SPECIAL REPORT 99-8

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Flow Control to Manage River Ice

Andrew M. Tuthill

July 1999

Abstract: This report describes flow-control methods for reducing ice problems in rivers. Objectives include reducing ice interference with winter hydroelectric production and navigation, ice jam flood mitigation, as well as ensuring minimum winter flows for fish and water supply. The winter season is divided into three periods. During early winter, the main objective of flow control is to promote the rapid formation of a smooth, stable ice cover. For the midwinter period, the aim of the river regulation is to maintain an intact ice cover and avoid premature ice breakup. During the final winter period, the goal is to minimize adverse effects of ice breakup. Examples illustrate the methods and objectives, emphasizing innovative approaches. Available flow regulation planning tools are described and valuable research directions identified.

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PREFACE

Andrew M. Tuthill, Research Hydraulic Engineer, Ice Engineering Research Division, U.S. Army Cold Regions Research and Engineering Laboratory, prepared this report. The Civil Works, Cold Regions Engineering Program, work unit, Ice Mitigation Measures in Navigable Rivers, funded this work.

Dr. J.-C. Tatinclaux and Kathleen White of CRREL provided technical reviews, and Mark Hardenberg was editor. Randy Crissman of the New York Power AuthorityÕs Niagara Falls project edited the section on Lake Erie and the upper Niagara River.

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Flow Control to Manage River Ice

ANDREW M. TUTHILL

INTRODUCTION

Winter flow control can reduce ice problems on rivers and waterways, benefiting the hydroelectric and navigation industries, and reducing the threat of ice jam flooding. Winter flow regulation can also reduce ice interference with the operation of locks and dams and mitigate ice problems upstream and downstream of water storage reservoirs. More recently, the interrelationships among flow regulation, ice processes, and winter fish habitat have gained increasing attention.

Flow reductions during critical early winter periods can speed the formation of a juxtaposed ice cover, decreasing the open water area for frazil ice production, and reducing the occurrence of freezeup ice jams and hanging dams. An additional benefit is that a juxtaposed cover is relatively smooth, offering less resistance to flow than the rougher, ÒshovedÓ ice cover that might form in the absence of flow control. During the last three or four decades, many hydroelectric producers in the northern U.S., Canada, and northern Europe have regulated flow during critical early winter periods to reduce ice-related head losses, at substantial economic gains. In addition to maximizing winter hydroelectric production, projects may control outflow to reduce the occurrence of freezeup ice jams and related flooding. The successful performance of ice retention booms may also depend on flow reductions during critical periods. Finally, the rapid formation of a smooth ice cover can benefit winter navigation by minimizing frazil ice production and ice cover thickness, thus reducing ice interference with navigation projects such as locks and dams.

During the midwinter period, flow control at dams can smooth and maintain the newly formed ice cover for the benefit of winter hydroelectric production and ice jam flood control. Following ice cover formation, gradual increases in flow smooth the underside of the ice cover, reducing hydraulic resistance and ice-related head losses at the intakes. Once a stable freezeup cover has formed, hydroelectric projects often return to their open-water generating capacity without adverse effects.

Where ice jam flood potential exists, project operators may try to minimize rapid fluctuations in stage and discharge that could break up the midwinter ice cover. However, this practice often conflicts with hydroelectric operations, where large daily fluctuations may be required to meet peak demands. In some situations, a hydroelectric diversion may be great enough to reduce the ice conveyance capacity of a river reach and actually contribute to ice jamming. The winter pool level of water supply and flood control reservoirs can affect the location and extent of freezeup ice jams on tributary streams.

Passing brash ice and flows at navigation projects while maintaining minimum pool levels presents additional operational challenges. During midwinter breakups, passing ice without damaging river structures or threatening navigation is an important operational issue. Finally, maintaining minimum channel depths for navigation and providing water supply and in-stream flow requirements for fish during low-flow periods are important midwinter flow-control issues.

Flow control can influence the timing and sequence of final river breakup and subsequent ice jams. The upstream pool level at a dam at the

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time of breakup can affect the stopping location of an ice run from upstream. Also, reservoir releases as a result of winter runoff events may influence breakup ice jam occurrence and severity in downstream channels. In addition, planned releases from river dams and reservoirs can delay or accelerate the breakup process in downstream reaches, depending on the ice-control objectives.

This report describes winter flow-control methods chronologically, starting with the early winter ice-formation period, followed by the midwinter ice-maintenance period, and concluding with the late winterÐearly spring ice-breakup period. Examples illustrate flow-control methods and their ice-control objectives. The report summarizes the current state of the art in flow-control methods to manage ice and the conclusions highlight areas where innovative methods and future research might have the greatest benefit in terms of managing river ice.

