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CRREL

Ice Jam Flood Assessment for the St. John River Basin, Aroostook County, Maine

James L. Wuebben, David S. Deck, Jon E. Zufelt
and Jean-Claude Tatinclaux

April 1995

Abstract

Ice jams occur almost every year on the Aroostook and St. John rivers in northern Maine. While most of these jams cause minor flooding or no flooding at all, ice jams have caused severe flooding six times in the last 20 years. In 1991 ice jams on the St. John River caused damage estimated at $14 million. This report reviews field observations of the ice regime on the rivers and discusses possible mitigation measures— ice retention structures, channel modifications and early warning systems. In addition, since the 1991 ice jam caused water levels to rise so quickly that people were stranded in their homes, the development and installation of an ice jam motion detection system is described. To aid in early warning, a system to predict the potential for ice jams and their severity that is based on a correlation of hydro-meteorological data with the ice regime is presented.

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US Army Corps
of Engineers®
Cold Regions Research &
Engineering Laboratory

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Prepared for
U.S ARMY ENGINEER DIVISION, NEW ENGLAND

PREFACE

This report was prepared by James L. Wuebben, David S. Deck and Jon E. Zufelt, Research Hydraulic Engineers, and Dr. Jean-Claude P. Tatinclaux, Chief, Ice Engineering Research Division, Research and Engineering Directorate, U.S. Army Cold Regions Research and Engineering Laboratory. The study reported here was conducted for the U.S. Army Engineer Division, New England. The report was technically reviewed by Kathleen White and Timothy Pangburn of CRREL.

The authors express their appreciation to John J. Gagnon, Civil Engineering Technician, Ice Engineering Research Division, for his help in the field observations and in running the HEC–2 program with ice option for the Aroostook River between Tinker and Caribou dams, and to Charles Clark, Electronics Technician, Ice Engineering Research Division, for his expert assistance in developing the ice motion detector.

Many thanks are also due to personnel of the Augusta District Office of USGS, especially to Derrill Cowing, for their assistance in gathering past data, in making available the DCP at Nine Mile Island, and in monitoring the ice motion detector signal.

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CONVERSION FACTORS: NON-SI UNITS TO SI UNITS OF MEASUREMENT

These conversion factors include all the significant digits given in the conversion tables in the ASTM *Metric Practice Guide* (E 380-93), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380-93).

Multiply	*By*	*To obtain*
inch	25.4	millimeter
foot	0.3048	meter
mile	1609.347	meter
foot^3 / second	0.0004719474	meter^3 / second
degrees Fahrenheit	$t_C = (t_F - 32) / 1.8$	degrees Celsius

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JAMES L. WUEBBEN, DAVID S. DECK, JON E. ZUFELT AND JEAN-CLAUDE TATINCLAUX

INTRODUCTION

An ice jam is a stationary accumulation of fragmented ice or frazil ice that restricts flow (IAHR 1986). These accumulations include freezeup jams as well as breakup jams. Freezeup jams are created by pieces of floating ice collecting during periods of relatively steady flow when the ice cover initially forms early in the winter season. Breakup jams, on the other hand, form during the often highly unsteady flow conditions when the ice cover breaks up because of significant rainfall, snowmelt or other increase in runoff.

In contrast to open water flooding, where high water levels directly result from excessive water discharge, ice-affected flooding results from added resistance to flow and blockage of flow caused by accumulations of ice. The formation of an ice cover or ice jam on a river roughly doubles the wetted perimeter of a wide channel. The added resistance to flow caused by the ice cover, along with the reduction in flow area caused by the ice, results in higher stages than a comparable open water discharge would produce. This is particularly true for the case of ice jams, which can cause flood stages comparable to rare open water events, despite discharge recurrence intervals on the order of 2 years or less (exceedence probabilities on the order of 0.5 or greater).

Ice jams occur almost every year both on the Aroostook River and the St. John River. While many of these ice jams result in minor or no flooding, there has been severe flooding and damage directly attributable to ice jams or made greater by ice six times over the past 20 years (1973–1992) (Table 1). Most recently, in the spring of 1991, devastating ice jam floods on the St. John River caused damage estimated at $14,000,000. On 9 and 10 April 1991, the two bridges in the village of Dickey, located in the town of Allagash, 1000 ft of state highway and 11 houses were destroyed (Fig. 1) and an additional 22 houses were damaged. On 13–14 April, ice jam floods on the Aroostook River caused damage to shoreline, roads, 16 houses in the town of Fort Fairfield and properties in the village of Crouseville located in the town of Washburn.

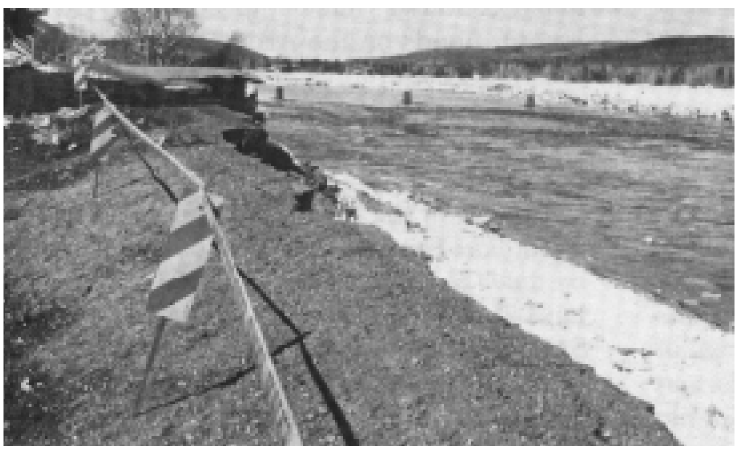
Except for the 1991 jam event, ice jam flooding at Fort Fairfield was previously reported on by the U.S. Army Engineer Division, New England (USACE 1987). On 15 May 1991, the U.S. Senate Committee on Environment and Public Works adopted a resolution requesting the Corps of Engineers to study the entire St. John River basin within the United States (Fig. 2) “in the interest of flood damage reduction particularly relating to ice jam flooding, recreation, water quality, irrigation, and related purposes to serve the needs of the State of Maine.” The New England Division (NED) then contacted CRREL for help in assessing ice jam flooding. Personnel of CRREL’s Ice Engineering Research Division (IERD) conducted a field study to determine the ice processes particular to the upper St. John River and to the Aroostook River, to identify the ice jam flooding problem areas of these rivers, and to determine where available means of alleviating ice jam flood damages may be applicable and should be further evaluated.

During the course of the study, contacts were made with representatives of local, State, and

Table 1. Major ice jam events.

Date	Comments
a. St. John River	
27–29 April 1973	2 in. rain with air temperatures 60°F. River flow Q at Fort Kent was approximately 136,000 ft^3/s with stage of 27 ft (20-year event).
29 April 1974	1.2 in. rain with air temperatures 60°F. Q at Dickey was approximately 87,000 ft^3/s with stage of 29 ft (elevation 619.8). Top of ice elevation was reported to be 621.5 at bridge. Bridge was hit and reportedly moved 4 ft.
	Stage at Fort Kent was 28 ft (25-year event). Ice hit low steel at bridge (as in 1991).
April 1979	Jam reported - No additional information.
April 1983	Jam reported - No additional information.
2 May 1984	26-ft stage at Dickey.
9 April 1991	Dickey disaster. Maximum ice backwater stage of 38 ft, 21-ft free flow stage, Q of 110,000 ft^3/s (100-year event), 25-ft shear walls measured.

Date	Comments
b. Aroostook River at Fort Fairfield	
30 April 1973	3 in. rain with air temperatures 60°F. Q at Washburn of 42,400 ft^3/s. Q at Fort Fairfield of 58,100 ft^3/s.
20 December 1973	1.15 in. rain with air temperatures near 50°F. $^1/_2$-mile jam in Fort Fairfield. Q at Washburn only 14,000 ft^3/s. Stage of 361.7 ft at bridge (est. at 357.7 with no ice).
1 May 1974	1.35 in. rain with air temperatures 60°F. Q was 42,800 ft^3/s at Washburn and 57,700 ft^3/s at Fort Fairfield.
3–6 April 1976	1.6 in. rain with air temperatures 40°F. Ice blocks measured to 43 in. Q at Washburn at 32,200 ft^3/s and at Fort Fairfield at 43,300 ft^3/s with record stage of 365.6 ft (est. at 360.7 with no ice).
16–19 April 1983	1.6 in. rain. Q at Washburn approximately 42,500 ft^3/s and Q at Fort Fairfield approximately 58,500 ft^3/s.
13–14 April 1991	1.7 in. rain. Q at Fort Fairfield of the order of 20,000 ft^3/s with flooding.



a. Bridge and road section destroyed.

b. Private home moved from foundation.

Figure 1. Ice jam damage in the town of Allagash, Maine, April 1991.

