sheet retention structures are needed, too.

b. Wicket Dams. A wicket dam is composed of a series of rectangular elements or wickets that are propped side-by-side and on-end to form a sloping dam face (Fig. 6-13). A typical wicket is 1 ft thick by 3-1/2 ft wide by 16 ft long. The elements are raised and lowered by a barge-mounted crane, and usually they increase the upstream water level from 6 to 12 ft. They have been used on rivers such as the Ohio and the Illinois for maintaining the water levels needed for navigation during times of low flows. In this way they intrinsically help to form and maintain an ice cover.

c. Light Piers and Towers. Light piers and towers are used to mark the locations of navigation channels and courses. These structures can be built on land, but many are built offshore, where they become frozen into the ice sheet. Should the ice sheet break free from shore, a high force can be applied to the pier or tower. If the force is great enough, either the ice or the tower will yield. A drawing of a light pier built in Lake St. Clair near Detroit, Michigan, is shown in Figure 6-14.

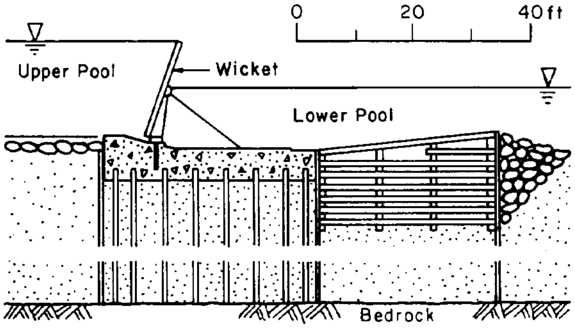


Figure 6-13. Typical section of a navigable pass portion of a wicket dam.

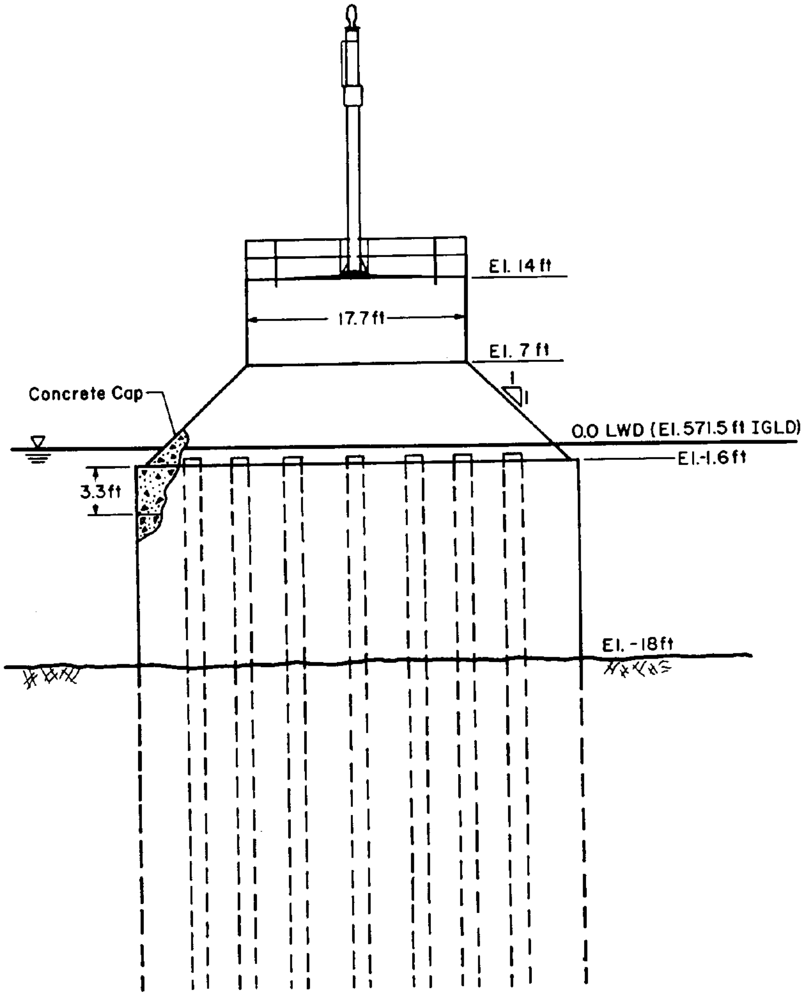


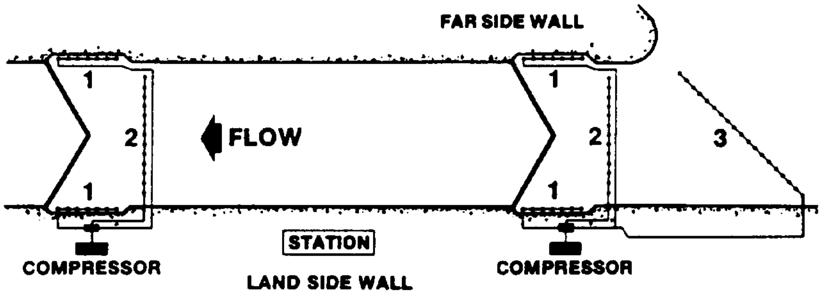
Figure 6-14. Light pier in Lake St. Clair, Michigan.

d. Bridge Piers. Bridge piers often constrict the river flow, and ice floes may collect at the piers in early winter to form an unconsolidated ice cover. Border ice growth on the piers can increase this narrowing effect at the water's surface if the spacing is small. Under some circumstances, however, this channel narrowing may lead to water velocities that are too high to allow an ice cover to form. Dynamic, static, and thermal ice pressures and ice abrasion must be considered in designing bridge piers.

Section II. Ice Control at Locks

6-5. General. Ice problems at locks have been identified and grouped into six categories. These are discussed in Chapter 3. Ice adhering to various lock surfaces and floating brash ice hinder normal lock operations and can delay barge movements for hours. The most notable problem with brash ice is its accumulation in the gate recess area, so that the gates cannot be completely opened. The most successful way to disperse ice is by means of high-flow air systems. These systems have up to three separate components (discussed below), each with a specific function that increases the ease of lockage operations.

6-6. High-Flow Air Systems. Air manifolds should be placed in three specific locations around a lock to completely mitigate the problems of brash ice (Fig. 6-15). 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 keeps brash ice from entering the lock or, in the case of



1. RECESS FLUSHER
2. SCREEN
3. DEFLECTOR

Figure 6-15. Schematic diagram of a complete high-flow air system, showing the three locationsfor air manifolds at a typical lock. Two compressors are shown, but one large compressor with long supply lines could also be employed, assuming the supply lines are adequately sized.

the downstream screen, clears ice from an area across the width of the chamber before the gate recess flushers are used. The third component is an optional one, depending on the physical layout of the lock and dam project. When there is some means for passing ice through or over a nearby spillway, the addition of 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.

6-7. High-Flow Single-Point Bubbler. 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.

6-8. 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 110-ft wide chamber, a diagonal deflector manifold length of at least 200 ft is required. Design calculations (Para. 6-10) will indicate that a compressor of at least 750-ft3/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 3-in.-diameter schedule 40 pipe should be considered. If a supply length of over 500 ft is required, then a 4-in. 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 2-in. pipe as a supply line (Fig. 6-16). 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 3-in.-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 3-in. supply line because of the volume of air being delivered (Fig. 6-17). 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.

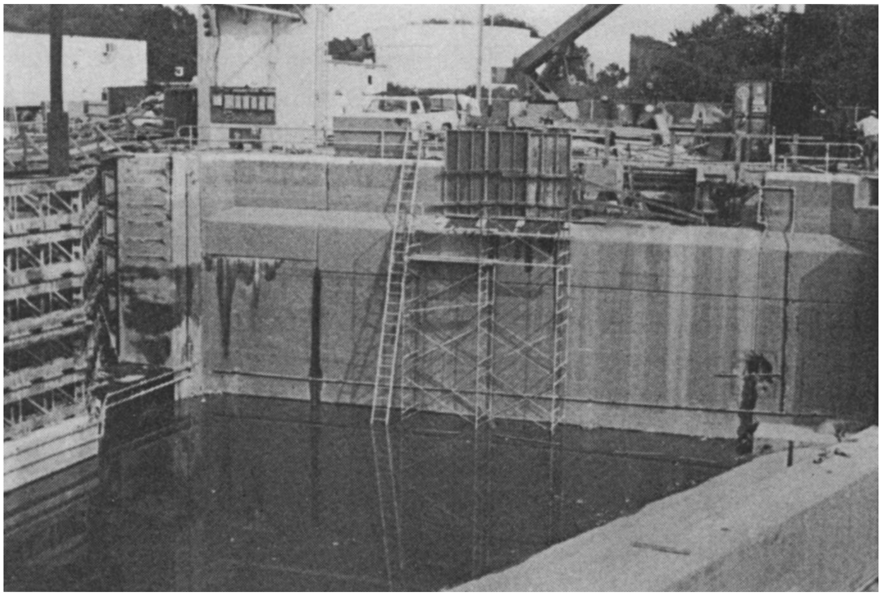


Figure 6-16. A flusher on the land wall of the upper gate recess composed of a supply line and the manifold with orifices at Peoria Lock on the Illinois Waterway. Note also the vertical supply lines for the recess flusher of the river wall gate and for the cross-chamber ail screen installed on the downstream-facing surface at the left (upper) end of the gate recess.

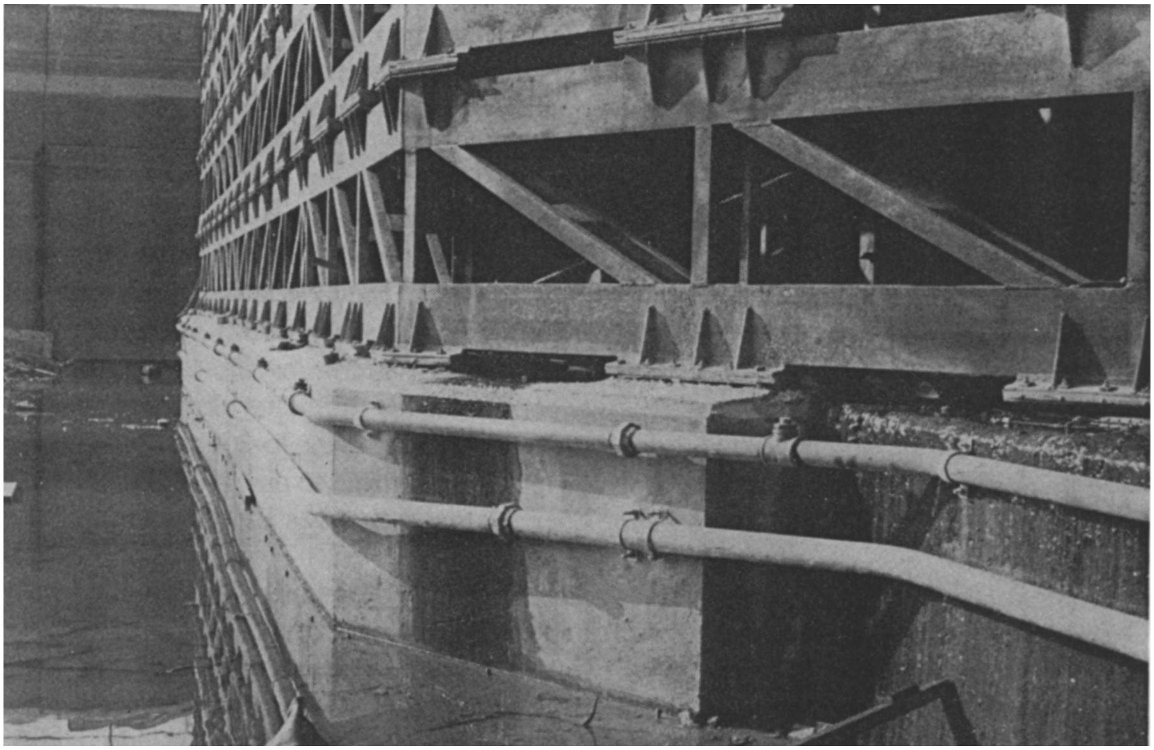


Figure 6-17. Downstream side of forebay sill, Peoria Lock. Air-screen manifold (top pipe) and supply line for river wall gate-recess flusher (bottom pipe) are attached to the sill face with U-straps. There is an orifice at each pipe tee location in the manifold.