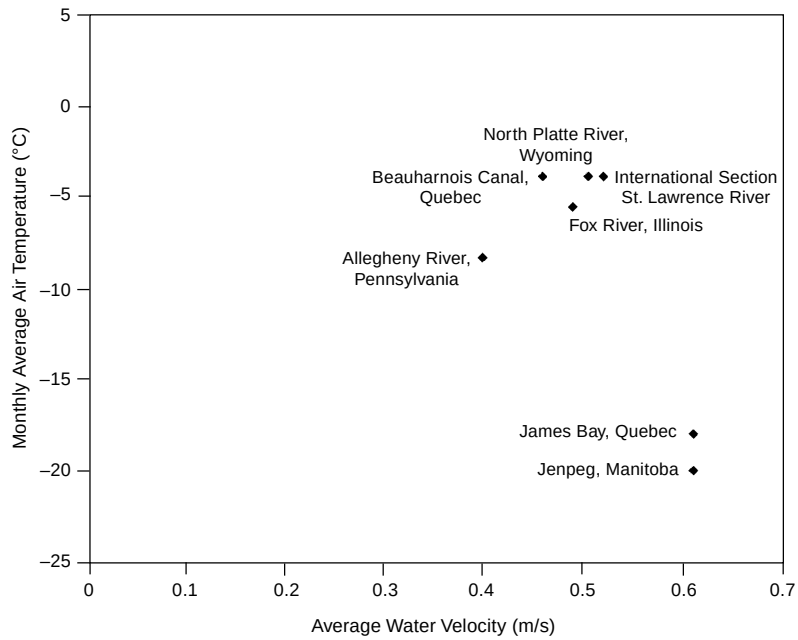

Figure 1. Monthly average air temperature vs. average water velocity during flow cutbacks for ice covers formation. Note that the James Bay and Jenpeg structures are located at about latitude 55° north while the others are located south of 45° north.

EARLY WINTER ICE-FORMATION PERIOD

Hydraulic conditions for ice formation

Flow control for ice formation usually requires that discharge be reduced at a river structure to promote the rapid growth of a relatively thin, hydraulically smooth ice cover by ice floe juxtaposition. In this dynamic process, frazil pans and ice floes come to rest, edge to edge, at the upstream border of the ice accumulation without underturning or being entrained underneath by the flow. Once a stable ice cover has formed, discharge can be gradually raised to open-water levels.

The accepted criteria for ice cover progression by juxtaposition, based on experience and theory, are a maximum water velocity of about 0.70 m/s and a Froude number* of less than 0.1 (Perham 1983). Under average early winter air temperatures in the northern tier of the U.S., optimal hydraulic conditions for rapid ice cover formation by juxtaposition are a velocity of about 0.46 m/s and a Froude number of 0.06 (Perham 1983, Jain et al. 1993). In colder, more northerly regions, the optimal ice-formation velocity is somewhat higher, as shown in Figure 1.

Velocity alone has been used as an ice-cover-formation criterion as well. In reaches where water velocities are at or below about 0.11 m/s, thermally grown sheet ice or border ice would be expected to form rather than a juxtaposed ice cover. At velocities between about 0.70 and 1.5 m/s, a thicker ÒshovedÕÕ ice accumulation usually forms. In this velocity range, instead of accumulating edge to edge, ice pieces typically underturn at the upstream border of the stationary ice cover. Arriving floes may also be entrained by the current to deposit on the underside of the accumulation in the form of hanging dams. A shoved ice cover is usually much thicker and hydraulically rougher than a juxtaposed cover, resulting in greater head losses. Also, for the same ice supply, the shoved cover is shorter, leaving a larger open water area upstream to produce frazil. These factors make the shoved ice cover less desirable than a juxtaposed ice cover for hydroelectric

* Froude number: $F = v/\sqrt{gh}$ where v = average water velocity; g = acceleration due to gravity; and h = average flow depth.

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production, winter navigation, and ice jam flood control. In most cases, reaches where water velocity exceeds about 1.5 m/s will remain open all winter.

Flow cutbacks for ice formation at hydroelectric projects

Major hydroelectric producers on northern rivers reduce flow through their power stations at critical times to promote ice cover growth upstream of their intakes. The goal is to form an ice cover by the juxtaposition of arriving frazil pans and floes. Because the flow reduction causes a temporary decrease in electrical production, it should be as short as possible, and take place at the optimum time for rapid ice cover formation. From the standpoint of winter-long hydroelectric production at a large facility, the savings resulting from flow control for ice management can be substantial.

Operators use a number of strategies to determine optimal timing and duration of flow cutbacks. These include monitoring air and water temperatures and weather trends. Water surface elevations (WSE) are monitored at points upstream of generating facilities to detect the onset of ice-related head losses or hanging dams. Field observations, both from the ground and the air, are used to detect border ice and floating ice, and, later, the spatial extent and condition of the progressing ice cover. Theoretical methods and numerical models have also been used successfully to predict the timing of ice occurrence and ice cover progression, giving operators some lead time to plan their flow reductions. Flow control for ice cover formation may require basin-wide coordination among hydroelectric producers and water-control organizations.

Four examples illustrating important aspects of flow control at the hydroelectric projects are listed in Table 1. The first two are located on the St. Lawrence River between Lake Ontario and Montreal and the second two are in northern Canada.

St. Lawrence River: New York, Ontario, and Quebec

For the past three decades, hydroelectric producers on the St. Lawrence River have used flow control in conjunction with ice booms to promote rapid, early winter ice cover formation upstream of the power stations at the International Section and on the Beauharnois Canal. The timing and magnitude of the flow regulation is based on weather forecasts, and air and water temperature, as well as the position of the edge of the ice cover as it progresses upstream from the dam. The overall goal is to prevent ice jams and maximize winter hydroelectric production. The International Joint Commission regulates flow in the Great Lakes and St. Lawrence River, with the overall goals of maintaining water levels and preventing flooding. There is no winter navigation on the St. Lawrence upstream of the port of Montreal.