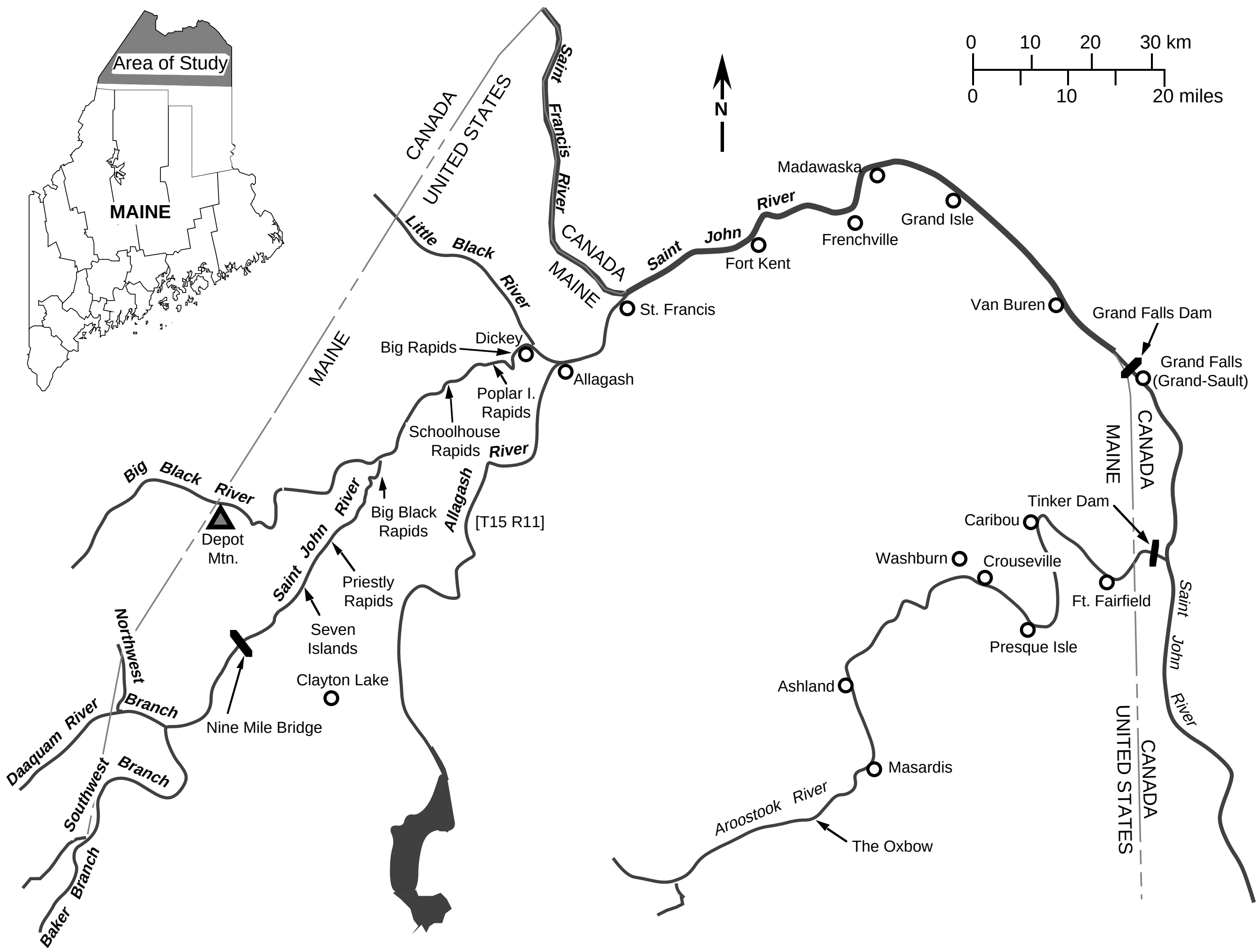


Figure 2. St. John River basin.

Federal agencies, namely the Augusta District Office of the U. S. Geological Survey (USGS), the Maine Emergency Management Agency, the Maine Department of Transportation, the Maine River Advisory Group, the St. John River Flood Forecast Center (Fredericton, New Brunswick, Canada), the International Paper Company, Maine Public Service Co. in Presque Isle, and R. Gardner, a selectman of the town of Allagash, who is also a river observer for the New Brunswick Forecast Center. Local residents also supplied eyewitness accounts of past events, which, while incomplete and subjective, were still helpful in interpreting the field observations made by CRREL personnel and in defining the ice processes during freezeup and breakup in the upper St. John River and in the Aroostook River.

In addition to field observations, we planned to review historical data. This review was, however, limited to the Fort Fairfield area on the Aroostook River for which there were sufficient reliable data on historical hydro-meteorological conditions; the review is described below.

REVIEW OF HISTORICAL HYDRO-METEOROLOGICAL DATA IN THE FORT FAIRFIELD–CARIBOU AREA

The Aroostook River is a tributary of the St. John River in northern Maine and western New Brunswick. The Aroostook River originates at the confluence of the Munsungan and Millinocket Rivers, and flows in a northeasterly direction for about 105 miles until its confluence with the St. John River at Aroostook Junction, New Brunswick. The U.S.–Canadian border is located about 5 miles upstream of the confluence, just below the town of Fort Fairfield, Maine. The Tinker Dam hydroelectric project is located 2 miles downstream of the international border. The project has a drainage area of 2370 miles^2, and an operating head of 85 ft. Above Tinker Dam, the Aroostook River has a fall of 365 ft in just over 100 miles. The average annual precipitation over the Aroostook River watershed is about 37 in., with snowfall averaging about 100 in. There are no long-term streamflow records at

Fort Fairfield, the gage there being discontinued in 1910. A gage located upstream in the town of Washburn, Maine, has been in operation since 1930, however. Based on drainage area, the Washburn flow records have been transposed to the Fort Fairfield area.

The largest recorded discharge at the Washburn gage was 43,400 ft^3/s on 19 April 1983. This would correspond to a discharge of about 58,500 ft^3/s at Fort Fairfield. Typical winter discharges for the Aroostook are on the order of 1000 ft^3/s. Ice jams occur during most years on the Aroostook River, and are frequently responsible for the maximum annual stages. In its study of local flood protection for the town of Fort Fairfield, NED (USACE 1987) determined that peak annual stages at the Washburn USGS gage site resulted from ice jams in 22 out of 53 years, or 42% of the years reviewed. There were significant ice jam floods in Fort Fairfield in 1932, 1936, 1940, 1973, 1976 and 1991. The record flood stage at Fort Fairfield was caused by an ice jam flood in April 1976.

PREDICTING ICE JAM POTENTIAL

Although predicting ice jams and their severity is still beyond the state of the art, it is sometimes possible to rate the likelihood of damaging ice jam floods on the basis of historical observations. Such a prediction mechanism could prove useful in estimating the potential for ice jams in a given year, both for early warning of potential flooding and for determining whether advance measures to limit ice-related flood damages are advisable. Using the method of Wuebben et al. (1992), we reviewed weather and hydrologic data from 1970 through the present to identify the winter season characteristics leading up to significant ice jam events. In addition, six significant ice jam events were examined separately.

Table 2 presents the factors that we examined, including freezing degree-days, snowfall and water discharge. Freezing degree-days can be used in a relatively simple equation to predict ice thickness h

$$h = c\,(\mathrm{FDD})^{0.5} \qquad (1)$$

Table 2. Ice jam potential analysis, Aroostook River at Fort Fairfield, Maine.

Year	*FDD** *(°F)*	*Ice thickness* *(in.)*	D_{max} *(J.D.)†*	$Q_{max\,W}$ *(ft³/s)*	$Q_{max\,FF}$ *(ft³/s)*	DQ_{max} *(J.D.)*	DQ_{10} *(J.D.)*	$DQ_{10}–D_{max}$ *(J.D.)*	$DQ_{max}–D_{max}$ *(J.D.)*	*Snow* Q_{10} *(in.)*
1970	2035	27	189	24,400	32,940	209	207	18	20	88
1971	2246	28	190	27,000	36,450	218	211	21	28	135
1972	2695	31	193	23,300	31,455	222	215	22	28	137
1973	2252	28	195	28,100	37,935	206	201	6	11	153
1974	2164	28	194	38,300	51,705	214	209	15	20	106
1975	2104	28	192	11,000	14,850	207	205	13	15	118
1976	2440	30	174	31,000	41,850	188	182	8	14	131
1977	2354	29	192	26,400	35,640	204	203	11	12	146
1978	2177	28	188	18,900	25,515	212	206	18	24	118
1979	1943	26	168	24,600	33,210	179	177	9	11	108
1980	1838	26	172	13,300	17,955	199	198	26	27	70
1981	1892	26	176	15,300	20,655	189	187	11	13	122
1982	2097	28	192	30,400	41,040	211	204	12	19	158
1983	1601	24	183	42,500	57,375	201	196	13	18	83
1984	2049	27	183	18,000	24,300	201	199	16	18	133
1985	2030	27	195	14,600	19,710	210	204	8	15	90
1986	2257	28	176	17,600	23,760	185	184	8	9	94
1987	2139	28	169	33,500	45,225	185	183	14	16	80
1988	1994	27	176	15,000	20,250	189	187	11	13	92
1989	2251	28	183	13,800	18,630	191	190	27	8	77
1990	2343	29	182	15,900	21,465	207	203	21	25	118
1991	1790	25	183	35,800	48,330	193	181	–2	10	93
min	1601	24	168	11,000	14,850	179	177	–2	8	70
max	2695	31	195	42,500	57,375	221	215	38	44	158
avg	2122	28	184	23,381	31,565	203	199	15	20	111
std dev	233	1.6	8.6	8,582	11,586	12	11	8	8	24

* Freezing degree-days.
† Julian Days.

where FDD is the accumulated degree days of freezing (degrees Fahrenheit), and c is an empirical constant to account for wind exposure and snow cover. For this analysis, and for h expressed in inches, the value of the constant was taken as $c = 0.60$. While eq 1 was developed to predict ice growth on still bodies of water rather than flowing rivers that generate and accumulate frazil, it provides a useful, if approximate, estimate of the relative quantities of ice present from year to year.