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 4,4,4,6,8,10, 10, and 10 ft. 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 an 8-ft orifice spacing. For locks with a width of 110 ft, a 96-ft-long manifold is used; 13 orifices are placed along that manifold.

g. Deflector. For a diagonal deflector in the upper lock approach area, a 200-ft 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 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, 3/8-in.-diameter holes were drilled in the pipe plugs to serve as the orifices.

6-9. 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 one 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 (Fig. 6-18 and 6-19).

6-10. 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,

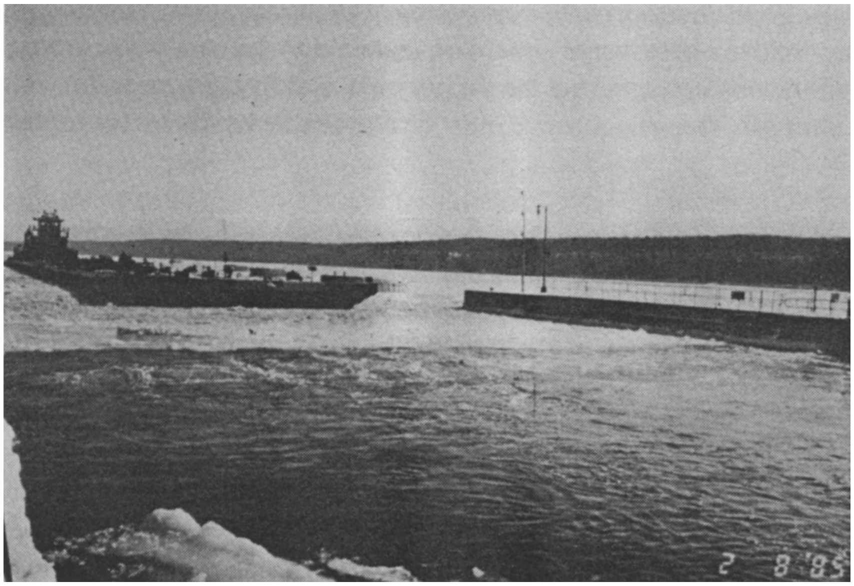


Figure 6-18. Upper screen in operation at Starved Rock Lock, Illinois Waterway. Most brash ice is prevented from entering lock chamber, even with the entry of downbound tows.

Figure 6-19. 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.

length and size of manifold line, depth of submergence, orifice size, and orifice 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:

$$P_d = P_w + \frac{(P_c - P_w)}{4} \tag{6-1}$$

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:

$$P_{d\,(new)} = P_w + (P_{d\,(old)} - P_w)\left[\frac{P_c - P_w}{P - P_w}\right] \tag{6-2}$$

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:

$$Q_o = C_d \frac{\pi d^2}{4} \sqrt{2\Delta P/\rho_a} \tag{6-3}$$

where C_d = discharge coefficient, sharped-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 due to friction between orifices and in the supply line(ΔP_f) is calculated using the friction loss equation for turbulent flow conditions:

$$\Delta P_f = \frac{f \rho_a \ell v^2}{D2g} \tag{6-4}$$

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

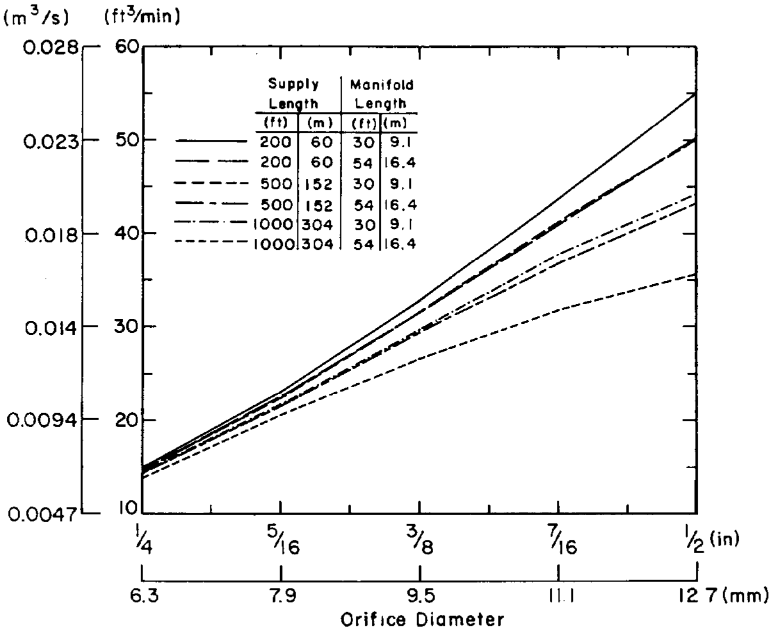


Figure 6-20. Performance curvesfor gate-recessflushers, showing the average air discharge from each orifice plotted with respect to orifice diameter, for combinations of three supply-line lengths and two manifold lengths. The 2-in. diameter manifolds are either 30-ft nominal length for 56-ft wide locks, or 54-ft nominal length for 110-ft wide locks, submerged 2O ft below the water surface. Six orifices at nominal spacings of 4,4,4,6, and 8 ft are present in the 30-ft manifolds, and three additional orifices at nominal 10 ft spacings are present in the 54-ft manifolds.

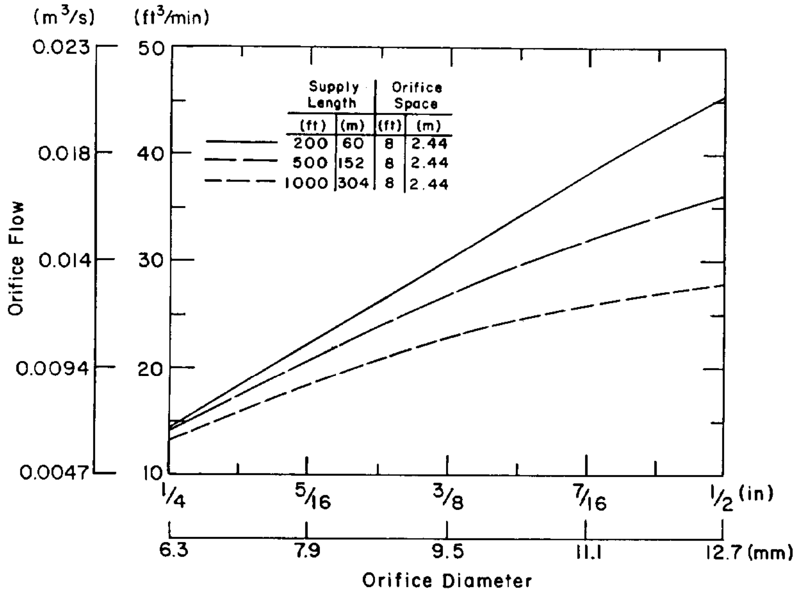


Figure 6-21. Performance curves for an air screen, showing the average air discharge from each orifice plotted with respect to orifice diameter, for three supply-line lengths. The 2.5-in. diameter, 96-ft long manifold is typical for a 110-ft wide lock, and has 13 orifices at 8-ft spacings, 20 ft below the water surface.

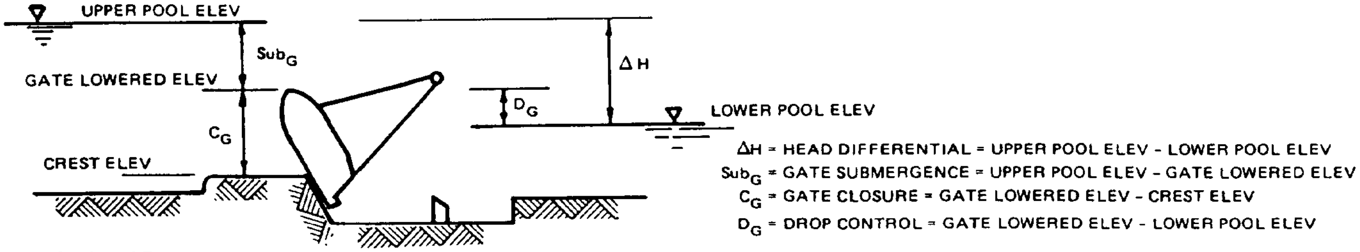
pressure, and submergence depth. The output from the program lists: hydrostatic pressure, calculated output pressure, calculated compressor discharge, friction drop in diffuser line, friction drop in supply line, and excess dead-end pressure. To illustrate how changes in the system parameters affect the operating characteristics, Figures 6-20 and 6-21 show the effect on changes in the flow through an orifice with respect to changes in orifice diameters.

6-11. 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.

Section III. Ice Passage Through Dams

6-12. General. 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, will have to be addressed in each of the river systems.

6-13. 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. The use of submergible gates to pass ice in the North Central Division is encouraged, whereas the Ohio River Division does not allow the existing submergible gates to be operated. The specific problems and comments regarding the varied use of submergible gates are well documented in the Louisville report. Figure 6-22 summarizes many of the submergible gates considered in the study. A recent rehabilitation project on the Illinois Waterway installed submergible gates at Marseilles Dam specifically for improving 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



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 6-22. Summary of submergible gates and their problems (after U.S. Army 1987) Many of these were considered in the Louisville District study of the use of submergible gates for passing ice (U.S. Army 1985).

problem. However, a benefit of using submergible gates is that, since the gate is kept under the water, many gate freezeup problems are eliminated.

6-14. Roller Gates. Roller gates are used extensively on the Mississippi River. At some 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 other 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. (At Lock 10 in the St. Paul District, the roller gates are not designed to be submergible, but they are the operative gates in winter.) 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.

6-15. 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.

6-16. Gate Limitations in Winter. As detailed in Chapter 3, Paragraphs 3-3a (7) through (9), successful operation of dam gates in winter, regardless of gate types, is impeded by accumulated forebay ice, by ice buildup on gate and pier structures 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 section are employed.

6-17. 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 6-23 shows such an operation. This appears to be an effective way to pass ice through the lock system, thus clearing the upper approach area.