International Section

Six booms are installed annually on the International Section of the St. Lawrence, 64 km upstream of the 3200-MW Moses-Saunders Power Dam, near Massena, New York (Fig. 2). The project is

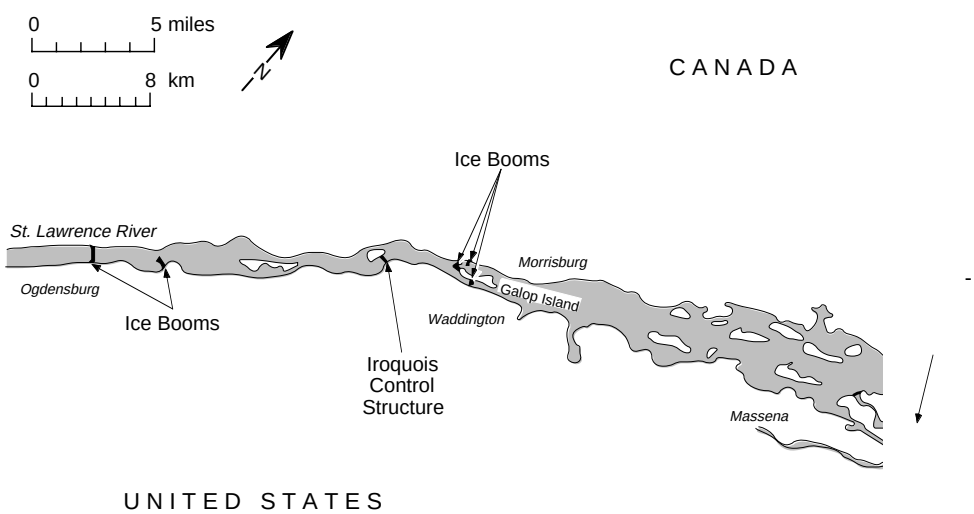

Figure 2. International Section of the St. Lawrence River.

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Table 1. Flow control for ice cover formation at major hydroelectric projects.

River/Reach	Structure	Generating capacity (MW)	Average discharge before cutback (m^3/s)	Average discharge during cutback (m^3/s)	Water velocity during cutback (m/s)	Froude Number during cutback	Ice-control structures	Factors influencing timing and duration of flow reduction
St. Lawrence/ International Section	Moses-Saunders Dam	3200	6510	6230	0.52	0.05	Six ice booms	T_a, T_w, WSE, aerial obs., field meas. t_i, basinwide coordination.*
St. Lawrence/ Beauharnois Canal	Beauharnois Dam	1600	6650	4530	0.46	0.05	Six ice booms	T_a, T_w, WSE, field obs., basinwide coordination, boom force monitoring.
Lake Winnipeg Regulation/ Nelson River	Jenpeg control structure	3600	2550	1650	£0.61	0.070	Ice boom	T_a£ 20°C, wind, weather forecast, WSE, field obs., basinwide coordination.
James Bay/ La Grande River complex	Three power stations	10,270	4300	1420	£0.61	0.06		T_a, T_w, WSE, field obs., basinwide coordination, Ice formation prediction model.

*T_a = Air temperature.
T_w = Water temperature.
WSE = Water surface elevation.
t_i = Ice thickness.

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operated jointly by the New York Power Authority (NYPA) and Ontario Hydro (OH). The ice booms and the flow-control measures were adopted following massive ice jams that formed during the first season of operation of the Moses-Saunders Dam in 1958Ð59. As a result of the jams, discharge through the power stations on the St. Lawrence was reduced by about 1130 m^3/s for most of the winter, water intakes downstream at Montreal were above water, and upstream property along Lake Ontario was threatened by flooding.

Flow at the dam is adjusted according to weather conditions, air and water temperatures, and the location of the edge of the ice cover as it progresses upstream. Although the average cutback flow of 6230 m^3/s is not significantly lower than the long-term average January flow of 6510 m^3/s (Table 1), outflow from Lake Ontario during the early winter can be as high as 8490 m^3/s (New York Power Authority 1970). When the ice cover on Lake St. Lawrence reaches Morrisburg, flow at the Moses-Saunders Dam is reduced if air temperature is at or below Ð8°C, to allow a juxtaposed ice cover to progress up this higher velocity reach. A quality ice cover cannot form in this reach at higher air temperatures, even at the cutback discharge (Wigle et al. 1981). As the cover progresses upstream around the Galop Island, where four booms are located, discharge is regulated to maintain surface velocities of about 0.52 m/s (Perham 1974). When the cover reaches the Iroquois Control Structure, the gates are lowered into the water to promote continued upstream progression towards Ogdensburg, where two additional booms are located. Once the ice cover has formed and stabilized, discharge is returned to seasonal levels.