The fourth column in Table 2 (D_{max}) is the Julian day (days since 1 October of the year in question) when the FDD term began to decrease. Low values for this term indicate relatively early warming and, therefore, significant ice deterioration and melting was likely before a significant increase in runoff and resulting breakup. The next two columns, $Q_{max\ W}$ and $Q_{max\ FF}$, list the maximum mean daily discharge for Washburn and Fort Fairfield during the estimated time of ice cover breakup. As described previously, the values for Washburn are derived directly from the USGS gage records, while the Fort Fairfield values are transposed from the Washburn gage based on drainage area.

Columns 7 and 8 indicate the Julian dates when the maximum discharge occurred (DQ_{max}) and when the discharge first exceeded 10,000 ft^3/s (DQ_{10}) respectively. We know that it takes a certain magnitude of discharge and stage increase to release an ice cover and to allow it to move downstream. For typical flood hydrographs, the required increase in stage is on the order of three or four ice thicknesses above freezeup levels. If the increase in discharge is rapid or the ice deteriorated, the required increase in stage may be less. For the 2.5 ft of ice measured on the lower Aroostook River on 25 March 1992, this rule of thumb would have required a stage increase in excess of 7.5 ft. However, there was significant deterioration of ice strength and thickness prior to breakup. Under the assumption that the ice had thinned to about 1.5 ft, the required stage rise would have been only about 4.5 ft.

Lacking direct field observations of ice breakup, there is some uncertainty as to the actual date of breakup and peak flooding. For the typical freezeup and midwinter discharge of about 1000 ft^3/s in the study area, however, a spring runoff event of between 10,000 and 15,000 ft^3/s should be sufficient to initiate breakup. Further, a review of the Washburn gage data shows that in most years the discharges before breakup on the Aroostook are well below 10,000 ft^3/s, and then in a matter of days increase to levels well above 15,000 ft^3/s. On this basis, we have used discharges surpassing 10,000 ft^3/s as an indicator of probable ice cover breakup. The required breakup discharge varies, however, with the actual freezeup discharge for a given year as well as variations in the other terms listed in Table 2. The index dates of DQ_{max} and DQ_{10}, when compared to the date of maximum freezing degree days D_{max}, can be used to reflect the arrival of significant spring runoff attributable to warm weather. Columns 9 and 10 present the difference, in days, between the onset of negative freezing degree days and increased runoff.

Finally, the last column lists the total snowfall prior to the jam. Ideally, the effects of snow cover would be accounted for through the depth of snow remaining on the ice prior to breakup, but such information is not generally available. Instead, we have used total snowfall as an indicator. Thick snow covers prior to breakup can insulate the ice from deterioration by warm weather and solar radiation. In the absence of snow, even a relatively thick ice cover can be weakened by solar radiation to reduce ice jam flooding potential. In addition to insulating the ice cover, the melting of a thick snow cover can significantly increase the rate of rise of a flood hydrograph, further ensuring that a thick, strong ice cover is present at breakup

As previously mentioned, the Fort Fairfield area regularly experiences ice jams. In some years, however, the ice-related flooding is more severe. In Table 3, the same factors examined in Table 2 were evaluated for years with severe ice jam flooding. The 1973 flood happened in midwinter, and as a result the absolute magnitudes of some of the terms in Table 3 are quite different from those for other floods. Also, there are two sets of discharge values in Table 3 for each runoff event as determined from the Washburn gage records. The first line represents the maximum discharge during the runoff event. These values are comparable to those presented in Table 2. The second line of discharge data was determined for the dates of peak stages rather than peak discharge. These discharge values are typically much lower than the peak discharges, indicating that the ice cover or jam became unstable and washed downstream before the event peak was reached. Since these values are derived from tables of mean daily discharge, they do not nec-

Table 3. Analysis of major ice jam events, Fort Fairfield, Maine.

Year	*FDD** *(°F)*	*Ice thickness (in.)*	D_{max} *(J.D.)†*	$Q_{max\ W}$ *(ft³/s)*	$Q_{max\ FF}$ *(ft³/s)*	DQ_{max} *(J.D.)*	DQ_{10} *(J.D.)*	$DQ_{10}–D_{max}$ *(J.D.)*	$DQ_{max}–D_{max}$ *(J.D.)*	*Snow* Q_{10} *(in.)*
1932	—	—	—	20,900	28,215	196	192	—	—	—
				10,700	14,445	192	192			
1936	—	—	—	37,000	49,950	174	171	—	—	—
				13,500	18,225	171	171			
1940	1874	26	190	26,100	35,235	197	197	7	7	63
				16,600	22,410	200	197	7	10	
1973	371	12	81	14,000	18,900	85	84	3	4	32
				14,000	18,900	85	84	3	4	
1976	2440	30	174	31,000	41,850	188	182	8	14	131
				27,600	37,260	186	182	8	12	
1991	1790	25	183	35,800	48,330	194	181	–2	11	93
				14,200	19,200	196	189	6	13	

* Freezing degree-days.
† Julian Days.

essarily correspond to the actual river discharges present during peak flooding, but they are unquestionably closer to the correct values than peak discharges for the entire events.

The variables selected for review in Tables 2 and 3 are those that we have found to be significant indicators of river behavior during breakup on other rivers. Not all proved useful on the Aroostook, however. For example, the calculated ice thickness varies modestly between 24 and 31 in., and three out of the four major floods in Table 3 for which data were available had below-average ice thickness. Similarly, while the very large ice jam flood of 1976 happened during a

Table 4. Field trips.

Date	*Sites visited*
Mid-November	St. John River (Fort Kent–Nine Mile). Aroostook River (Fort Fairfield–Masardis).
12 Dec 91	Aerial flight from Tinker Dam to the Oxbow on Aroostook River and to split between Northwest and Southwest Branches of St. John River.
16 Dec 91	Repeat of 12 Dec aerial flights.
17 Dec 91	Overland visit of Nine Mile site.
22–23 Dec 91	Overland: Nine Mile to Big Black River on St. John River.
30 Dec 91	St. John River: Allagash to Seven Islands.
7–9 Jan 92	St. John River: Nine Mile to Dickey–Van Buren to Fort Kent. Aroostook River: Fort Fairfield to Washburn.
21–24 Jan 92	St. John River: Dickey to Baker Branch. Aroostook River: Washburn to Ashland.
24–26 Feb 92	St. John River: Nine Mile (installation of ice motion detector) to Seven Islands, Big Black River gage near Depot Mountain.
27 Feb 92	Aerial video: Caribou to Fort Fairfield on Aroostook River then up St. John River to Nine Mile.
11–12 Mar 92	St. John River: Daaquam River to Fort Kent, and up Big Black River to Depot Mountain gaging station. Also Grand Isle to Fort Kent and 10 miles of Allagash River. Aroostook River: Washburn to Fort Fairfield.
24–25 Mar 92	Aroostook River: Fort Fairfield to the Oxbow.
29 Mar 92	Aroostook River: The Oxbow to Washburn.
30–31 Mar 92	Aroostook River: Fort Fairfield, Masardis.
1 Apr 92	Public meeting at Fort Kent.
4 Apr 92	Aroostook River.
7 Apr 92	Aerial Flight: Source of Aroostook River to Fort Fairfield, then up the St. John River to about Nine Mile.
9 Apr 92	Aroostook River: Masardis to Fort Fairfield.
13 Apr 92	Aroostook River.
17–18 Apr 92	Aroostook and St. John Rivers. Aerial flight: Frenchville to Daaquam River and Baker bridge.
21 Apr 92	Aroostook River: Fort Fairfield to Caribou. St. John River: Flight from Fort Kent to Northwest Branch.
22 Apr 92	St. John River: Daaquam River to Nine Mile.
23 Apr 92	Nine Mile to Big Black, Depot Mountain gage to Fort Kent.

heavy snow year, the other events listed had total snowfall amounts well below average. As stated previously, however, it is really snow on the ice before breakup that is significant. For the 1991 flood, while the total snowfall before breakup was 18 in. below average, there was still 6 to 12 in. of snow on the ground at Caribou, Maine. This amount of snow is sufficient to prevent decay from solar radiation and to insulate the ice from high daytime air temperatures.