Section IV. Lock and Dam Deicing

6-18. General. As described in Chapter 3, 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 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

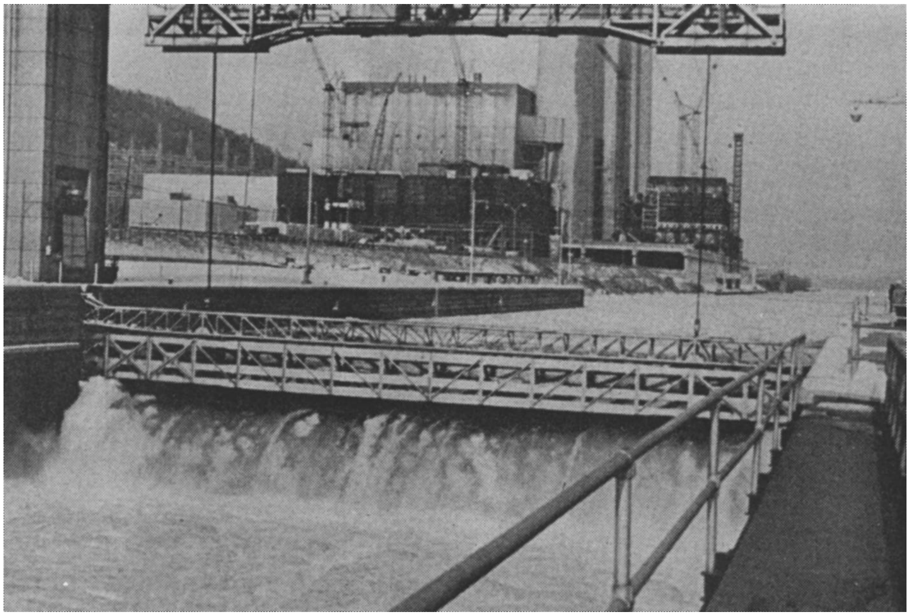


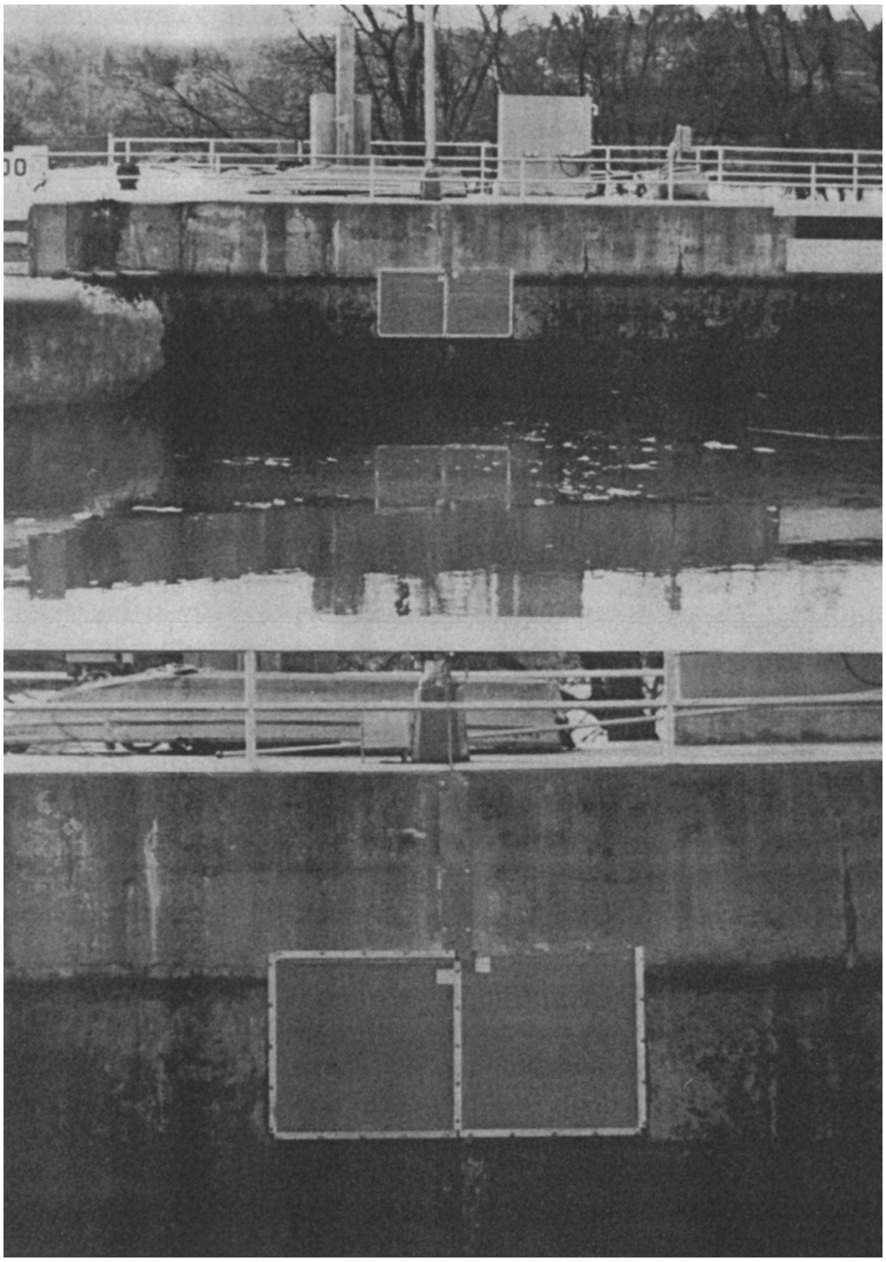
Figure 6-23. Ice passage at New Cumberland Lock on the Ohio River. The partially raised bulkhead of the auxiliary lock chamber allows flow to carry ice out of the lock approach area.

projects currently are time-consuming and expensive. This section addresses several approaches to solving the problems of surface ice formation and adhesion.

6-19. Thermal Measures Against Wall Icing. Ice adhesion on walls can be prevented by maintaining wall temperatures above 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, 3/4-in.-diameter stainless steel pipes should be installed, 6 to 8 in. 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 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 3 to 4 in. deep in the wall.

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 4 x 8 ft. Variable power ratings are also available. The mats shown in Figure 6-24 are 100 W/ft^2. These panels are each



a. General view.

b. Detail showing plate over vertical groove in wall above heat mats, which contains electrical leads.

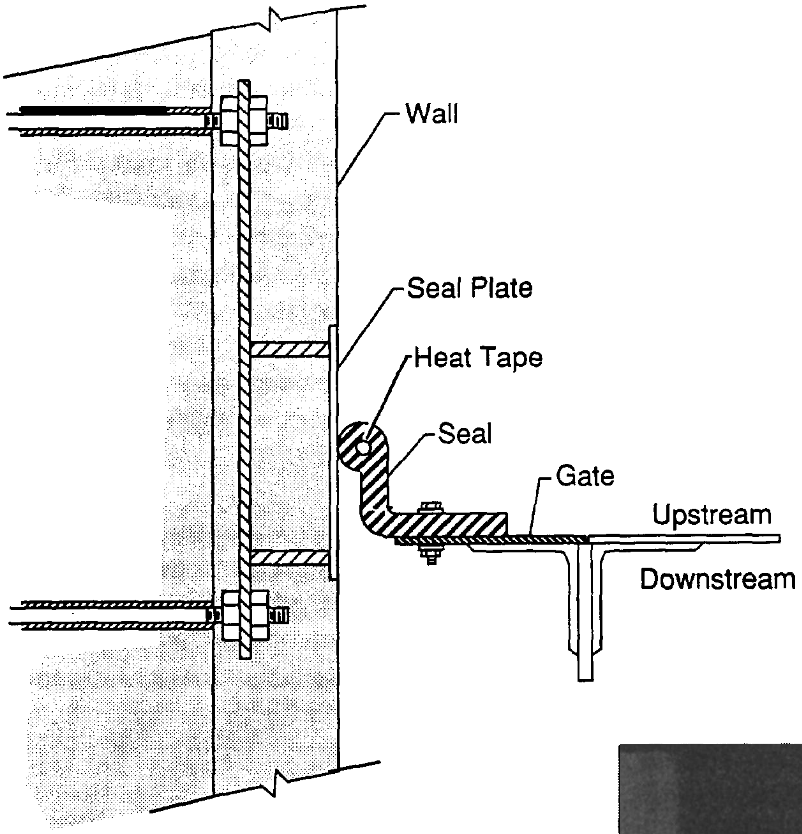
Figure 6-24. Fiberglass-reinforced plastic heat mats installed on a miter gate recess wall at Starved Rock Lock on the Illinois Waterway.

4 x 4 ft x 1/4-in.-thick. The mats are very effective in keeping the wall clear of ice. Material costs (1988) for such a mat material are about $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). 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. The self-regulating heat trace tape, 208 V ac at 37 W/ft at 32°F, was cut from a spool to a length of 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 and the inserted heater are shown in Figure 6-25. The 1988 cost of Huntington J-seal Mold no. 3493 is $14.50/ft. The seal is currently manufactured 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 $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. 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.

6-20. 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 semi-permanent 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.

a. 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 polycarbonate-polysiloxane 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. 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



a. Diagram.

b. Heat tape installed in the hollow channel of a J-seal.

Figure 6-25. J-seal installation on tainter gate.

and algae. Once the surface is clean and dry, the solution can be sprayed on using an airless spray gun system. A single pass will deposit a coat 1 to 2 mils thick. Three coats are recommended for a coating thickness of about 5 mils. Achieving this final thickness requires about 6 gal/1000 ft^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 55-gal. drum fitted with a bracket to hold the drill motor is a suitable mixing container. Batches of up to 40 gal. 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. 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.

b. 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 since 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. 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 4 x 8 ft x 1/2-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, 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 \$7/ft^2.

CHAPTER 7
OPERATIONAL SOLUTIONS

Section I. Vessel Scheduling or Convoying

7-1. Introduction. Frequent vessel passages through ice-covered navigation channels under frigid conditions generates 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.

7-2. 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.

7-3. 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. Assuming 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 specialcase 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 between 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 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

7-4. 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 3: 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. Several of these problems 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.

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

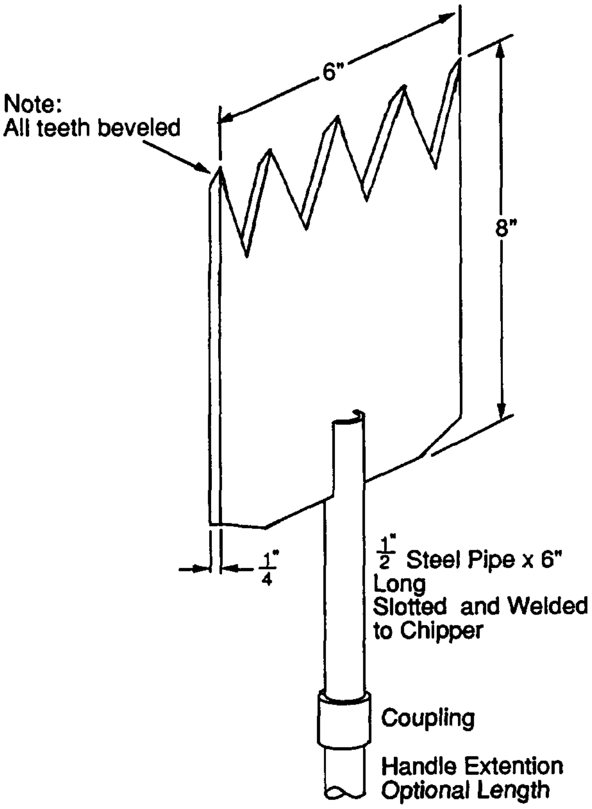


Figure 7-l. Effective design for a manual ice-chipping tool.

are widely used by lock personnel at sites that experience winter icing problems. Figure 7-l 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 is limited. 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 Noncontact Tools. Two techniques for ice removal using noncontacting 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.

7-5. 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.

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.

7-6. 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 Para. 6-19a). 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 Para. 6-19c). 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. Warm Water Use

7-7. Introduction. Most rivers have sources of warm water that either already suppress some ice formation or may be used to cause some ice suppression. The most obvious are power plants that discharge heated water into the river. Typically, there will be a narrow band of open water for some distance downstream of these plants when the river is otherwise ice-covered. In other cases reservoirs, even with ice covers, may contain water above the freezing point of 32°F. When this water is released, it will flow some distance downstream before it begins to freeze. This section describes the effect on ice covers of these sources of warm water and provides approximate means of estimating this effect.