Beauharnois Canal

Between the International Section and Montreal, the Beauharnois Canal diverts between 3960 and 7360 m^3/s of the St. Lawrence River discharge through the Hydro Quebec 1600-MW Beauharnois Power Station. In early winter, flow through the turbines is reduced to about 4530 m^3/s to allow an ice cover to form behind a series of six ice booms installed along the 24-km length of the canal. Operators at Beauharnois have found that the optimum water velocity for the rapid formation of a smooth ice cover is 0.46 m/s (Perham and Racicot 1975). The timing and duration of the flow reduction is determined through field monitoring, which is similar to the program of NYPA and OH on the International Section. In addition, anchor lines on the forebay boom are equipped with load cells for continuous force measurement. The highest forces are found during the early stages of the ice-formation period, as an unconsolidated ice cover forms behind the boom. At this time, discharge is maintained at the cutback level. Once the ice cover consolidates and freezes to the channel sides, the measured boom force falls off, indicating that the discharge can be increased. The boom load cells are also used to time flow reductions during ice cover breakup. Ice management at Beauharnois increases annual winter hydroelectric production by an estimated 200 MW (Perham and Racicot 1975).

Northern Canada: Lake Winnipeg Diversion

The Jenpeg Control Structure at a latitude of 54°N regulates the outflow from Lake Winnipeg, feeding the large hydrostations on the lower Nelson River. These stations have a combined generating capacity of about 3600 MW. An ice stabilization program that includes a flow cutback during November is estimated to save Manitoba Hydro C$2 million annually (Zbigniewicz 1997). In addition to flow control, the program includes monitoring of weather forecasts, discharges, and water levels; surveying ice conditions from the air; and installing an ice boom upstream of the Jenpeg forebay each year. When border ice and a high concentration of frazil pans appear upstream of the boom, operators reduce flow from 2550 to 1670 m^3/s, which lowers water velocities to about 0.61 m/s. Additional requirements for flow reduction are an extended forecast for clear skies, northerly winds, and air temperatures of Ð20°C or below. Because the cutback at Jenpeg reduces the electrical production on the lower Nelson River Stations during the peak demand period of December, it must be as brief as possible.

Northern Canada: La Grande River Complex

Three powerhouses on the La Grande River Complex east of James Bay in Quebec at latitude 53°N have a combined generating capacity of 10,270 MW. In the 48-km-long reach between the first two stations, a November flow reduction from 4300 to 1420 m^3/s promotes the rapid formation of a smooth ice cover. Average water velocity during the cutback is about 0.61 m/s. In addition to field monitoring of air and water temperatures and water levels, an ice cover prediction model aids operators on the timing and magnitude of the flow changes (Drouin and Hausser 1984).

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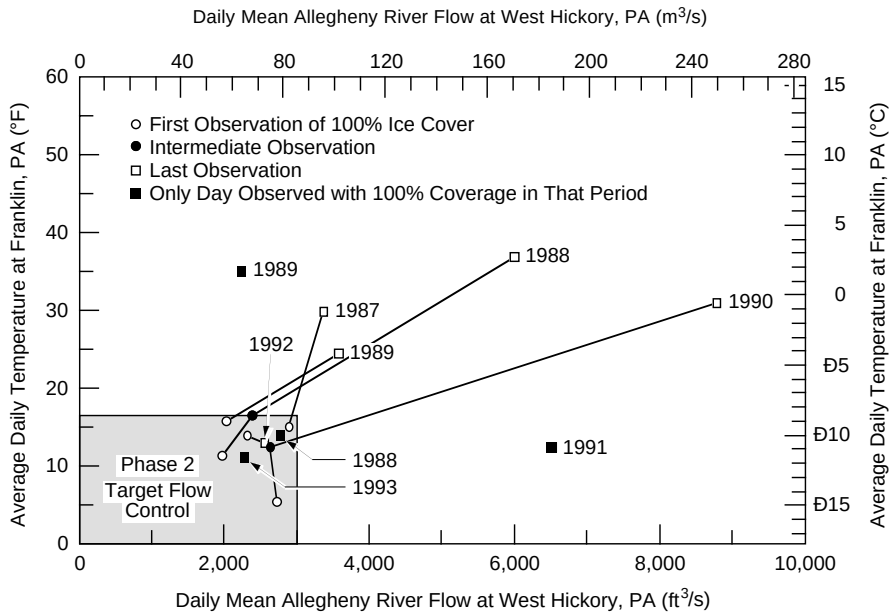

Figure 3. Observed river discharge and air temperatures at the Allegheny River ice boom during periods of complete ice cover formation. (After Daly and Gooch 1994.)

Early winter flow regulation to control freezeup ice jam flooding

Controlling river discharge during the freezeup period can reduce freezeup ice jams and related flooding. Also, by minimizing the volume of ice formed over the course of the winter, the severity of breakup ice jam flooding can be reduced. The operational methods and objectives are similar to those described in the previous section. On smaller, steeper pool-riffle rivers, flow may be reduced at an upstream dam to allow an ice cover to form on downstream reaches, either naturally or behind an ice-retention structure, such a weir or boom.