Perhaps the most indicative of the terms in Tables 2 and 3 are those in columns 9 and 10 dealing with the interval between the onset of warm weather and significant increases in discharge. As described previously, large values of these terms generally indicate a slow warming, with adequate time for melting and decay of the ice cover prior to breakup. Conversely, the value of –2 for the 1991 flood indicates that water discharge increased beyond the 10,000-ft^3/s threshold, while mean daily temperatures were still below freezing. Such low values for these two terms would indicate that the ice cover deteriorated less and was near its late-winter thickness and strength. Values listed for the specific events in Table 3 are on the order of one standard deviation or more below the average values for 1970–91. Of the two terms, $DQ_{10} - D_{max}$ and $DQ_{max} - D_{max}$, it would appear that the first is the more reliable indicator. Warm weather, capable of generating flows in excess of 10,000 ft^3/s within about 8 days or fewer following the onset of mean daily temperatures above freezing, would appear to be prime cause for severe flooding in Fort Fairfield.

Table 5. Ice thickness measurements.

Location	*Ice thickness (in.)*	*Total depth (top ice to bed) (in.)*
a. St. John River		
8 Jan 92		
Nine Mile	20–24 6 holes	60–84
21 Jan 92		
N.W. Branch at confluence with Daaquam River	33, 27	42, 36
Daaquam River at confluence	19, 19	36, 33
0.6 mile downstream of confluence	13	36
4.5 miles downstream of confluence	16	22
Confluence of S.W. and N.W. branches	22	30
Confluence of S.W. and Baker branches	28	30
Cascade Road bridge	19, 17	30, 36
22 Jan 92		
Moody bridge	24	26
2 miles downstream of Moody bridge	21	48
6 miles downstream of Moody bridge	22	56
10 miles downstream of Moody bridge	27	—
22 Jan 92		
0.6 mile upstream of 7 Islands	28, 24	72, 36
7 Islands	17	57
Priestly Islands	24	26
23 Jan 92		
Base of Poplar Rapids	30	48
Base of Big Rapids	23	36
23 Jan 92		
Left channel at St. Clair Island	28	48
Dickey bridge	20	36
1 mile downstream of Dickey	29	56
1.6 miles downstream of Dickey	23	84
2 miles downstream of Dickey	30	60
b. Aroostook River		
23 Jan 92		
Boat launch off of Gardner Brook Road—Wade		
2 miles upstream of boat launch	24	48
3.8 miles upstream of boat launch	23	48
7.5 miles upstream of boat launch	23	90
14 miles upstream of boat launch in Ashland at brook entering under Wrightville Road	22	96
25 Mar 92		
Fort Fairfield adjacent to N.B. border	31	—
0.3 mile downstream Route 1A bridge in business district	29	—
0.3 mile upstream of Route 1A bridge	32	—
Across from Strickland Road	28	—
Presque Isle, downstream of Route 1 bridge	18	—
1.2 miles upstream Route 1 bridge	16	—
Washburn—right channel at Stratton Island	24	grounded
Masardis at USGS gage	30	—
Oxbow check point	33	—

FIELD OBSERVATIONS IN THE ST. JOHN RIVER BASIN, 1991–92 SEASON

Field observations were made from early December 1991 to April 1992. They covered more than 200 miles of river and necessitated the use of aircraft and snowmobiles, since the upper river reaches were only marginally accessible by truck from the major logging roads that were winter maintained. The field trips are listed in Table 4.

The field observations consisted of visual observations, video recordings and ice thickness measurements at selected locations (Table 5). They were complemented by near-real-time data on river stage, precipitation and air temperatures provided by the USGS network of stream gaging stations equipped with telemetry and located throughout the St. John River basin. In addition, an experimental ice motion detector was installed at the USGS stream gaging station at Nine Mile reach on the upper St. John to see if such an early warning system could assist the existing forecast models used by the National Weather Service and the New Brunswick Forecast Center. This simple apparatus, described below, successfully transmitted the exact time of the first ice movement at the Nine Mile reach.

ICE MOTION DETECTOR

On 24–26 February 1992, two experimental ice motion detectors were installed at Nine Mile bridge on the upper St. John River. Each sensor consisted of two pairs of electrical wires. Each pair, of different length, is joined at one end by a waterproof connection and at the other end is connected to a series of resistors, which in turn are connected to the USGS Nine Mile stream gaging station's Data Collection Platform (DCP). An electrical diagram for the system is shown in Figure 3. The voltage measured by the DCP determines if both pairs of wires are intact, if one or the other pair has broken, or if both pairs have broken.

A 4- to 6-in. deep groove was cut into the ice cover from the bank perpendicular to the river flow. Both pairs of wires were laid into the groove and covered with packed snow and ice chips (Fig. 4). One pair extended 100 ft outward,

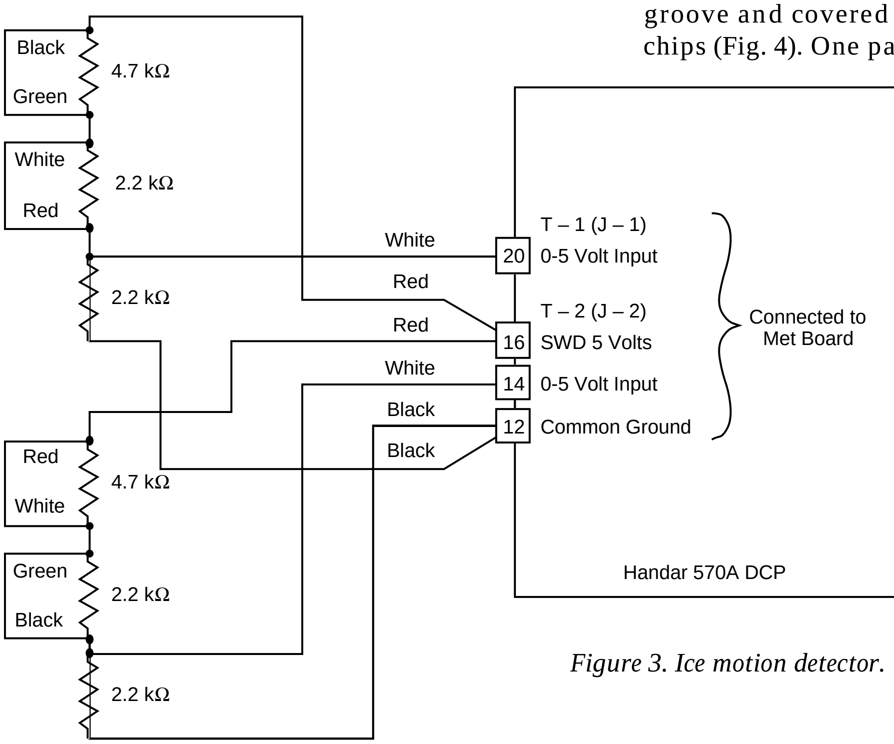


Figure 3. Ice motion detector.

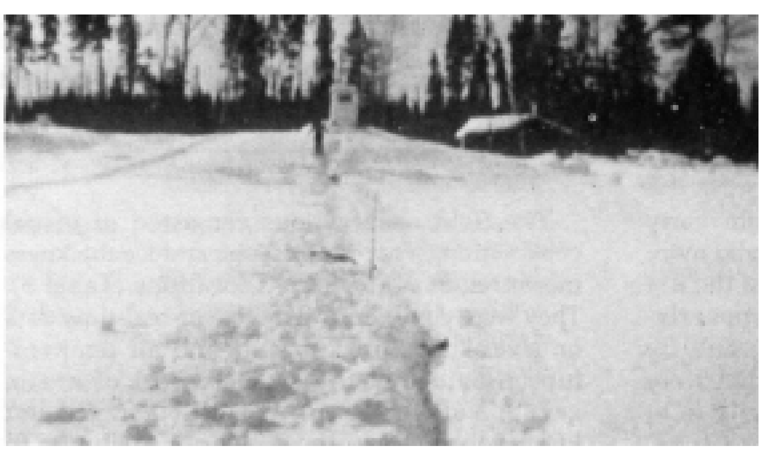


Figure 4. Installation of ice motion detector at Nine Mile, St. John River, Maine.

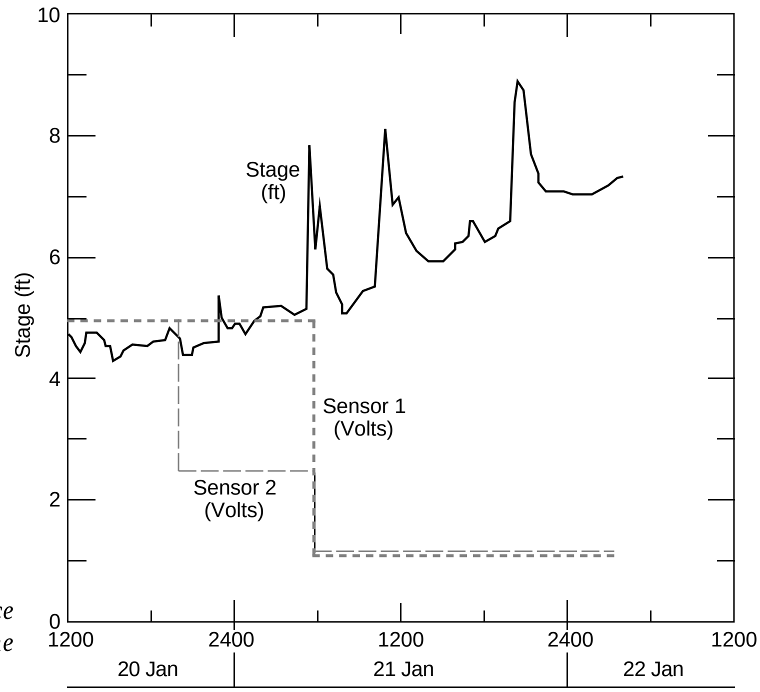


Figure 5. Comparison of signals from ice motion detector and stage gage at Nine Mile.

the other 175 ft. This difference in length was introduced to account for the possibility that the ice may not break up simultaneously across the whole river width. We also felt that two pairs of wires per detector would improve their reliability, since there is always the possibility that one pair may be damaged by chafing of the protective insulation because of minor ice motion, or other causes.