7-8. Sources of Warm Water. Besides the two main sources of warm water in winter mentioned above, there are other sources such as the discharge of treated sewage, warm waste water from industrial plants, and, occasionally, warm springs, but generally all of these release too little heat to cause more than very local effects on the natural ice cover. In seeking to use warm water as an aid to river ice management, it is important to realize under what conditions the warm water may be effective, and the extent of the influence.

a. Power Plants. Both fossil fuel power plants (using coal or oil) and nuclear power plants require cooling in the process of generating electrical power. This cooling generates waste heat that is then discharged into the environment, either directly to the atmosphere by use of cooling towers, or indirectly by first discharging the heat to a water body that then transfers the heat to the atmosphere. If an existing plant already has cooling towers, it is unlikely that the plant will be able to discharge the heat to a water body because of the large capital costs of having two cooling

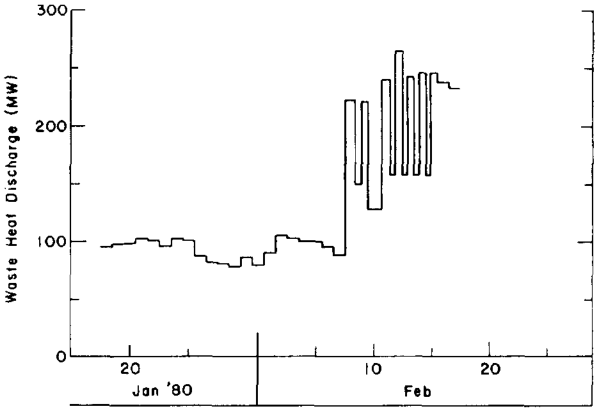


Figure 7-2. Record of waste heat discharge from a power plant that uses Mississippi River water for cooling. Prior to 8 February, much of the plant was down for maintenance; thereafter, it operated alternately between full and partial load.

systems. However, many plants do use rivers as the heat sink. The warm water released results in ice suppression that in some instances can be helpful in managing ice problems. Power plants operate either as base load plants, at a more or less constant capacity, or as peaking power plants to supply power at the time of greatest demand. The actual operating characteristics can only be ascertained from the utility companies directly. In Figure 7-2 the waste heat discharge of a power plant on the Mississippi River, 7 miles upstream of Lock and Dam No. 15, during January and February of 1980 is shown to illustrate the nature of the output that might be expected (Ashton 1979). During January of 1980, a large part of the plant was shut down for maintenance, and even after that the plant was not running continuously at full load. As a consequence, the waste heat discharge was variable. Nearly all plants maintain a record of input and output water temperatures, which, along with the cooling water discharge rates, enables calculation of the waste heat discharge. The waste heat discharge is determined from these data according to

$$Q = \gamma C_p N \left(T_{out} - T_{in}\right) \tag{7-1}$$

where

Q = waste heat release rate (Btu/hr)
γ = specific weight of water (62.4 lb/ft^3)
C_p = specific heat of water (1.0 Btu/lb°F)
N = cooling water discharge rate (ft^3/s)
T_{in} = intake cooling water temperature
T_{out} = outfall cooling water temperature.

As an example, in early February one unit of the plant whose output is shown in Figure 7-2 had an intake temperature of 32°F, an outfall temperature of 49°F, and a discharge rate of 89 ft^3/s. Thus

$$Q = \left(62.4 \frac{\text{lb}}{\text{ft}^3}\right) \left(1.0 \frac{\text{Btu}}{\text{lb°F}}\right) \left(\frac{89\text{ft}^3}{\text{s}}\right) \left(49°\text{F} - 32°\text{F}\right)$$

$$= 94{,}400 \text{ Btu/s} = 340 \times 10^6 \text{ Btu/hr or } 99{,}600 \text{ kW.}$$

This rate of energy release is greater than the electrical output of the plant, since typically coal and oil plants have 40 percent efficiency, and nuclear plants have even less at about 33 percent. Thus, coal plants discharge as heat energy to the cooling water about 1-1/2 times the amount of electrical energy put out over the transmission lines, and nuclear plants about twice as much. These ratios are useful for quick assessments of ice suppression, as will be discussed below.

b. Reservoirs. In many reservoirs the water beneath the ice cover is above the freezing point. When this water is released during the winter, it takes some time and distance before it is cooled by the atmosphere down to the freezing point, after which further heat loss results in ice formation. If the warm water release encounters ice before it has cooled to the freezing point, it will melt the ice until the water is at the freezing point. The extent of melting or the distance to cool to the freezing point depends on both the release flow rate and the water temperature. This distance depends also on how cold the atmosphere is. Methods to predict the distance or extent of melting are described below. The biggest uncertainty is the temperature of the reservoir water, which is usually below the 39°F temperature of maximum density, and depends on the particular sequence of meteorological conditions at the time of freezeup and the extent of throughflow during the winter. Water released from the bottom of reservoirs will usually be warmer than water released from near the top. Direct measurement of the release water temperature is the most certain way of assessing the flow temperature.

7-9. Warm Water in the Context of Ice Production. In the Pittsburgh District on the Ohio River there are nine power plants that discharge warm water at a total rate of about 5500 MW over a distance of 125 miles. At 14°F the heat loss from open water over this reach is about 15,000 MW, so that the warm water reduces ice production by about 37%. At -4°F the loss from open water is about 30,000 MW, so the warm water reduces ice production by about 18%. If the ice is 2 in. thick, the ice production rate under natural conditions is equivalent to a heat loss rate of about 7500 MW at 14°F and 15,000 MW at -4°F, so the reduced ice production is on the order of 75% at 14°F and 37% at -4°F. In the Huntington District there are four power plants on the Ohio River that discharge a total of 4200 MW over a distance of 310 miles. The heat loss from open water over this reach at 14°F is on the order of 40,000 MW, so the warm water reduces ice production by about 10%. At -4°F the reduction is on the order of 5%.

a. Clearly, the magnitudes of warm water discharge are small when compared with the overall energy exchange rates between the river and the atmosphere, and cannot be expected to mitigate ice problems over the entire reaches. Close to the plants, however, the suppression can be significant in affecting local ice conditions.

b. The fact that large quantities of warm water are discharged into the river does not mean that the water temperatures are excessively high. In fact, in winter the temperatures of the warm water discharges rapidly approach the freezing point. In one observation for example, 3000 ft downstream of the Riverside Power Plant on the Mississippi River, the highest water temperature in a plume from a 200-MW release was only 35°F. However, even small increases in water temperature above the freezing point can stop ice from thickening. As an example, if the air temperature is -4°F and the ice is 6 in. thick, the thickening rate is about 1.9 in. per day, if the water temperature is at the freezing point. If the water velocity is 1.5 ft/s and the temperature is 32.16°F (or 0.16°F above freezing) it will stop the thickening, that is, the heat transferred to the ice from the water exactly equals the heat loss to the atmosphere. Under the same conditions but with 12-in. thick ice, a water temperature of 32.10°F stops further thickening. Thus, one of the effects of warm water discharge into a cold river is to limit the ice production that otherwise might occur.

7-10. Effects on River Ice of Warm Water Release. Warm water effects are discussed below by first evaluating natural conditions, and then discussing various modes of heat introduction to the river.

a. Natural Conditions. To assess the effects on river ice of a warm water discharge, it is important to appreciate the magnitude of temperatures, natural ice conditions in the river, and the heat losses to the atmosphere that cause ice formation. The water temperatures of rivers more or less follow the average air temperatures through the annual cycle until those temperatures go below the freezing point. At that time the water, instead of cooling below the freezing point, forms ice in proportion to the heat loss to the atmosphere, and the ice acts as a buffer preventing further temperature decline. Throughout the period of ice cover, water temperatures remain very close to the freezing point both as a consequence of turbulent mixing, which prevents stratification, and as a consequence of continually flowing past the ice cover, which is a heat sink for the river water. Only in still water or at extremely slow velocities can any significant stratification develop. There is a minor heat gain from energy stored in the bottom sediments during the preceding summer (O’Neill and Ashton 1981), and a minor gain from viscous dissipation or friction in the flow, but these gains are very small relative to the heat losses at the surface. In general, when there are significant amounts of ice present in a river, the assumption that the water temperature is at 32°F is very accurate. This is particularly useful when assessing the effects of adding warm water, since all the energy of the warm water is used either to melt ice or is lost to the atmosphere in open water areas.

(1) Ice conditions in a river vary widely from site to site, depending on many factors. These are discussed in earlier chapters. From the standpoint of the effects of warm water, the ice may be classified as moving or stationary. If the ice is moving, the effect of the warm water is to reduce the volume of ice passed downstream in proportion to the amount of heat discharged. Nearly all the energy discharged into flows with moving ice is used to melt ice. In the case of an intact, stationary ice cover, the waste heat is used to melt the ice or suppress its otherwise natural thickening, as well as being directly lost to the atmosphere in the open water areas formed by the warm water. In a sense the open water areas formed in the ice cover act as a short circuit to the atmosphere for some of the waste heat, at least to the extent that the heat transfer rate is greater at larger values of the water vs. air temperature difference than would be true for an open water surface at 32°F.

(2) This leads directly to the subject of natural heat losses from rivers in winter. Two cases are important - the open water case and the ice-covered case. In the case of open water, the heat losses may be calculated using detailedenergy budget methods, which consider the daily or diurnal variations of long wave radiation gains and losses, short wave radiation gains, sensible heat losses

to the air due to either free convection (when the air is still) or forced convection (when the air is windy), and evaporation losses. The variables involved include time of year, time of day, latitude, air temperature, humidity, wind speed, and cloud cover. For some studies such energy budget methods are necessary, but they involve considerable calculation effort, plus field data as input. For many studies a simpler method is adequate for estimates of the effects of warm water discharge. This method consists of simply combining all the energy budget effects into a single heat transfer coefficient applied to the difference between the water temperature and the air temperature (Ashton 1982). The heat loss per unit area of open water surface q_{wa} is then given by

$$q_{wa} = H_{wa}(T_w - T_a) \tag{7-2}$$

where

H_{wa} = heat transfer coefficient
T_w = water temperature
T_a = air temperature.

H_{wa} depends on all the variables that determine the energy budget, but is typically between 2.7 and 4.5 Btu/hr ft^2°F, with the higher values associated with higher wind speeds. As an example, if the air temperature is 10°F and the water temperature is 33°F and H_{wa} = 3.5 Btu/hr ft^2°F, the heat loss is

$$q_{wa} = 3.5 \frac{\text{Btu}}{\text{hr ft}^2\ {}^\circ\text{F}} \times (33 - 10\ {}^\circ\text{F}) = 80.5 \frac{\text{Btu}}{\text{hr ft}^2} . \tag{7-3}$$

(3) Once an ice cover is on top of the water, it acts to insulate the water, with the insulation effect increasing as the ice thickens. A snow layer increases the insulation effect even more. And, since the water below is at 32°F, the heat losses are directly transformed into ice production. A simple layer analysis enables estimates of the heat loss through the ice (and snow) cover. As shown in Figure 7-3, the air temperature is denoted by T_a, the top surface ice temperature by T_s, the bottom surface ice temperature by T_m, which is always at the melting-freezing temperature of 32°F. The thermal conductivity of the ice is denoted by k_i and the ice thickness by h. It is important to note, particularly for thin ice covers, that the top surface temperature is not the same as the air temperature; if it were there would be negligible heat loss to the atmosphere and no ice thickening.