In 1982, the Pittsburgh District of the U.S. Army Corps of Engineers installed an ice boom on the Allegheny River immediately upstream of the Oil Creek confluence at Oil City, Pennsylvania, to initiate a stable ice cover and reduce the volume of frazil deposited in the confluence area each winter. Before the boom was installed and an ice control weir built on Oil Creek in 1989, the freezeup ice jam on the main stem Allegheny often blocked the breakup ice run on Oil Creek, resulting in an ice jam at the creek confluence and severe ice jam floods in Oil City.

Successful performance of the boom depends on flow reductions at the Kinzua Dam, located on the Allegheny, 106 km upstream, during the initial ice-formation period. At the average winter discharge of about 200 m^3/s, conditions at the boom site are unfavorable for ice retention, with a velocity of about 0.61 m/s and a Froude number of about 0.14. Through analysis of field observed data, Daly and Gooch (1994) found that, since 1988, a 100% ice cover typically forms behind the boom when average daily air temperature is below about Ð8°C, and Allegheny River discharge upstream at West Hickory, Pennsylvania, is below about 85 m^3/s (Fig. 3). Within this flow range, the average water velocity at the boom is about 0.40 m/s and the Froude number about 0.1. The information shown in Figure 3 helps water controllers at the Pittsburgh District time the flow cutback at Kinzua Dam. The timing and magnitude of the flow cutback for ice control must be weighed against other regulatory objectives, such as providing flood storage capacity and maintaining in-stream flow minimums for fish.

Early winter flow control for winter navigation

Most of the major rivers in the U.S. with winter navigation are controlled by stage-regulated lock and dam projects on their main stems, with discharge-regulated flood control projects on their tributaries. Although flow control for ice cover formation has potential benefits to winter navigation, there are few, if any, documented cases of its use. For rivers with winter-long navigation, the

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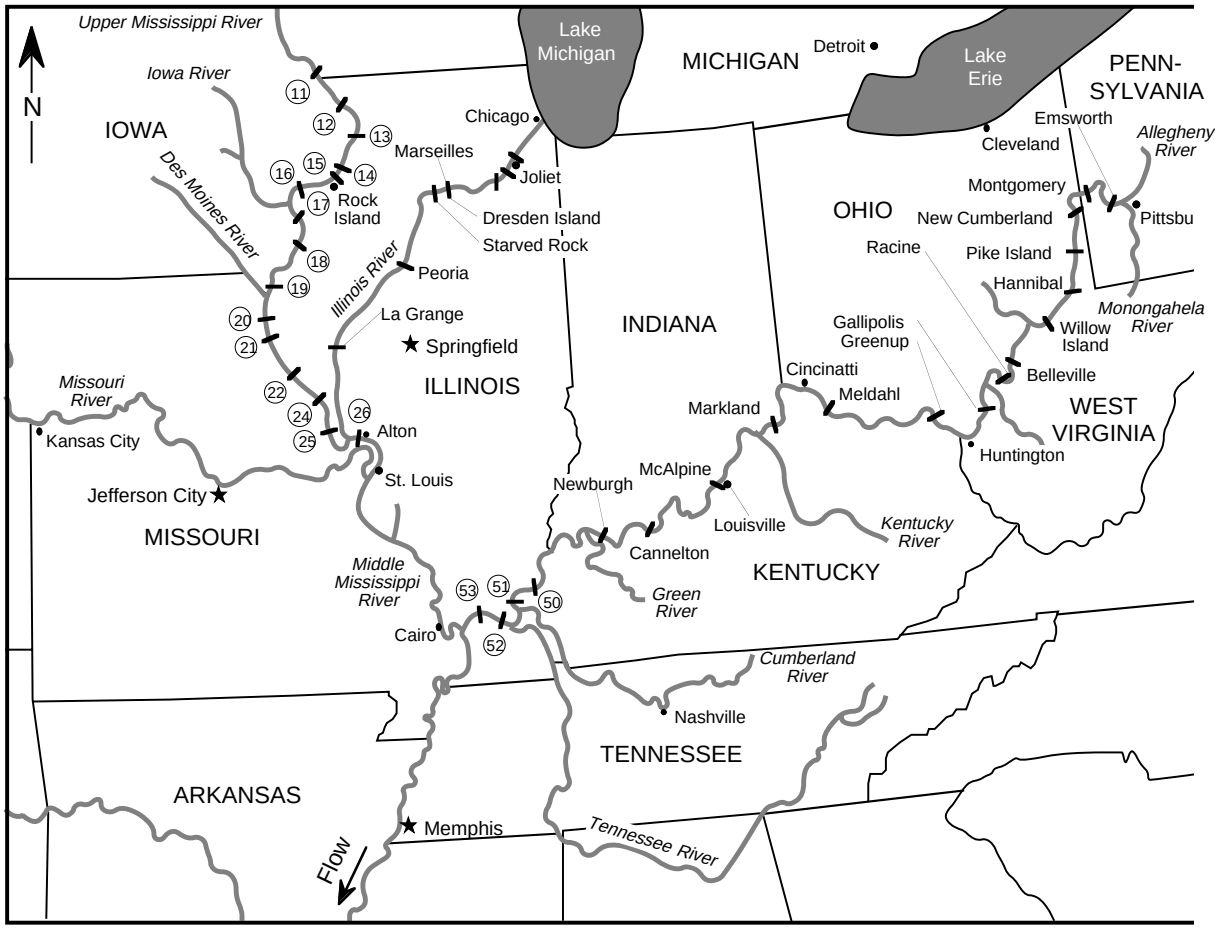