The voltage output from the motion detectors at the Nine Mile bridge DCP is shown together with the water level gage reading on Figure 5. The output indicates that the ice broke up between 0615 and 0645 on 21 April, when stage and discharge rapidly increased.

FREEZEUP OBSERVATIONS

Both rivers began to freeze on 5 December, when large amounts of frazil were being generated as the result of low air temperatures of 0°F. Temperatures remained low through 8 December, ranging from –10 to –20°F, and rose to about 15°F through 11 December, when freezeup was essentially complete. We made an air flight on 12 December to confirm the ice cover extent.

St. John River

On 12 December a freezeup jam existed from the St. John River–Aroostook River confluence in New Brunswick upstream for about $^1/_2$ mile. The river was then open up to the base of Grand Falls Dam (17 miles). Another stable cover extended upstream from the dam to just below the bridge in Madawaska (or about 37 miles). This cover consisted primarily of a single layer of very large pans, except for a short reach at Grand Isle, where there had been some shoving. The river remained open until just below Michaud Island in Frenchville or about 7 miles. Another stable cover began at this location and proceeded up to about 2 miles downstream of the Fort Kent bridge or nearly 10 miles. Above the bridge, the river was primarily open until the vicinity of the St. John town line, a distance of about 10 miles. At this point, ledge outcrops initiated the downstream edge of the final ice cover reach. Except as noted below, this iced-over reach extended to at least the confluence of the southwest and northwest branches of the St. John River, 100 miles upstream from Fort Kent, where our observations ended.

A partially open lead existed for about $^1/_2$ mile downstream of the St. Francis River confluence. Additional open leads also were apparent at Big Rapids, Poplar Island Rapids, Schoolhouse Rapids, Big Black Rapids and Priestly Rapids. Large frazil accumulations were also observed, as would be expected in these fast water reaches. The majority of the remaining ice cover was formed primarily from the juxtaposition of single layered floes.

On 16 December the Northwest Branch was 100% ice-covered up to the Daaquam River, which was also iced over to the Quebec border. This ice was once again composed of smooth, juxtaposed floes with little indication of shoving. The Southwest Branch had a smooth cover at our access points, the Boise Cascade Road and at the confluence of Baker Branch.

The Big Black River was completely frozen over up to the USGS gage near Depot Mountain on 23 December. The Allagash River was fully ice covered up to at least Township 15, Range 11 (T15 R11).

We measured ice thickness from Allagash to the upper basin at the Daaquam River and Baker Branch during 21–24 January. These revealed a solid ice thickness ranging from 13–33 in., with the great majority of measurements being in the range of 20–28 in. By the end of January, most of the open water reaches observed on 12 December were frozen over.

Aroostook River

On 12 December the river was open from its confluence with the St. John River to Tinker Dam in New Brunswick, 2 miles upstream. A stable cover then extended for about 17 miles to approximately $^{1}/_{2}$ mile below the dam in Caribou. Another ice cover was located between the dam and a point upstream of the Village of Sheridan in Ashland, a distance of 40 miles, where a large, open channel began. The open river reach extended 8 miles up to the confluence of Squa Pan Stream in Masardis. From this point, the river was fully ice covered for about 16 miles up to at least the Oxbow, where our observations ceased.

The entire ice cover appeared to be a single layer of frazil pans formed by juxtaposition, with very little evidence of pushes or shoves. We observed no areas of massive frazil deposition in the river. During 21–24 January, we measured a consistent solid ice thickness of 22–24 in. We found no frazil deposits; the previously open reach from Ashland to Masardis was now fully covered.

Ice thicknesses were again measured on 24 and 25 March at random locations from the New Brunswick border to the Oxbow. The solid ice thickness now ranged from 24–33 in., with an additional lone measurement of 16 in. The $^{1}/_{2}$-mile reach below the dam in Caribou was now about 50% ice covered.

BREAKUP OBSERVATIONS

St. John River

Ice breakup was slow, orderly and relatively uneventful, with no overbank flooding reported at any inhabited areas. The breakup began on 28 March when moderate rain and higher air temperatures resulted in a period of slow ice melting through 2 April. All of the snow cover on top of the ice melted at the same time following a short cold spell. High air temperatures returned (about 30 to 45°F) from 4 to 10 April, which caused considerable additional rotting of the ice cover.

An observation flight made on 7 April showed numerous small open leads and jams between Madawaska and St. Francis. We also spotted small open leads at Allagash, Big Rapids, Poplar Island Rapids and Schoolhouse Rapids, with the rest of the upper reaches showing some small areas of flooded ice. The air temperatures had returned to the about 35°F on 15 April, reached about 55°F by 18 April and finally about 60°F on 19 and 20 April.

Ground observations and an air flight on 18 April revealed that most of the remaining ice was very rotted. Stable ice remained from Grand Falls Dam to Van Buren, with the river then being totally open from immediately downstream of the Grand Isle town line to Madawaska Village. There was only about 1 mile of rotted ice in Frenchville and the river was again open until the Fort Kent bridge. The ice upstream of Fort Kent was rotted with many open leads and small jams. A very large lead was observed below the confluence with the St. Francis River and the Big Rapids were mostly open. From this point upstream to about Moody bridge, the ice appeared very rotted with many small open leads. The remaining ice-covered reach, up to the Daaquam River and the Baker Branch, showed no open channels and no indication of breakup.

The ice remaining above Dickey, up to the vicinity of the Big Black River, broke up and ran on 20 April, jamming from the Allagash River confluence area up to Dickey at 1800 hours. This ice released early on 21 April and re-jammed above the ledges in St. John near the Fort Kent line. A major jam at the Priestly–Deadwater area let go and ran through Allagash on the 22 April, causing the jam at the ledges to release and run through Fort Kent. A massive jam of ice from the Northwest and Southwest branches ran by Moody bridge at about 1230 hours on 22 April and went through Allagash and Fort Kent during the afternoon on 23 April. The upper river was ice free at this time and all the ice running downstream continued to move. No ice-related flooding was reported.

Aroostook River

The Aroostook River breakup also began on 28 March and was also a slow and orderly process that only produced minor overbank flow in some low flood plains. On 29 March the majority of the river reaches had some water flowing on top of the ice, with occasional areas being up to 100% flooded. More than 1 in. of rain had fallen in the upper basin and the air temperatures were about 35 to 40°F.

On 30 March, we observed more flooding of the ice cover and a continuing rising stage. A small jam began to form at the Garfield–Ashland line at about 1230 hours. The ice also began to break up near the Caribou Water Works, located about 1 mile below the dam, at 1700 hours. A flight taken on 31 March revealed that the entire length of the Aroostook was primed for breakup. The ice was flooded nearly everywhere and there were numerous small jams and open leads. On 1 April the stage continued to slowly rise but the ice conditions remained relatively unchanged. By 2 April it was apparent that there would be no rapid breakup, although the ice had finally released from shore and was floating freely.

A 7 April flight, taken to continue documenting the breakup, revealed that the numerous open leads and small jams were continuing to expand and the extent of open water had increased significantly. A 3-mile reach was now open below the confluence of Squa Pan Stream in Masardis and another 3-mile open reach existed downstream of the dam in Caribou. A small accumulation of fragmented floes was located near the USGS Washburn gage, where open water had been observed on 4 April.

There was an open reach about 600 ft long below the Masardis gage on 9 April and the open reach downstream of Squa Pan was now 6 miles long and ended at a small jam below the Ashland bridge. Another small jam was located at Sheridan Village. A significant jam that had been at Washburn since 8 April released at about 1430–1500 hours on 9 April and re-jammed at the Village of Crouseville. This new jam was 2 miles long and produced some flooding of a small junkyard located in a low floodplain on the right bank at 1700 hours. Open water extended upstream of the jam through the Washburn gage site to Donnelly Island in Wade. Sheet ice began there and continued upstream to a 1-mile jam, whose toe was just below the Gardner Brook Road boat launch.

On 9 April, the dam in Caribou still had 7 miles of ice behind it, and no ice had yet passed over it. The open river above the ice reached to 1 mile above the Route 1 bridge in Presque Isle. At Fort Fairfield, fractured sheet ice extended from below the bridge to 1 mile upstream. The toe of a 1-mile jam was located at this point and the rest of the river to Caribou was now open.