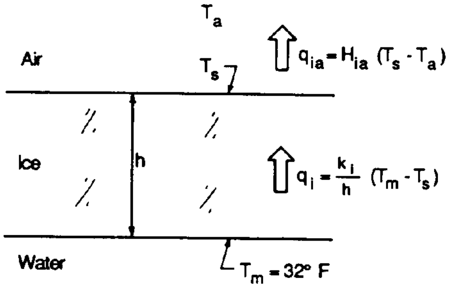


Figure 7-3. Schematic diagram showing notation and heat transfer equations governing the heat flow from a water body through an ice cover to the atmosphere.

As a first approximation, which is very good for most purposes, the heat flow may be analyzed as a quasi-steady state process such that the temperature profile in the ice varies linearly from T_m to T_s over the thickness of the ice. The heat flow through the ice is then given by

$$q_i = \frac{k_i}{h}(T_m - T_s) \cdot \tag{7-4}$$

The heat loss to the atmosphere from the ice q_{ia} can be written similar to that from an open water surface with T_s substituted for T_w in Equation 7-2 to give

$$q_{ia} = H_{ia}(T_s - T_a) \cdot \tag{7-5}$$

The heat flow through the ice equals the heat loss at the surface, so that $q_{ia} = q_i$, which allows T_s to be eliminated between Equations 7-4 and 7-5 and gives

$$q_i = q_{ia} = \frac{T_m - T_a}{\frac{h}{k_i} + \frac{1}{H_{ia}}} \tag{7-6}$$

This result may be compared to the heat losses from an open water surface to show the insulating effect of the ice cover. In Figure 7-4 the ratios of heat losses (q_i) through the cover to the open water losses (q_{wa}) are shown as functions of ice thickness, for the range of heat transfer coefficients usually found; 6 in. of ice reduces the heat loss by 50% or more.

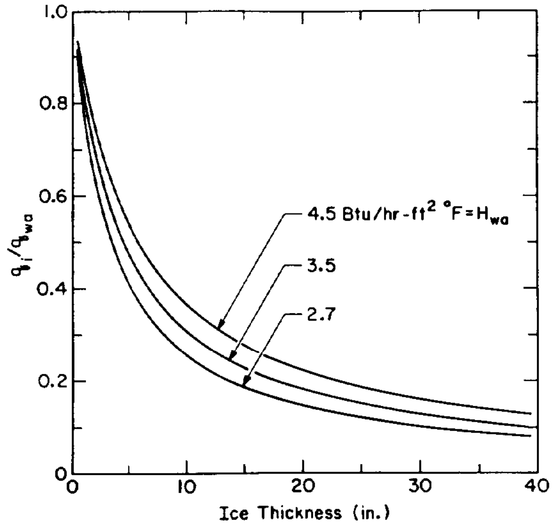


Figure 7-4. Ratio of heat loss through an ice cover (q_i) to heat loss from an open water surface (q_{wa}) versus ice thickness, for three values of the heat transfer coefficient, H_{wa} (or the equivalent H_{ia} for heat transfer from ice to air).

(4) This heat flux through the ice is also the heat flux upward from the bottom surface, which causes the ice to thicken at the bottom. The thickening rate is inversely proportional to the heat of fusion ***(L)*** times the specific weight of ice, so that the thickening rate is given by

$$\frac{dh}{dt} = \frac{1}{\gamma_i L}\left[\frac{T_m - T_a}{\frac{h}{k_i} + \frac{1}{H_{ia}}}\right] \tag{7-7}$$

For most practical river ice problems, the specific weight γ_i, the heat of fusion ***L,*** and the thermal conductivity k_i may be treated as constants with values for pure ice as follows:

γ_i = 57.2 lb/ft^3
L = 144 Btu/lb
k_i = 1.30 Btu/hr ft °F.

Using these values the thickening rate is given by

$$\frac{dh}{dt} = 0.0029\left[\frac{T_m - T_a}{0.769h + \frac{1}{H_{ia}}}\right] \text{ (ft/day).} \tag{7-8}$$

As an example, for T_m = 32°F, T_a = -5°F (very cold), h = 0.5 ft, and H_{ia} = 3.5 Btu/hr ft^2°F, the thickening rate is 0.16 ft/day or about 2 in. per day. When the ice is 1-ft thick, for the same conditions the thickening rate drops to 1.2 in. per day. Figure 7-5 shows thickening rates to be expected as functions of average daily air temperature and ice thickness, assuming H_{ia} = 3.5 Btu/hr ft^2 °F.

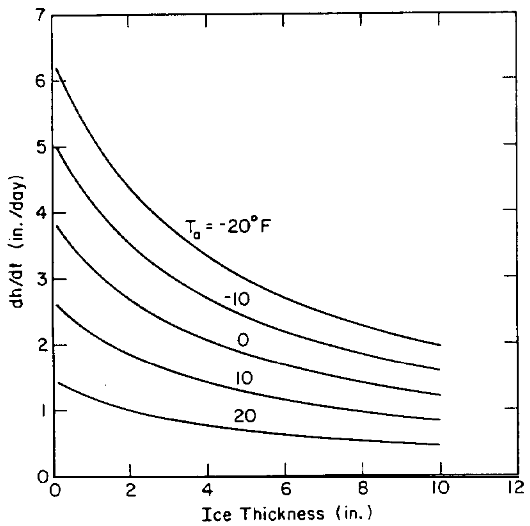


Figure 7-5. Rate of ice thickening versus ice thickness, for five values of average daily air temperature. H_{ia} *= 3.5 Btu/hr ft*^{2}*°F is assumed.*

(5) The above calculations overestimate the thickening rate, or rate of ice production, if there is a snow cover on the ice. Typically, the thermal conductivity of the snow cover is about one-tenth that of the ice cover, so it has the insulating effect of ten times its thickness of solid ice.

(6) There are several purposes to the above calculations. First, they may be used to estimate rates of ice production as a function of air temperature and ice thickness. Second, the results of the calculations show that the ice production is greatly reduced as the ice thickens, which, in turn, suggests that the effectiveness of warm water discharged into a river is greatest when the ice is thicker, since a smaller amount of heat is required to stop the growth of the ice cover. Thus, while warm water discharge may not have a great effect in preventing initial ice formation, it may have a significant effect in limiting ice production over significant reaches of the river.

(7) In summary, there are two main effects of warm water released into ice-covered rivers. First, the heat locally suppresses the ice completely and creates open water areas near the point of release. Second, the heat acts to limit the ice thickness at regions downstream and beneath the ice cover. Both effects may be calculated using methods described below. The effectiveness of the warm water depends a great deal on specific site conditions and the nature of the ice formation that would occur otherwise.

b. Fully Mixed Releases. The water release from a reservoir is generally above freezing and results in complete suppression of ice for a certain distance downstream, and partial suppression of the ice further downstream beneath the ice cover. There are methods available (Ashton 1979) to simulate these effects that take into account the unsteady nature of the air temperature and release rates, but they are too detailed for full treatment here. Instead, some steady-state example calculations are presented as well as some results from unsteady simulations, so as to give an appreciation of whether or not a warm water release causes a significant effect. Occasionally, the effluent from a power plant is diffused uniformly across the receiving river flow, but this is more the exception than the rule. In general this form of release on larger rivers results in insignificant lengths of open water, but a definite suppression of the ice growth (thickness) downstream.

(1) Introduction. Three example cases are considered: a reservoir discharging 1000 ft^3/s at 36°F into a river 400 ft wide, a reservoir discharging 5000 ft^3/s at 36°F into a river 500 ft wide, and a very large power plant of nominal capacity of 2400 MW discharging 4800 MW of waste heat through a diffusing system into a river 2000 ft wide. As a first approximation, the area of open water, and hence the distance to the upstream edge of the ice cover, can be determined for low air temperatures by estimating the heat transfer coefficient and applying it to the average temperature difference between the water and the air.

(2) Example 1.

(a) Conditions.

—Reservoir discharge: 1000 ft^3/s at $T_w = 36°F$

—Available heat discharge:

$Q = \gamma C_p N (T_w - T_m) = 62.4 \times 1.0 \times 1000 \times 3600 \text{ s/hr} \times (36 - 32)$

$Q = 899 \times 10^6$ Btu/hr

—Open water area: $A = Q/q_{wa} = \dfrac{Q}{H_{wa}(T_w - T_a)}$

—Width of open water : $W = 400$ ft

—Length of open water : $L = A/W$

—For H_{wa} = 3.5 Btu/hr ft^2°F:

T_a (°F)	$T_w - T_a$ (°F)	A (ft^2)	L (ft)
20	12	21.4×10^6	53,500
10	22	11.7×10^6	29,200
0	32	8.0×10^6	20,100
−10	42	6.1×10^6	15,300

(b) Discussion. This reservoir release maintains open water in the river downstream a distance up to 10 miles when the weather is mild in winter, and the distance shortens to a little less than 3 miles when the weather is very cold (-10°F is the average daily temperature and not the extreme overnight low). The heat release is equivalent to 240 MW, which is about the rate of heat released from a fossil-fueled power plant of nominal capacity of 160 MW. The discharge over two months adds up to 120,000 acre-ft, and requires a significant reservoir if it is to have that capacity of warm water at the beginning of the ice-covered period.

(3) Example 2.

(a) Conditions.

-Reservoir discharge: 5000 ft^3/s at $T_w = 36°F$

-Available heat discharge:

$Q = \gamma C_p N (T_w - T_m) = 62.4 \times 1.0 \times 5000 \times 3600 \text{ s/hr} \times (36 - 32)$

$Q = 4490 \times 10^6$ Btu/hr

-Open water area: $A = Q/q_{wa} = \dfrac{Q}{H_{wa}(T_w - T_a)}$

-Width of open water: $W = 500$ ft

-Length of open water: $L = A/W$

-For H_{wa} = 3.5 Btu/hr ft^2 °F:

T_a (°F)	$T_w - T_a$ (°F)	A (ft^2)	L (ft)
20	12	107×10^6	214,000
10	22	58×10^6	117,000
0	32	40×10^6	80,000

(b) Discussion. This is a large reservoir release with open water about 11.6 miles downstream even at -10°F air temperature. The heat release is equivalent to 1200 MW, which is about the heat released from a fossil-fueled power plant of 800 MW capacity. The discharge over two months is 600,000 acre-ft.

(4) Example 3.

(a) Conditions. A large power plant of nominal capacity 2400 MW is discharging 4800 MW through a diffusing system into a river 2000 ft wide, Temperature rise in the river depends on the river flow, but under the simplified assumptions used here, the open water area can be calculated approximately without that knowledge since it is based on the required water surface area to remove the heat content. This surface area depends on the temperature difference between the water and the air, and the water temperature will be very near 32°F.