ⓝ Circled numbers indicate Lock and Dam numbers

Figure 4. Major waterways with winter navigation in the United States.

best ice management strategy is to rapidly form and maintain stable ice covers along the margins of a smooth-sided navigation channel (Tuthill 1998). This section examines current flow regulation and its effect on ice cover formation on the upper Mississippi and Illinois Rivers, as well as the potential for flow control for ice cover formation on the Ohio River. The Illinois Waterway is the preferred winter navigation route in the Midwest because ice conditions are relatively less severe than on the upper Mississippi. The upper Mississippi is closed to winter navigation above Lock and Dam 20, whereas the entire Illinois Waterway and Ohio River remain open to navigation all winter. Figure 4 shows these rivers and the locations of major navigation dams.

Illinois Waterway and Upper Mississippi River

Early winter flows on the Illinois Waterway and Upper Mississippi River are typically low and relatively steady, creating ideal conditions for the formation of smooth ice covers. Winter navigation may delay ice cover formation by continually re-breaking the ice cover on the navigation channel and preserving open water areas where frazil ice can be produced. The broken ice may jam at channel constrictions impeding navigation, or accumulate and cause problems upstream of locks and dams. These issues are addressed in the Mid-winter Periodsection, as is ice passage at navigation projects during that time.

On the upper Mississippi and Illinois River basins, discharge-controlled tributary inflow accounts for only a small portion of the total main stem discharge during the freezeup period. Table 2 shows average winter flows from the two major discharge-controlled tributaries of the upper Mississippi below Rock Island. These data indicate that retaining all reservoir outflow during the ice-formation period would reduce the main stem discharge by only about 5%.

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Table 2. Major discharge-regulated tributaries of the Upper Mississippi River.

Tributary	Winter average discharge (Dec.ÐJan.ÐFeb.) near confluence (m^3/s) Tributary	Mainstem	Q trib/ Q mainstem (percent)	Tributary drainage area (D_a) at at mouth (km^2)	Flood-control reservoirs	Total controlled D_a (km^2)	Portion of total D_a (percent)
Des Moines River	82	1086	7.5	38,900	Saylorville Lake Red Rock Lake	15,140	39
Iowa River	32	1086	2.9	10,370	Coralville Lake	8480	80

The potential for reducing Illinois River discharge by storing water during freezeup is even more limited. Even if tributary flow reductions were deemed beneficial for forming ice covers on the main stem, it is unlikely that such reductions would significantly affect ice processes because the tributary flow amounts to but a small fraction of the main stem flow.* On these waterways, tributary flood control reservoirs are typically drawn down in the fall and maintained at low levels during the winter in anticipation of spring runoff events. To maintain storage capacity, reservoir inflow during winter typically equals outflow. Even if discharge-controlled tributary inflow did represent a significant portion of the main stem river flow, it would probably be difficult to convince water controllers that the ice-control benefits of retaining water would justify the lost flood storage capacity.

Ohio River

Early winter discharge and water velocity can be much higher and more variable on the Ohio River than on the Illinois and upper Mississippi, even though 30% of the total discharge from the Ohio basin upstream of Pittsburgh is controlled. The Ohio River has experienced a number of severe ice years, including 1918, 1940, 1948, 1963, 1971, 1977, 1978, and 1979. The worst recent winter was 1977Ð78, when a combination of extreme cold and high early December discharge produced heavy ice on the river. At many locations, water velocity was high enough to form shoved ice covers and jams, impeding navigation. A massive thaw with rain in late January resulted in breakup ice jams throughout the river system and caused what later became known as the ÒMarkland Dam Disaster,Ó described in a later section of this report.

A study by Jain et al. (1993) examined the possibility of controlling flow at tributary reservoirs in the upper Ohio basin to promote rapid formation of juxtaposed ice covers and minimize frazil production. Numerical models simulated ice cover formation downstream of Pittsburgh on the Montgomery and Hannibal pools, predicting water cooling, frazil growth, ice transport, and ice cover progression, under a variety of air temperature and river discharge scenarios. The progression model assumed that juxtaposition of floes would occur only if the Froude number at the upstream edge of the ice cover did not exceed 0.05. The study found that optimal discharges existed for minimizing the time required to form ice covers on the two pools. A generalized case was developed to determine the minimum time to form an ice cover for a range of downstream depths, pool lengths, river bed slopes, and average air temperatures.

In spite of the potential for severe ice events, a general lack of serious ice on the Ohio River from 1980 to the present has dampened any interest in flow control to manage ice on that river system.* If an interest did arise for basin-wide flow control to manage Ohio River ice, Corps water controllers at the Ohio River Regional Office in Cincinnati could use their FLOWSED unsteady flow model to schedule reservoir releases to create optimal hydraulic conditions for ice cover formation. Similarly, the St. Louis and Rock Island Districts are set up with the UNET model (U.S. Army 1997), which has the added advantages of an ice cover option and an ice cover progression routine.

MIDWINTER PERIOD

During the midwinter period, flow-control methods can alleviate ice problems faced by the

* Personal communication with William Koellner, Chief of Water Control, Rock Island District, U.S. Army Corps of Engineers, Rock Island, Illinois, April 1998.