On 10 April the intact ice observed above Caribou had been reduced to 6 miles in length and the open water reach extended to 2 miles above Presque Isle. The Crouseville jam had shrunk to $1^1/_2$ miles in length. We measured many ice blocks on shore to obtain their thickness and found them to have a range of 6–18 in. This indicated that there had been considerable melting of the ice, at least half of the original thickness, prior to the ice runs. The highest elevation of ice blocks above the existing water surface was about 5 ft, with the average range being 2–3 ft. This corresponded to the river being almost bankfull during the ice runs and jams in most locations. The ice was completely out from below the Masardis gage to Ashland and there was a small jam at the confluence of the St. Croix River.

On 13 April the Masardis village reach was fully open, with some ice still remaining between it and the gage. The river was then open until a small jam near the Sheridan RR bridge. The jams at Wade and Crouseville appeared to be unchanged. The Caribou Dam had about 5 miles of ice behind it and Fort Fairfield had approximately 1 mile of jammed ice above the bridge. There was an additional $^1/_2$ mile of slush accumulated upstream.

The Gardner Brook Road jam had melted down to $^1/_2$ mile in length and the Crouseville jam was reduced to 1 mile by 17 April. On 18 April the dam in Caribou had only 2 miles of ice remaining behind it and still no ice had passed over it. The Fort Fairfield area had only sheet ice left with its upstream edge now being $^1/_4$ mile below the bridge. The little remaining ice ran over Caribou's dam on the morning of 20 April.

SUMMARY OF FIELD OBSERVATIONS

Freezeup

Based on our observations and field measurements, which identified the river ice hydraulic characteristics, we feel that the freezeup process that we observed throughout the St. John Basin was, in general, the typical event: a rapid and easy freezeup with no apparent problems. There obviously are variations that could occur if the discharge at freezeup were significantly different or more unsteady, or, to a lesser degree, if the weather were either milder or more severe. We feel that these variations, however, would not be significant.

Breakup

Although the 1991–92 documented breakup was relatively mild and uneventful, we feel the timing of the running and jamming of the various ice reaches to be typical. Another winter of observations and measurements is required to verify this.

We identified three general ice reaches during breakup within the study area on the St. John River. In each reach, the breakup process is initially independent of the events in the other reaches. The first reach is from Grand Falls, New Brunswick, to Fort Kent or about 60 miles, the second is from near the St. John town line to the Big Black River confluence area (50 miles), and the third covers the remaining upper reaches, up to the Northwest Branch, 53 miles upstream from the Big Black River.

The St. John River reach from the base of Big Rapids in Dickey to the confluence with the Allagash River sustains yearly ice jams. The severity of these jams mostly depends on how quickly the breakup takes place. The combination of rapid breakup and an earlier ice jam remaining in place at Dickey caused a record flood on 9 April 1991. The 1991 and 1992 breakups were close to the extreme. A fast stage rise combined with relatively competent ice during a runoff event results in early ice runs, as happened in 1991. In 1992, however, the slow melt and rotting prior to breakup provided for an easy ice-out and no flooding. More than 50% of the ice had melted in place before any of the ice runs in 1992.

The reach above the ledge outcrops near the St. John and Fort Kent line and the Grand Falls Dam pool are other major jam sites. Small, intermediate jams also occur in other reaches. The major jamming areas in the upper river include the Big Black River confluence, Priestly–Deadwater, Seven Islands and the confluence area of the Northwest and Southwest branches.

The Aroostook River also has three major ice reaches that act independently of each other. One reach extends about 12 miles from below the Caribou dam to Fort Fairfield, another from above the dam to the Village of Crouseville in Washburn or about 20 miles, and the third reach extends upstream from Crouseville.

The major ice jam flooding reaches on the Aroostook River include the Tinker Dam pool in Fort Fairfield, the flat, braided reach in Crouseville, the vicinity of the USGS Washburn gage, and above Donnelly Island in Wade.

All the major jamming sites on both rivers were found to be at transitions from a steeper to a milder river slope. These are classic ice jamming locations. The river simply has insufficient energy to transport the ice through these sites so that the ice slows or stops and begins to jam. A jam will remain stable for a longer period at those sites where flow cross section is large and, therefore, flow velocities are low.

ICE JAM MITIGATION MEASURES

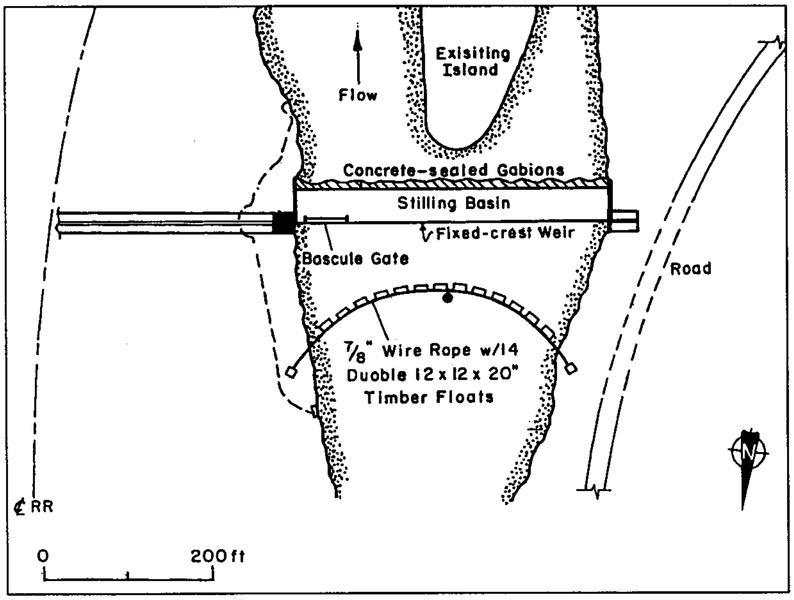
Our review of past ice jams and the field observations carried out during the 1991–92 winter season showed us that the ice jams on the St. John River and the Aroostook River are breakup jams. Ice jam flooding, therefore, can be alleviated in the St. John River basin by controlling ice runs during breakup. The engineering methods that are available to do this can be divided into four main categories: ice-control structures, channel modifications, operational techniques and early warning systems. Depending on location and ice conditions, these methods can be used alone or in combination.

Ice-control structures

The general purpose of an Ice-Control Structure (ICS) is to contain or delay ice runs until the ice-carrying capacity of the river downstream of the ICS is sufficient to avoid ice jamming and resulting flooding at critical downstream locations. An ICS can be located at an existing jam site or could create new jam sites at locations when no adverse effects will ensue. Ice-control structures include the following.

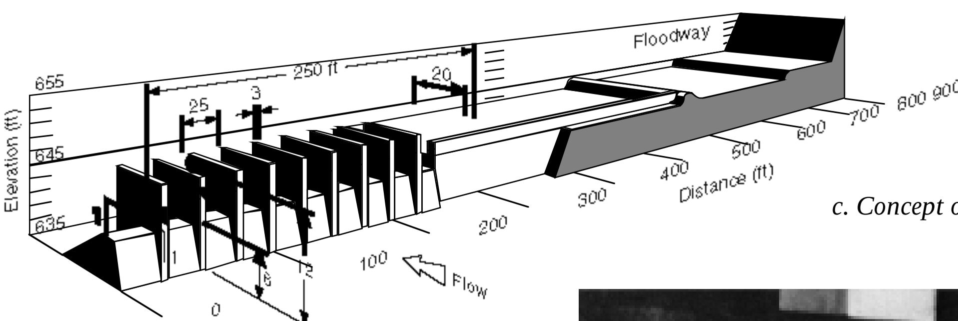
Weirs or small dams

Approximately 6 to 8 ft high, weirs either stabilize a naturally forming ice sheet or create a low velocity pool where an ice sheet will form. They also provide a local storage area to temporarily hold incoming brash ice during an upstream breakup. They can be equipped with ice-holding piers to enhance their ice-holding capacity, and with bascule gates to allow recreational navigation during the ice free seasons. Examples are the ICS on the Oil Creek, near Oil City, Pennsylvania, and a proposed ICS for Cazenovia Creek, near Buffalo, New York (Fig. 6).



a. General plan of Oil Creek ICS, Pennsylvania.

b. Oil Creek ICS in operation.



c. Concept of Cazenovia Creek ICS.

d. Hydraulic model of Cazenovia Creek ICS.

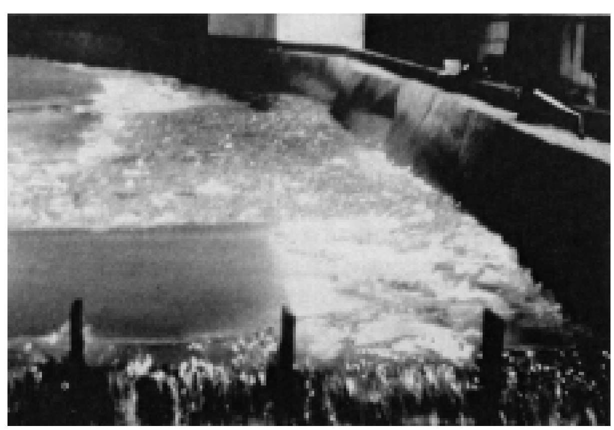


Figure 6. Examples of weirs or small dams.