—Available heat discharge:

$$Q = 4800\ \text{MW} \times \frac{10^6\ \text{Btu/hr}}{0.293\ \text{MW}}$$

$$Q = 16{,}400 \times 10^6\ \text{Btu/hr}$$

—Open water area: $A = Q/q_{\text{wa}} = \dfrac{Q}{H_{\text{wa}}\,(T_{\text{w}} - T_{\text{a}})}$

—Width of open water: W = 2000 ft
—Length of open water: $L = A/W$
—For H_{wa} = 3.5 Btu/hr ft^2°F, and $T_w - T_a$ = 32°F - T_a:

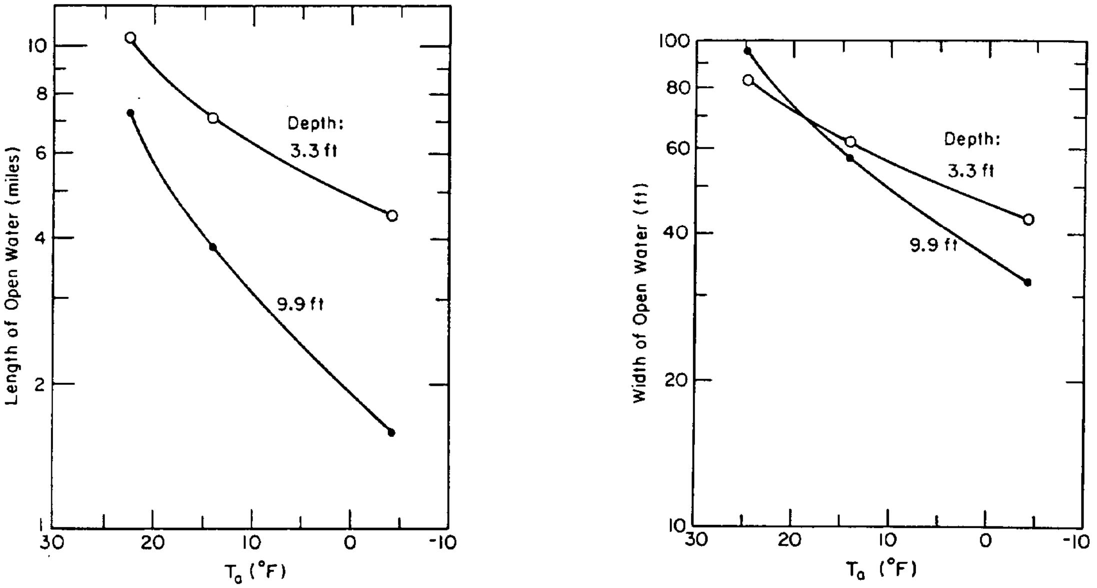
T_a (°F)	$T_w - T_a$ (°F)	A (ft^2)	L (ft)	L (mi)
20	12	390×10^6	195,000	37
10	22	213×10^6	106,000	20
0	32	146×10^6	73,000	14
–10	42	111×10^6	56,000	11

(b) Discussion. This is a very large power plant and a very large river. The effect on the ice is open water for many miles downstream when the air is mildly cool, but only 10 to 15 miles when the air temperatures are around 0°F. The simplified assumption, namely that the open water area is based only on the area required to remove the heat added, is probably not very accurate here, since the complete mixing by the diffuser probably results in water temperatures sufficiently close to freezing that ice will form on top of the slightly warm water if the flow is not too fast. For such a case a more detailed analysis would be needed. If skim ice forms, however, the warm water still prevents the ice from thickening as much as it would without the addition of heat. Note also that we did not need to know the velocity of the flow or the depth, but merely needed to assume that the flow was fast enough to mix the warm water, and carry it downstream.

c. Side Channel Releases. The most usual method of disposing of a power plant's waste heat to a river is to release it directly at the side of the river. This case is more difficult to analyze because now the rate of transverse mixing of the warm water plume across the river must be considered. As a general rule the open water area resulting from a side channel release is quite narrow, on the order of 50 to 100 ft, but very long, on the order of miles. While some of the heat is transferred directly to the atmosphere through the open water area, a significant amount of the heat is transferred to the bottom of the adjacent ice cover and to the bottom of the ice cover downstream of the end of the open water. From the standpoint of maximum decrease of the volume of ice that would be produced in the river without waste heat, this is the most effective use of the waste heat since, once under the ice cover, nearly all of the heat is used to retard ice thickening or to melt it. Simulations are available that enable estimates of the lengths and widths of open water and the amount of ice suppression that results beyond the open water, but they depend on the amount of heat released, the flow velocity, air temperature, depth of river, and the mixing characteristics of the river. For straight reaches of river, the simulations seem to yield reasonable estimates of open water extents.

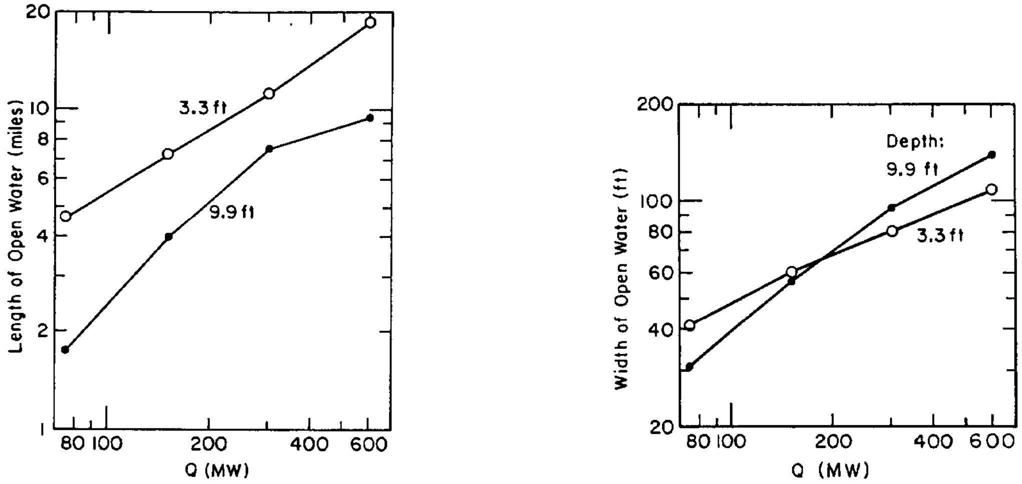
(1) In Figure 7-6 are presented parametric plots of the lengths and widths of open water that may be expected from a side channel release of warm water into rivers of 3.3 and 9.9 ft depths with flow velocities of 1.6 ft/s, as functions of air temperature and rates of heat release. These figures are useful to gain an appreciation of the nature of the ice suppression. Figure 7-6a shows that as the air gets colder, the length of open water decreases significantly. The length of open water is also much shorter for the deeper river than for the shallower river. Figure 7-6b shows that the width of open water is little affected by the depth, but of course is narrower at lower air temperatures. Figures 7-6c and 7-6d show the effect of different rates of heat release on the lengths and widths of open water. As expected, both the length and width increase with increasing warm water discharge.

(2) Not apparent from the various plots of Figure 7-6 are the relative amounts of heat from the warm water that are transferred directly to the atmosphere through the open water or are transferred to the underside of the ice. Less than 30 percent of the heat is transferred through the open water to the air in all cases. This means that 70 percent of the heat is transferred to the ice cover, and either retards thickening or causes thinning of the ice. This effect of the waste heat may extend for many miles further downstream, beyond the end of the open water reach. These effects



a. Length versus air temperature, heat discharge fixed at 150 MW.

b. Width versus air temperature, heat discharge fixed at 150 MW.



c. Length versus heat discharge rate, air temperature fixed at 14°F.

d. Width versus heat discharge rate, air temperature fixed at 14°F.

Figure 7-6. Length and width of open water resulting from side channel release of warm water into a river of either 3.3-ft or 9.9-ft depth, as functions of air temperature and heat discharge rate. In all cases the flow velocity is 1.6 ft/s.

have been simulated by numerical analysis but are too complex to be described quantitatively here, since the effects vary from site to site. Some general statements can be made, however. The rate of heat transfer to the bottom of the ice cover is more or less proportional to the product of the velocity and the amount by which the water temperature is above freezing. Even temperature differences as small as 0.1°F have effects that are important, so that any field measurements must use accurate thermometers. The deeper the water, the further downstream the waste heat will affect the ice. For depths on the order of 3 ft, the warm water will have cooled to very near freezing in about 3 miles, while for depths of about 12 ft the effect will extend for as far as 10 miles.

d. Mid-Channel Releases. Rarely is waste heat from a power plant discharged in the middle of a river. If it were, the effects would be similar to a side channel release and result in a long, narrow open water stretch. The open water would be wider than a side channel release but shorter because the warm water now mixes and spreads on both sides of the thermal plume, rather than only on one side. There may be cases where it would be desirable from an ice management viewpoint to release an existing source of warm water other than at the side. Before doing this, a simulation of the effects should be made to estimate whether the ice suppression would be effective at the particular site.

Section IV. Unconventional Energy Use

7-11. Introduction. 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 might be 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, as possible ways to more economically control ice at navigation projects. A study was conducted 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). The conclusions from that study are briefly summarized here.

7-12. Baseline Power Requirements. The study focused on the process of maintaining lock walls and miter-gate recess walls free of ice collars as the typical ice control task at navigation facilities. As a baseline for comparison of ice control techniques (whether they are conventional or unconventional techniques), the power levels needed to keep the collar formation areas of lock walls at or above 32°F were calculated after making certain assumptions for purposes of illustration.

a. Assumptions. Let the ice collar area along the two walls of a 600-ft-long lock chamber be defined as 6 ft high, for a total of 3600 ft^2 on each wall or 7200 ft^2 for the entire lock. A heat loss coefficient describing the heat transfer from the surface of the lock wall to the atmosphere is taken to be 3.5 Btu/hr ft^2°F.

b. Power Levels. For selected values of air temperature, the amount of power needed to keep the walls at 32°F in the example lock is as follows:

Air temperature (°F)	Heat loss rate (Btu/hr ft^2)	Theoretical maximum power required (kW)
23	32	66
5	94	199
-13	158	332

c. General. The sample power requirements shown above are for *net* heat rates *at* the lock wall surfaces. Consequently, actual power delivery would have to be higher to allow for inefficiencies and extraneous losses in delivering the energy to the walls. On the other hand, the power levels shown are for *continuous* delivery of energy to the wall surfaces, whether ice is present or not. In practical terms, intermittent delivery of heat to the lock walls may be all that is needed to control ice collar buildup. If supplying heat only half the time is sufficient (as is more than likely), the power requirement is reduced by half. Similarly, it is commonly found that only one wall needs attention because of ice adhering only to the wall that receives little or no direct sunlight; thus, the power needed is cut in half again. And further, it is probable that supplying heat to a band of wall 6 ft high is excessive, and the same result can be achieved by heating a band only 3 ft high; the power is halved still one more time, becoming only one-eighth the amount shown in the table above. Thus, for practical purposes, the following power levels should be kept in mind when studying the remainder of this section.

Air temperature (°F)	Practical total power required (kW)
23	8
5	25
-13	42

7-13. 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 32°F 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.

a. Application Modes. Three ways of applying the heat contained in groundwater were investigated for preventing or relieving ice buildup on the walls, recesses, or gates of a lock chamber-heating the entire mass of water in the lock chamber (which in turn would keep the lock walls ice-free), heating the water adjacent to the lock walls, and passing groundwater through pipes embedded in lock walls to raise the wall temperatures.

b. Whole-Lock Heating. This process amounts to continuously supplying groundwater to a lock chamber to replace the river water it contains, at a sufficiently large flow rate that the water does not cool below the freezing point before it is replaced by the continuous subsequent flow of groundwater. One of the practical problems of this approach is the tendency for thermal stratification in the water. Groundwater that is introduced at the water surface with a temperature greater than 39°F, the maximum density temperature, will spread out on the surface and cool to 39°F. Then it will sink to the bottom, permitting cooler water from below to rise to the surface. Consequently, this process *does not* protect the surface from freezing, and makes it necessary to expend energy to diffuse the introduced groundwater, and to keep the resulting blend of water well-mixed in the chamber.

(1) For illustration, consider a lock measuring 600 ft long, 110 ft wide, and 30 ft deep at high-pool level, or 15 ft deep at low-pool level. Assume the river water is not yet frozen, but that it is at the freezing temperature, 32°F. For two example values of groundwater temperature, 43 and 54°F, we want to know how much groundwater is needed to prevent freezing in the lock chamber, and what the power requirement for delivering it would be. Obviously, air temperatures are going to affect the answers, so for illustration three air temperatures (23, 5, and -13°F) will be used.