* Personal communication with Ronald Yates and George McKee, Water Control Center, Ohio River Division, U.S. Army Corps of Engineers, Cincinnati, Ohio, April 1998.

hydroelectric and the navigation industries, reduce upstream and downstream ice jam flood problems, and minimize disruption of municipal water supplies and winter fish habitat. This report defines the midwinter period as the time between the appearance of a stable ice cover and the onset of the final breakup period.

Midwinter flow manipulation:
Hydroelectric production and
ice jam flood control

After an ice cover has formed, hydroelectric operators strive to maintain intact ice covers in the reaches upstream and downstream of their projects until the onset of the final breakup period. In some cases, limiting the magnitude and rate of flow changes at the dam can preserve a river ice cover. Careful regulation of the dam outflow minimizes the amount of stage change in adjacent reaches. As a rough rule of thumb, an ice cover will break up if the stage increases by three to four times the ice thickness above the freezeup water level (Donchenko 1978). Many other factors are involved, however, such as the iceÕs condition and strength before breakup, channel geometry, and the rate of stage rise (Beltaos 1984, Ferrick and Mulherin 1989). The negative effects of midwinter breakups include ice jam flooding and the reappearance of open water reaches for frazil production. Once the midwinter ice cover has formed, the large hydroelectric projects on the St Lawrence River and in northern Canada return to a relatively steady daily flow, similar to the open water discharge level. This flow increase following ice cover formation significantly smoothes the under side of the ice cover, decreasing its hydraulic resistance with time.

Where large diurnal fluctuations are required to meet hydroelectric peaking demands, it may be difficult or impossible to maintain an intact ice cover, particularly in the reach downstream of the project. Operators may be forced to limit the magnitude of their daily peak discharge to avoid downstream ice jam flooding. The following examples of Oahe Dam on the upper Missouri River, and Whitehorse Rapids on the Yukon River illustrate the difficulties of meeting peak hydroelectric demands while avoiding ice jam flooding. Timely diversion cutbacks can avert ice jams at hydroelectric projects that withdraw a major portion of the total river flow. The projects on the Upper Niagara River at Niagara Falls, New York, are an example.

Missouri River: Oahe Dam,
Pierre, South Dakota

Oahe Dam, which is operated by the U.S. Army Corps of Engineers, is located on the Missouri River, 10 km upstream of the city of Pierre, South Dakota. To meet hydroelectric demands, outflow from Oahe Dam on the Missouri River fluctuates daily between about 280 and 900 m^3/s, within a maximum range of 0 to 1560 m^3/s. Each winter, a sheet ice cover forms downstream of Pierre, on the pool above Big Bend Dam. During extremely cold periods, a freezeup ice jam may progress from the head of the pool, past Pierre, as far upstream as Oahe Dam. The presence of this jam, combined with the daily peaking operations at the dam, can result in flooding of the low-lying portions of the city.

Unfortunately, the extreme cold that causes the worst ice jam conditions at Pierre coincides with regional peak electrical demand, complicating the decision to cut back releases from Oahe Dam. Although no hard and fast rule exists, prior to 1995, operators typically cut back the peak flow to about 710 m^3/s once water levels exceeded defined ÒalertstagesÓ at two river gages located within the developed area of the city. It is possible that riverbed aggradation at the head of the Big Bend Pool has exacerbated the ice jam problem at Pierre in recent years.

Daly et al. (1997) analyzed field data and used numerical hydraulic models to develop separate ice-affected stage frequency curves based on cutbacks to 710 and 990 m^3/s once the alert stages at Pierre were exceeded. The analysis used actual and adjusted historical hourly flows from selected Òworst-iceÓ periods during the winters of 1967 to 1995. Additional stage frequency relationships were developed for estimated future aggraded channel conditions. The study provided the Corps of Engineers with guidance on flow control as a tool for ice jam flood mitigation. The work also produced estimates of the frequency and duration of future flow cutbacks, as shown in Figure 5.

Yukon River: Whitehorse Rapids,
Yukon Territory, Canada

The Whitehorse Rapids Power Station located just upstream of Whitehorse, Yukon Territory, provides the city with electricity. To maintain the downstream ice cover and avoid ice-related flooding, winter outflow from the plant is limited to 60% of its 276-m^3/s capacity, and daily peaking flows are limited to within 10% of the daily average flow. Through numerical modeling and a pro-