Figure 7. Example of rock-filled crib, Cherryfield, Maine.

Modified ice booms

Booms are ice holding devices, such as submarine nets, attached to steel cables anchored on both banks. For ice breakup control, they resist the downstream movement of an ice run, providing time for downstream reaches to clear themselves of ice. They can be used in conjunction with an ice control weir or small dam and are usually removed at the end of the ice season.

Rock-filled timber cribs

Approximately 8 to 16 ft at the base, cribs should protrude about 10 ft above normal water surface elevation. They temporarily hold an ice jam at an existing ice jam site and delay ice runs. Such timber cribs have been built at Cherryfield, Maine (Fig. 7).

Channel modifications

Bypass channel

A bypass channel is built to carry flow around an existing ice jam site, thereby reducing the water level behind the jam and consequent flooding. It, therefore, also reduces the water pressure head exerted on the jam, and delays jam failure. A bypass channel can be used alone, as was proposed at Port Jervis, New York, or in conjunction with an ice control structure (e.g., Cazenovia Creek structure, Fig. 6c and d).

Spur dikes

Constructed of heavy riprap or similar to timber cribs, spur dikes protrude into the flow to about one-third of the river width. They serve the same purpose as the timber cribs (Fig. 8).

Dredging

Dredging is a jam enhancement method that can be used primarily at existing ice jam sites. By deepening the river channel, flow velocities and slope of the energy grade line are reduced. The stability of ice jams is increased, thereby delaying jam blow out (jam release). It also increases local ice storage (Fig. 9).

Operational techniques

Such techniques may be useful in controlling ice jamming when flood control or hydropower projects exist on an ice-jam prone river and their flow release can be controlled over a sufficient range. Depending on the existing locations of ice jams with respect to the projects, and the type of ice jams, project operations can be altered to mitigate ice jams and their flooding. Output flow at a project can be reduced

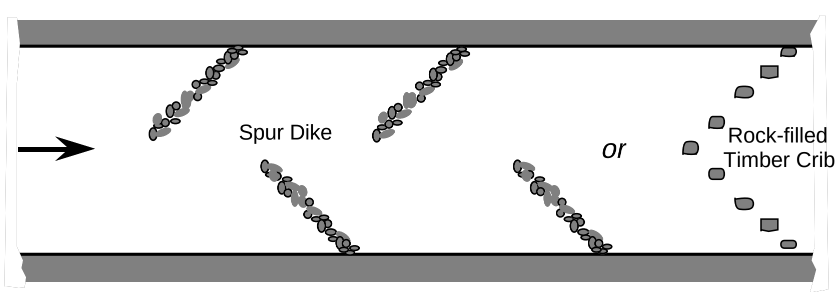


Figure 8. Spur dikes and rock-filled timber cribs for ice control.

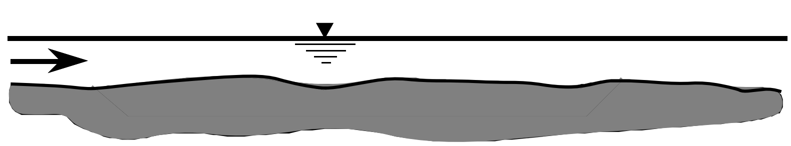


Figure 9. River bed excavation for ice jam enhancement.

and the upstream pool raised to stabilize an upstream ice cover, or increase ice storage capacity, or move the ice jam location further upstream. On the other hand, increased output flow can force an early run of the ice below the project, if the breakup has begun or is imminent. Two conditions are paramount in the use of operational techniques to control ice jams, namely that there is sufficient capability in flow control to achieve the desired results, and that no adverse effects will be caused at undesirable locations either upstream or downstream from the project.

Early warning of ice jam events

One consequence of the field study was confirmation of the value of the experimental ice motion sensor installed at Nine Mile bridge for early warning of ice breakup. Such ice motion sensors would complement existing forecasts by the National Weather Service and St. John River Flood Forecast Center to warn of ice breakup. An early warning could allow state and local officials to take appropriate action to reduce the effect of ice jams.

APPLICATION TO THE ST. JOHN RIVER BASIN

The field observation program of the 1991–92 winter has allowed us to identify general areas where direct ice control could be beneficial. The possible methods applicable to each area are listed below. We also recommend creation of an early warning network as part of any future ice jam mitigation plans.

St. John River

Allagash–Dickey area and upper St. John reaches

ICS or jam enhancement upstream of Dickey. Sites that should be considered include St. Clair Island above Big Rapids, the confluence area with Big Black River, Priestly Deadwater reach, and Seven Islands reach. Methods to evaluate are:

1. Weir with gate for open water canoe passage.
2. Excavation of St. Clair Island.
3. Cribs–spur dikes.
4. Modified booms.

Grand Isle. At this location, conventional dikes should be considered, as should operational changes at Grand Falls Dam. In addition, the early warning network should be improved by installing ice motion detection sensors at the following places:

1. Existing Nine Mile, Dickey, Fort Kent and Allagash DCP stations.
2. New sites at Big Black River confluence, above Big Rapids, or Priestly.
3. Bridges (consider one or all sites).

Aroostook River

Washburn–Wade area

An ICS or a jam enhancement method should be used at Donnelly Island reach in Wade, such as:

1. Overflow weir (e.g., at Gardner Creek Road boat launch).
2. Cribs–spur dikes.
3. Modified booms.
4. Excavation.

Crouseville area

Road alterations or dikes in the village, or both, should be considered as follows:

1. Improve existing bypass channel on left bank.
2. Raise low spot of Route 164 east of village by 5 ft.
3. Conventional dike at same site.

Fort Fairfield–Caribou dam reach

An ICS or a jam enhancement method should be used upstream of town. Sites to evaluate are the island area approximately 2000 ft upstream of the Route 1 bridge and the Haley Island area, which is about 5 miles upstream of the bridge. Methods to evaluate include:

1. Weir, possibly with bypass channel.
2. Excavation of islands.
3. Cribs–spur dikes with or without excavating.
4. Modified booms.

In addition, an ICS from $^1/_4$ to 3 miles upstream of Caribou's dam should be built. Potential methods include:

1. Timber cribs.
2. Spur dikes.
3. Modified boom.

Conventional dikes should be constructed in the village and operational changes at Tinker Dam should be considered.

The existing early warning network should be improved by adding ice movement sensors. This can be done by the following:

1. Using existing DCP stations at Washburn and Masardis.
2. Developing new sites above and below the dam in Caribou.

PRELIMINARY EVALUATION OF AN ICE-CONTROL STRUCTURE AT FORT FAIRFIELD

Ice-related flooding tends to be local and highly site specific. Without sufficient prior field observations, it is difficult to predict where jams will form along a river. However, most breakup jams are the result of ice moving downstream until it encounters a strong, intact downstream ice cover or other surface obstruction, or a significant reduction in water surface slope. At Fort Fairfield, the Tinker Dam reservoir provides a relatively quiescent body of water, with a water surface slope much milder than that of the river upstream. The Tinker Dam hydroelectric project is located 2 miles downstream of the U.S.–Canadian border, and about 5 miles downstream of the Limestone Road bridge in Fort Fairfield. The reservoir drainage area is 2370 miles^2, and the project operates at a head of 85 ft. The river above the dam has a fall of about 365 ft over a length of 105 miles. During the ice breakup period, ice entering the Tinker Dam pool from upstream loses its impetus, stalls and accumulates. At the downstream end, or toe, of the jam, the ice accumulation results in a gradually varied flow profile in the transition reach as water depth increases towards the deeper normal flow depth associated with the thicker, rougher ice conditions. If the jam is long enough, a fully developed or equilibrium jam reach may form, in which ice and flow conditions are relatively uniform. From the upstream end, or head, of the jam, flow depth again makes a transition towards the lower flow depths associated with the open water conditions upstream. The longitudinal profile of a typical fully developed breakup ice jam is shown in Figure 10.

Owing to the complex interaction of hydrological and meteorological conditions, it is very difficult to predict the occurrence, location and severity of a breakup ice jam, even for areas known to be prone to jamming. Analysis is often limited to estimating upper and lower limits of probable stages. If a jam is known (or assumed) to form at a given location, it is possible to estimate the maximum resulting flood levels. It can be shown that for a given scenario of water discharge and ice conditions, the maximum water levels will occur within the equilibrium portion of the jam described earlier. Since ice and flow conditions are relatively uniform within the equilibrium reach, it is a fairly simple matter to estimate the water levels in this portion of the jam. Depending on where a jam forms, and whether there is sufficient upstream ice discharge to form a jam long enough to develop an equilibrium reach, actual water levels may be less and the estimate will be conservative.