(2) Assuming that sufficient mixing is achieved to avoid the thermal stratification problem, the amounts of power lost from the water surface to the air and the corresponding amounts of warm groundwater needed to replace those losses are:

Air temperature (°F)	*Power loss (kW)*	*Flow (gal./min) at groundwater temperatures of:*	
		43°F	*54°F*
23	609	378	189
5	1830	1130	567
-13	3050	1890	944

(3) If sufficient mixing is not achieved, these groundwater flow rates would need to be multiplied by a factor of 3.5 to ensure that the surface temperature never went below 32°F. Thus, under the unmixed condition, and in the particular case of 5°F air and 43°F groundwater, a flow of 3960 gal./min would be needed. In the example of a 600 x 110-ft lock, at low pool, groundwater flow at this rate would be needed for over 31 hours to fill the chamber and replace the river water.

(4) Any of the above values represent potentially large amounts of groundwater withdrawal. Again, selecting the example in which air is at 5°F and groundwater is at 43°F, the flow rate for the *well-mixed* condition (1130 gal./min) is equivalent to the entire water demand of a community of 9000 people (at 180 gal./day per capita). For the unmixed condition, the equivalent community has about 31,600 persons. If large amounts of groundwater are withdrawn from wells close to a river, the temperature of the well water in winter may become lower than expected, because

recharge of the withdrawn groundwater by the cooler river water may take place. If wells are located farther from the river, or if recharge by river water does not occur, there could be problems arising from a decline of the water-table elevation.

(5) What is well-mixed? If the example flow of 1130 gal./min were introduced into a lock chamber through two 7.6-in. diameter nozzles at a mean velocity of 4 ft/s, each jet would penetrate about 67 ft before the mean jet velocity dropped to 0.5 ft/s. Assessing the mixing by means of a densimetric Froude Number leads to a value on the order of 0.001, and thus to the conclusion that the water is not well-mixed. Additional mixing would be required to ensure that the heat of the introduced groundwater would be dispersed adequately to keep the water surface above 32°F.

(6) The power requirements for the extraction and mixing of groundwater should be estimated to compare with the power needed to achieve ice control by other means. In using groundwater, it is reasonable to consider, for example, that the groundwater withdrawal could require two 1000-gal./min, 100-ft head pumps, which when used together would call for about 60 kW. Mixing the water in an efficient manner in the lock chamber could call for two more pumps (1000-gal./min, 50-ft head), having a power requirement of about 38 kW. The total requirement of 98 kW is a significant power expenditure compared to other means of lock ice control, and compared to the baseline power values given earlier in Paragraph 7-12. On this basis, the whole-lock heating approach has limited attractiveness.

c. Near-Wall Heating. If the flow of groundwater were to be directed only along the lock walls, where the formation of ice collars is to be prevented, it should be possible to keep the wall surfaces at a high enough temperature, and use a lesser amount of groundwater, than in the whole-lock heating scheme. (It would still be necessary, however, for the heat introduced by the groundwater to balance the heat lost to the atmosphere.) A way of doing this would be to use a manifold along each lock wall below the ice collar area, and to discharge the warmer groundwater through orifices in such a way as to develop flow circulations that would bathe the walls with a blend of water above 32°F.

(1) Assume that the walls will be kept free of ice if strips of the water surface that are 3 ft wide along each wall and extend the length of the 600-ft lock are kept free of ice by balancing the heat loss to the atmosphere with groundwater flow. As in the whole-lock heating example, two values of groundwater temperature (43 and 54°F) and three values of air temperature (23, 5, and -13°F) are used below to illustrate the groundwater flow requirement:

Air temperature (°F)	*Power loss (kW)*	*Flow (gal./min) at groundwater temperatures of:*	
		43°F	*54°F*
23	33	21	10
5	100	62	31
-13	166	103	52

These groundwater flows are quite modest. Note that these values are related to those for the whole-lock heating approach by a factor relating the two different water-surface areas to be kept unfrozen in each approach:

(2 x 3 x 600) / (110 x 600) = 0.055.

(2) The groundwater flows identified above are too small to develop sufficient circulation to mix water along the lock walls, and so the actual amount of groundwater required is determined by the flows needed for achieving sufficient mixing, rather than by the amount of heat in the groundwater. The question now becomes: What are the flow requirements for a water-jet manifold to achieve sufficient mixing while delivering warm groundwater to the area adjacent to the lock walls? To answer this, assume the following criteria: For each wall, the induced velocity at the water surface should be 1 ft/s, the manifold (minimum 9-in. diameter) is at a depth of 10 ft and has 100 nozzles that are each 0.5 in. in diameter and spaced 6 ft apart along the 600-ft length of the lock. Under these conditions, the discharge through each manifold would be 2330 gal./min, or 4660 gal./min if both walls are equipped with manifolds. By use of a densimetric Froude Number criterion, the water would be considered marginally well-mixed. It is clear that the discharge needed for mixing is much greater than that needed for heating, and even exceeds the groundwater discharges under the whole-lock heating concept when the latter uses pumps to achieve mixing.

(3) A remaining possibility for near-wall heating would be to blend river water and groundwater before putting it through the manifold, so that the resulting temperature is still effective in keeping the wall ice-free, while the more readily available river water reduces the need for extraordinary amounts of groundwater. For example, 50 gal./min of groundwater at 43°F blended with 2300 gal./min of river water at 32°F would yield 2350 gal./min issuing from the manifold, having a temperature of 32.23°F. However, such an arrangement would need careful design to avoid heat loss that would allow the blend to cool to 32°F before reaching the lock walls.

(4) Any near-wall heating scheme has the drawback of placing a large manifold pipe at or near the base of the wall or walls. This protrusion generally would be regarded as unacceptable. In a new lock or a major rehabilitation, such a manifold could be incorporated into the wall, with only the nozzles exposed. Another drawback is that greater flows than cited above would be needed if the manifold were more than 10 ft below the water surface.

d. Embedded-Pipe Heating. Circulating warm groundwater through pipes embedded in the lock walls would seem to be an efficient way to use the heat energy in the groundwater, as the heating of the mass of the walls precedes loss of the heat energy to the air. The study shows that the mass of the walls absorbs so much heat as to make this approach unattractive.

(1) Assume that groundwater at 57°F is flowing through an embedded pipe, and the *pipe-wall* temperature is constant at 32°F 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 32°F throughout its mass. Two sizes of pipe and two flow amounts for each size were analyzed. The following table shows how much energy is transferred from the groundwater to the surroundings of the pipe (i.e., the lock

wall mass) in a pipe length of 200 ft. Also shown is the temperature of the groundwater at the end of the 200-ft run.

Pipe size (in.)	*Flow per pipe (gal./min)*	*Energy transferred in 200-ft pipe run (kW)*	*Water temperature at end of 200-ft pipe run (°F)*
1	10	37	32.2
1	15	57	32.4
2	40	136	34.2
2	60	200	34.5

(2) Note that the values above are to keep the *pipe-wall* temperature at 32°F. The real case would be to keep the *lock-wall* temperature at or above 32°F; 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 200-ft 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 ft, 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 32°F 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.

7-14. 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.

a. The heat-transfer medium chosen for the illustration was groundwater at an initial temperature of 50°F. The specific flow rate selected was 1 gal./min per 50 ft^2 of collector area. (Higher specific flow rates would yield lower temperature increases in the fluid, and vice versa, but essentially identical heat gains would result in either case.) The results of the illustration are as follows:

Air temperature (°F)	*Efficiencies (%) at solar radiation values (Btu/hr ft^2) of:*			*Temperature increases (°F) at solar radiation values (Btu/hr ft^2) of:*		
	95	*127*	*159*	*95*	*127*	*159*
23	50	56	60	4.9	7.1	9.6
14	43	51	55	4.2	6.4	8.9
-4	28	39	46	2.7	5.1	7.5

b. Efficiency drops markedly as air temperature decreases. This is because heat loss from a collector is proportional to the temperature difference between the heat-transfer liquid (50°F in this case) and the air. Also note in the table that the temperature increase never exceeds 10°F. For 1 gal./min, this amounts to a power gain of only 1.4 kW, and in the worst case (i.e., lower air temperature and less solar radiation), it is as little as 0.4 kW.

c. Cloudy days, lower air temperatures, 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 combine to discourage extensive consideration of solar energy for lock ice control, in view of the performance levels that can be anticipated.

7-15. 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 illustrate the amounts of power potentially available from wind.

a. For many locations on the inland waterways, an average winter wind speed may be represented by 9 mph. A wind turbine having 20-ft diameter blades and operating at 50 percent efficiency in this wind condition can generate an average power output of about 0.6 kW, according to commonly used formulas. This means, for example, that five or six such wind turbines would be needed to provide power for continuous operation of the comparatively small (32 ft^2) lock-wall heating panels discussed in Paragraph 6-17b and shown in Figure 6-24.

b. As with solar energy, the variability of the energy source and the capital costs of the installations and equipment combine to make wind energy utilization for ice control at locks appear to be unattractive.

7-16. Conclusions. The study concluded that none of the unconventional energy sources that were examined (sensible heat from groundwater, heating of a transfer medium by solar energy, or electricity generated from wind energy) offered great promise over other more conventional means of ice control at locks and dams.

a. Recommended Alternative. The study endorsed electrical heating as a reasonably attractive method for controlling ice, and urged consideration of using an as-yet unconventional means of generating electricity on-site: prefabricated, portable, packaged power plants. The study described a concept then (1988) in the development and demonstration stage for low-head micro-hydroelectric power plants. These packaged plants were of two sizes: one producing 500 kW at a net head of 18 ft and a discharge of 400 ft^3/s, and the other a 1250-kW unit operating with a 12-ft head and 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.

b. Hydropower Potentials. To place all of the values of power mentioned in Section IV in a context that can be related to micro-hydroelectric power-plant potentials, combinations of discharge, net head, and resulting power output are listed as follows:

Discharge (ft^3/s)	*Power output (kW) (at 80% efficiency) at net heads of:*			
	5 ft	*10 ft*	*l5 ft*	*20 ft*
250	85	170	255	340
500	170	340	510	680
1000	340	680	1015	1355
1500	510	1015	1525	2035
2000	680	1355	2035	2710

c. General. 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 in those cases where private power development is not likely, the use of dedicated, portable, packaged hydropower units as described above (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.

CHAPTER 8
MODEL TESTS

8-1. General. 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. The presence of ice adds serious complications to small-scale modeling because it adds a boundary at the top surface of the water body having different surface characteristics than the bed of the waterway. Moreover, whenever the mechanical properties of ice affect the problem under study, these must be duplicated 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 (gravity forces, inertia forces, viscous forces, shear forces, mechanical forces, etc.) in such a way that the ratio between any two forces in the model is equal to the corresponding ratio 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.

8-2. Modeling Broken Ice. In phenomena that do not involve a solid ice sheet but only ice floes, the main forces to consider are usually gravity forces, but 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 considered 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 significant reduction in cost. An example of such a study is found in Calkins et al. (1982).

8-3. 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), the mechanical properties of ice (bending strength, crushing strength, shear strength, and ice friction) become important and must be properly modeled in the laboratory.

a. Model ice grown from a solution of salt or urea in water has been developed that can yield the required properties as long as the model scale is greater than some limiting value. This limiting scale will depend upon the mode of failure of the ice sheet. (For example, the limiting scale is approximately 1:40 for ice failing in bending.) A refrigerated facility is necessary for this type of modeling. Discussion of a model study conducted in a refrigerated facility is given in Deck (1985) and in Gooch and Deck (1990).

b. 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.