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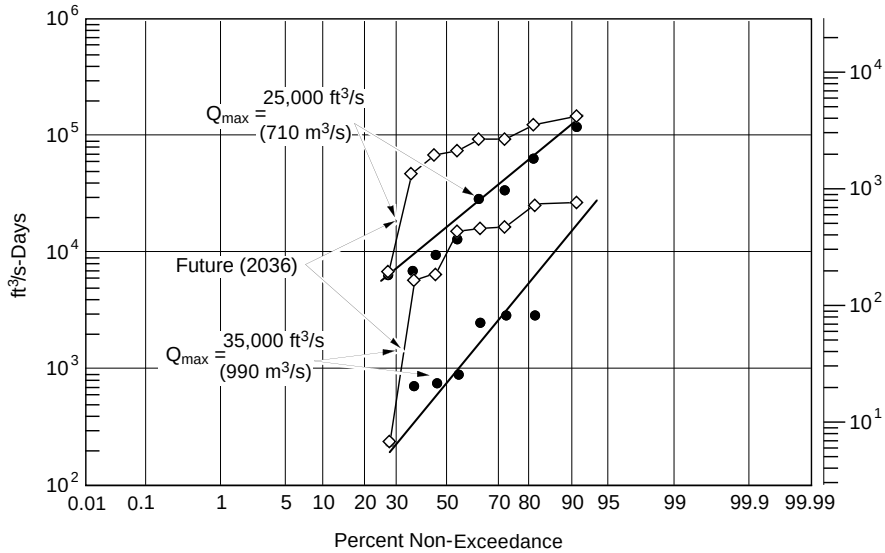

Figure 5. Annual probability of flow constraints in m³/s-days and ft³/s-days for future and existing conditions at Oahe Dam, Pierre, South Dakota. (After Daly et al. 1997.)

gram of field tests, Breland (1995) concluded that it would be possible to increase the winter outflow to 83% of the plant capacity without adversely affecting downstream ice conditions, or increasing the flood risk to low-lying areas in Whitehorse. The ICESIM* model was used to first simulate ice cover formation over a range of discharges, then to calculate water surface profiles resulting from different peak flow levels. Field observations during the winter of 1994 found the model to be a reasonable, though somewhat conservative, predictor of stage because the actual river ice proved to be smoother and thinner than the ice cover predicted by ICESIM.

Based on field test results, Breland found that large increases in flow are possible once the ice cover has been given time to smooth. The magnitude of this increase depends on the observed ice conditions of any given year and it should not exceed the ice coverÕs ability to flex vertically without breaking up. The flow increase should not force significant water flow on top of the ice. Breland recommended that the water levels resulting from the increase in discharge should not exceed the peak water levels observed during the ice-formation period. Finally, the flow increase should not be great enough to fracture, shove, or cause breakup of the ice cover.

* Acres American, Ltd., developed the ICESIM model.

Upper Niagara River:
Niagara Falls, New York

On the Upper Niagara River, early to midwinter ice jams have historically caused flooding and interfered with hydroelectric production . The New York Power AuthorityÕs (NYPA) Niagara Power Project in the U.S. and the Ontario Hydro (OH) stations in Canada have a combined generating capacity of about 4700 MW and can potentially divert as much as 4730 m³/s of the total average river flow of 5660 m³/s. However, the 1950 Niagara Treaty between the U.S. and Canada limits the total diversion flow at any particular time.

Ice jams on the Upper Niagara River result from storm surge events that break up the ice cover on the eastern portion of Lake Erie and drive ice over the Lake ErieÐNiagara River ice boom. The surges can raise the lake level at Buffalo by up to 2 m and nearly double the water discharge in the Upper Niagara River. It takes about 12 hours for the ice to travel the 56 km from Lake Erie to the power plant intakes, located on the banks of a relatively shallow reach of the river above Niagara Falls known as the Grass Island Pool (Crissman et al. 1994). Figure 6 shows an ice jam in front of the NYPA intakes in February of 1964.

Studies by NYPA (1998) examined the ice and flow processes that lead to ice stoppages and jams on the Upper Niagara River. The approach com-

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Figure 6. Ice jam at the intakes of the NYPA Niagara Falls Power Project on the Upper Niagara River. (Photo courtesy of P.A.S.N.Y.)

bined analyses of historical ice events with the use of physical and numerical hydraulic models (Shen and Su 1997) to assess operational and structural alternatives to mitigate ice jams. The numerical modeling results indicated that, under certain lake ice run scenarios, ice stoppages and jams in the vicinity of the NYPA intakes might be prevented or at least delayed by altering the schedules for diversion flows. The studies found that for long-duration (more than 24 hours), high-volume lake ice runs, ice jams are likely regardless of the hydropower diversion flows.

As part of their ice mitigation program, NYPA and OH have developed an extensive ice monitoring and ice management program that continuously informs project operators of ice conditions and provides advance warning of lake ice runs. Water levels and flows are monitored and displayed graphically for the operators. Low-light-level television cameras are used to monitor ice conditions near the intakes. In addition, a marine radar system continuously maps the ice surface in the vicinity of the NYPA intakes and is used to estimate ice concentrations and identify areas of moving or stopped ice. The radar is especially valuable at night when other means of observing ice near the intakes are not possible. Finally, video cameras, mounted on the roof the Marine Midland Center in Buffalo, continuously monitor ice conditions in the vicinity of the Lake ErieÐNiagara River ice boom (Crissman and Lalumiere 1997). Much of this information is disseminated via computer networks to operators at the NYPA and OH power plants.

Midwinter flow control and winter navigation

Most of the winter navigation in the northern U.S. takes place on rivers with stage-regulated navigation dams, such as the Illinois, Ohio, and upper Mississippi Rivers. During periods of heavy ice, winter flows on the Illinois and upper Mississippi are typically low, and relatively steady. At these projects, operators must clear brash ice from the upstream approach to the locks and move the ice through gates past the dam.

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