8-4. 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 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 field conditions under more or less normal 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.

8-5. Model Distortion. 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. The distortion does impose, however, a reevaluation of the roughness to be used in the model to correctly simulate the head losses occurring in nature. The distortion affects the scale of the thickness and mechanical properties of the ice to be formed in the model, as well as the extrapolation of the model test results to full-scale conditions. The distortion ratio, i.e., the ratio of vertical scale to horizontal scale, should be kept to a minimum and, under the present state of the art, no greater than 4 to 1.

8-6. 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 a critical ingredient to the success of the study and to the reliability of its results. Physical modeling can be a very powerful tool in deciding between various potential designs for a project or between 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.

APPENDIX A

BIBLIOGRAPHY

Ashton, G.D. (1979) "Suppression of River Ice by Thermal Effluents," CRREL Report 79-30, December 1979; U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Ashton, G.D. (1982) "Theory of Thermal Control and Prevention of Ice in Rivers and Lakes," in: ***Advances in Hydrosciences,*** Vol. 13, Academic Press, New York, p. 131-185.

Ashton, G.D., ed. (1986) "River and Lake Ice Engineering," Water Resources Publications, Littleton, Colorado.

Calkins, D., Deck, D., and Sodhi, D. (1982) "Hydraulic Model Study of Port Huron Ice Control Structure," CRREL Report 82-34, November 1982; U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Deck, D. (1985) "Cazenovia Creek Physical Ice Model Study," Report to U.S. Army Engineer District, Buffalo, 1985; U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire (unpublished).

Evans, B.M., and Mata, L. (1984) "Acquisition of 35-mm Oblique Photographs for Stereoscopic Analysis and Measurement," *Photogrammetric Engineering and Remote Sensing,* Vol. 50, No. 11, p. 1581-1590.

Gatto, L.W. (1988a) "Ice Conditions Along the Ohio River As Observed on Landsat Images, 1972-85," CRREL Special Report 88-1, January 1988; U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Gatto, L.W. (1988b) "Ice Conditions Along the Allegheny and Monongahela Rivers As Observed on Landsat Images, 1972-85," CRREL Special Report 88-6, May 1988; U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Gatto, L.W., and Daly, S.F. (1986) "Ice Conditions Along the Allegheny, Monongahela, and Ohio Rivers, 1983-84," CRREL Internal Report 930, May 1986; U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire (unpublished).

Gatto, L.W., Daly, S.F., and Carey, K.L. (1986) "Ice Atlas, 1984- 1985: Ohio River, Allegheny River, Monongahela River," CRREL Special Report 86-23, August 1986; U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Gatto, L.W., Daly, S.F., and Carey, K.L. (1987a) "River Ice Mapping with Landsat and Video Imagery," *Proceedings, Pecora XI Symposium,* Sioux Falls, SD (May 5-7, 1987); American Society for Photogrammetry and Remote Sensing, Falls Church, Virginia.

Gatto, L.W., Daly, S.F., and Carey, K.L. (1987b) "Ice Atlas, 1985-1986: Monongahela River, Allegheny River, Ohio River, Illinois River, Kankakee River," CRREL Special Report 87-20, November 1987; U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Gooch, G., and Deck, D. (1990) "Model Study of the Cazenovia Creek Ice Control Structure," CRREL Special Report 90-29, August 1990; U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Maggio, R.C., and Baker, R.D. (1988) "Techniques for Acquisition of Aerial Video Imagery,"

Photogrammetric Engineering and Remote Sensing, Vol. 54, No. 2, p. 229-231.

Meisner, D.E. (1986) "Fundamentals of Airborne Video Remote Sensing," *Remote Sensing of Environment,* Vol. 19, p. 63-79.

Meisner, D.E., and Lindstrom, O.M. (1985) "Design and Operation of a Color Infrared Aerial Video System," *Photogrammetric Engineering and Remote Sensing,* Vol. 51, No. 5, p. 555-560.

Nakato, T., Ettema, R., and Toda, K. (1988) "Unconventional Energy Sources for Ice Control at Lock and Dam Installations," Report to U.S. Army Cold Regions Research and Engineering Laboratory, May 1988; Iowa Institute of Hydraulic Research, The University of Iowa, Iowa City, Iowa. (Also in preparation as a CRREL Special Report.)

O'Neill, K., and Ashton, G.D. (1981) "Bottom Heat Transfer to Water Bodies in Winter," CRREL Special Report 81 - 18, September 198 1; U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Perham, R. (1985) "Determining the Effectiveness of a Navigable Ice Boom," CRREL Special Report 85-17, October 1985; U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Perham, R. (1988a) "Inventory of Ice Problem Sites and Remedial Ice Control Structures," CRREL Special Report 88-7, July 1988; U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Perham, R. (1988b) "Ice Control in River Harbors and Fleeting Areas," CRREL Special Report 88-12, August 1988; U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Shafer, R.V., and Degler, S.A. (1986) "35-mm Photography: An Inexpensive Remote Sensing Tool," *Photogrammetric Engineering and Remote Sensing,* Vol. 52, No. 6, p. 833-837.

U.S. Army (1985) "Submergible Gate Use Within the Corps: Case Studies," Report to U.S. Army Cold Regions Research and Engineering Laboratory, June 1985; prepared by U.S. Army Corps of Engineers, Louisville (Kentucky) District.

U.S. Army (1987) "Hydraulic Design of Navigation Dams," EM 1110-2-1605, 12 May 1987; Corps of Engineers, Washington, DC.

Zufelt, J., and Calkins, D. (1985) "Survey of Ice Problem Areas in Navigable Waterways," CRREL Special Report 85-2, April 1985; U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

SUPPLEMENTAL REFERENCES

Arcone, S., and Delaney, A. (1987) "Airborne River-Ice Thickness Profiling with Helicopter-Borne UHF Short-Pulse Radar," *Journal of Glaciology,* Vol. 33, No. 115.

Arcone, S., Delaney, A., and Perham, R. (1986) "Short-Pulse Radar Investigations of Fresh-water Ice Sheets and Brash Ice," CRREL Report 86-6, June 1986; U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Daly, S., and Arcone, S. (1989) "Airborne Radar Survey of a Brash Ice Jam in the St. Clair River," CRREL Report 89-2, February 1989; U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Jain, S., Ettema, R., and Park, I. (1988) “Flow Regulation for Controlled River Ice Formation,” Report to U.S. Army Cold Regions Research and Engineering Laboratory, June 1988; Iowa Institute of Hydraulic Research, The University of Iowa, Iowa City, Iowa. (Also in preparation as a CRREL Special Report.)

Michel, B. (1978) “Ice Mechanics,” Les Presses de l’Universite Laval, Quebec City, Quebec, Canada.

Tatinclaux, J.-C., and Martinson, C. (1988) “Development of a River Ice Prow,” CRREL Report 88-9, July 1988; U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

U.S. Army (1985) “Ice Control on Miter Gate Arms,” ETL 1110-2-295, 20 June 1985; Corps of Engineers, Washington, DC.

U.S. Army (1989a) “Reduced Winter Leakage in Gates With J-Seals,” ETL 1110-2-319, 24 August 1989; Corps of Engineers, Washington, DC.

U.S. Army (1989b) “Methods to Reduce Ice Accumulation on Miter Gate Recess Walls,” ETL 1110-2-320, 24 August 1989; Corps of Engineers, Washington, DC.

APPENDIX B

TERMS AND DEFINITIONS

The following terms and definitions have largely been adopted from a list developed by the International Association for Hydraulic Research (IAHR).

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 (Date)	Date of definite breaking or movement of ice because of melting, currents, or rise of water level.
Beginning of Freezeup (Date)	Date on which ice forming a stable winter ice cover is first observed on the water surface.
Black Ice	Transparent ice formed in rivers and lakes.
Border Ice	An ice sheet in the form of a long border attached to the bank or shore; shore ice.
Brash Ice	Accumulations of floating ice made up of fragments not more than 6 ft across; the wreckage of other forms of ice.
Breakup	Disintegration of ice cover.
Breakup Date	The date on which a body of water is first observed to be entirely clear of ice and remains clear thereafter.
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.
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 surface area, both ice-covered and ice-free, at a specific location or over a defined area.
USACRREL	— U. S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.
Degree-Day	— A measure of the departure of the mean daily temperature from a given standard, usually 32°F in the context of freezing (negative departure) or thawing (positive departure). For example, a day with an average temperature of 27°F represents 5 freezing degree-days. Cumulative degree-days are simply the sum of any number of degree-days. For example, the cumulative freezing degree-days of a week with mean daily temperatures of 27, 32, 37, 30, 27, 24, and 27°F are 20 freezing degree-days.
Drifting Ice	— Pieces of floating ice moving under the action of wind or currents, or both.
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 developed by the impact of a moving ice cover or floe on an object. Pressure occurring at moment of first contact termed Ice Impact.
Floating Ice	— Any form of ice floating in water.
Floc	— A cluster of frazil particles.
Flooded Ice	— Ice that has been flooded by melt water or river water and is heavily loaded by water and wet snow.
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 water.
Frazil Slush	— An agglomerate of loosely packed frazil that floats or accumulates under an ice cover.

Freezeup Date — The date on which the water body was first observed to be completely frozen over.

Freezeup Period — Period of initial formation of an ice cover.

Frost Smoke — Fog-like clouds from the 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 — $F_D = V/(gD)^{-1}$ where V = mean velocity, g = acceleration due to gravity, and D = water depth.

Frozen Frazil Slush — Accumulation of slush that has completely frozen.

Glare Ice — Ice cover with a smooth, highly reflective surface; it may be an ice coating on another solid surface, or it may be a sheet on a water surface.

Grounded Ice — Ice that has run aground or is in contact with ground underneath it.

Hanging (ice) Dam — A mass of ice composed mainly of slush 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, usually associated with shorelines.

Hummock — A hillock of broken 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 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 3 ft in extent.
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	— The 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.
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 pieces of any size.
Ice Sheet	— A smooth, continuous ice cover.
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.
Lead	— Long, narrow opening in the ice.
Manning Equation	— $V = 1.486\, R^{2/3} S^{1/2}/n$, where V = mean flow velocity, R = hydraulic radius, S = hydraulic slope (all in English units), and n = a coefficient of roughness, commonly known as Manning's n.
Mush Ice	— A floating accumulation of very fine ice fragments (around 0.1 in. 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.
Pancake Ice	— Circular flat pieces of ice with raised rims; the shape and rim are caused by repeated collisions.

Pressure Ridge	— A line or wall of broken ice forced up by pressure.
Puddle	— An accumulation of melt water on ice, mainly due to melting snow but in the more advanced stages also due to 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.
Rotten Ice	— Ice in an advanced stage of disintegration.
Rough Ice	— General term for ice covers with rough surfaces.
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	— The 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. It appears white owing to the presence of air bubbles.
Snow Slush	— Snow that is saturated with water and is located on the surface of an ice cover, or snow that is a viscous mass floating in water after a heavy snowfall.

Static Ice Pressure — Pressure developed by a static ice cover from externally applied forces or from thermal expansion and certain freezing phenomena.

Stranded Ice — Ice that has been floating and has been deposited on the shore by a lowering of the water level.

Surface Crack — Crack visible at the surface.

Thaw Holes — Vertical holes in ice formed when surface puddles melt through to the underlying water.

Thermal Crack — Crack caused by contraction of ice because of a change in temperature.

Through Crack — Crack extending through the ice cover. Sometimes called a wet crack.

Unconsolidated (Ice Cover) — Loose mass of floating ice.

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).