Water surface profiles for the Aroostook River were calculated using the HEC–2 computer program (USACE 1990). This analysis was based on a verified open water HEC–2 data deck and downstream rating curve prepared by NED personnel. The original deck provided to CRREL

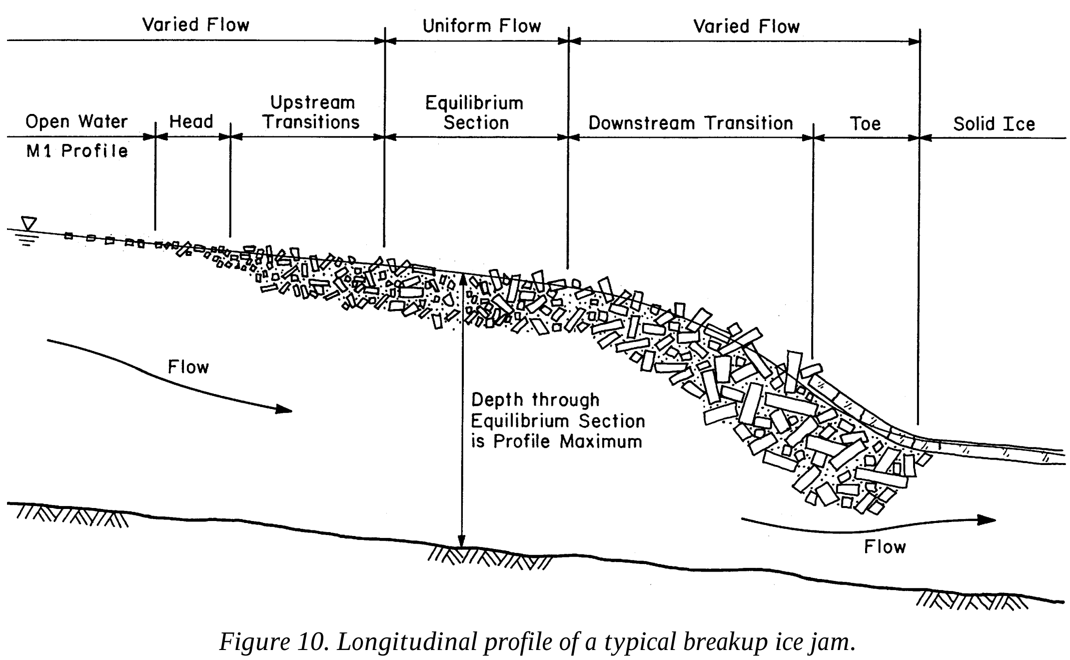


Figure 10. Longitudinal profile of a typical breakup ice jam.

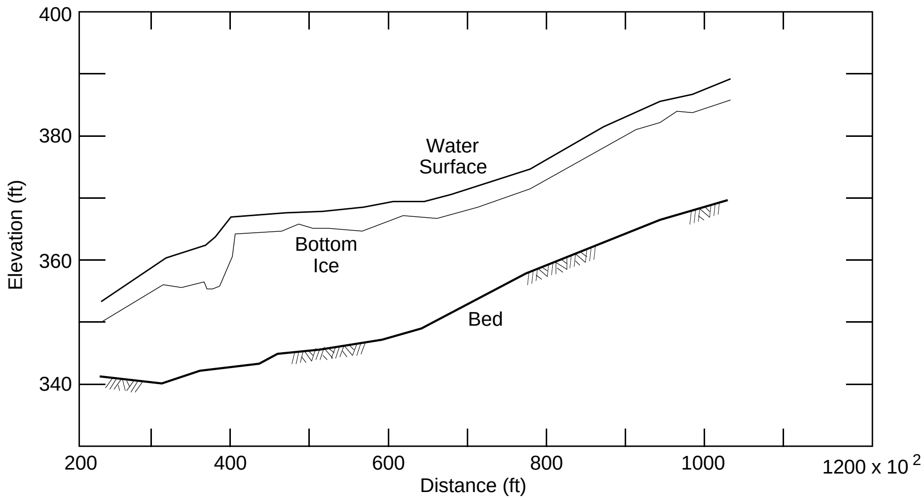


Figure 11. Water surface profile for an equilibrium ice jam on the Aroostook River between Fort Fairfield and Caribou dam.

covered approximately 5 miles of the river, extending from river station 236+54 at the U.S.–Canadian border to river station 490+70. This original data deck was extended by CRREL to river station 1034+00, which is just below the dam in the town of Caribou, so that the relative effectiveness of alternative ice control options could be compared as described later. Cross-section data for the extended deck were derived from USGS 7.5-minute topographic maps. Manning's *n* values were retained from the original data deck. The extended portion of the data deck has not been verified against field data and should be considered only approximate.

The Limestone Road bridge in Fort Fairfield is located at river station 402+84. Because the HEC–2 ice option is actually a modification of the standard bridge option, ice cannot normally be simulated at cross sections where bridge code appears in the data file. Two approaches may be used to overcome this problem. First, the ice cover may be zeroed out for cross sections describing the bridge. Since bridge widths (in the direction of flow) are quite small relative to the river lengths normally modeled with HEC–2, the absence of ice in the bridge throat has a very local effect on the computed water surface profile. Except for the immediate vicinity of a bridge, the effect of deleting the ice cover over such a short distance is normally negligible. Another option is to delete the bridge from the simulation if the ice effects are determined to be of greater significance. For the Aroostook River, the bridge code was deleted from the data deck.

The extended HEC–2 data deck was used to calculate the water surface profile attributable to an equilibrium ice jam formed at a discharge of 20,000 ft^3/s, assuming an unlimited ice supply, as shown in Figure 11. This constitutes the maximum ice-related stage possible for that discharge that was selected as being representative of the Aroostook River flow at Fort Fairfield at breakup.

Ice-affected water levels

The first step in the analysis of ice-affected water levels was a review of the significant ice jam floods described in an earlier section. For those events, information was available on the date, discharge and peak stage reached at the Limestone Road bridge. This information was used to verify the performance of the HEC–2 analysis using the ice option. Lacking was information on the locations of the toe of the jams, jam thickness, length or ice volumes. Without field observations of the toe location, we had no alternative but to assume that the ice cover throughout the river was fragmented and free to thicken into an equilibrium jam in response to the forces imposed by the flowing water. As described earlier, this assumption would result in the maximum possible water levels for a given discharge. Actual water levels are almost always less and lie somewhere between the limiting conditions of open water, a solid cover of sheet ice, and a fully developed equilibrium ice jam. The solid ice cover case would represent the minimum ice-affected stage, while the equilibrium ice jam case would represent the maximum stage possible for a given discharge.

Figure 12 shows an ice-affected rating curve

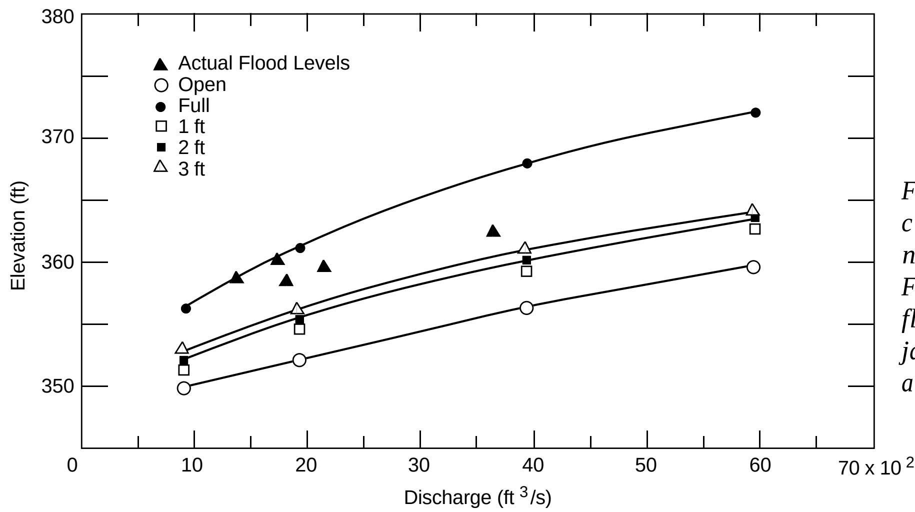


Figure 12. Ice-affected rating curves of the Aroostook River, near Limestone Road bridge, Fort Fairfield. Shown are the flood levels reached during ice jams in 1932, 1936, 1940, 1973 and 1976.

developed for river station 402+84, which corresponds to the Limestone Road bridge. The curves represent open water, ice-covered and ice-jammed conditions in order of increasing stage. The figure shows the calculated ice-affected water levels for discharges up to a 25-year open water flood (60,000 ft^3/s). It is unlikely, however, that an ice cover would remain intact for discharges much greater than 10,000 ft^3/s or that a jam would remain stable for discharges as large as a 5-year open water flood (43,000 ft^3/s). For the major ice-related floods reviewed in Table 3, peak stages for all but one were reached at discharges of no more than 23,000 ft^3/s. The remaining flood, in 1976, had a discharge on the order of 37,000 ft^3/s. A 2-year flood is on the order of 31,000 ft^3/s. Prior to reaching a 5-year recurrence interval discharge, it is likely that any ice jam would release, and water levels would return to open water levels. Thus, the true rating curve would likely follow the curve for an ice cover of appropriate thickness up to a discharge of 10,000 to 15,000 ft^3/s, and would then increase to levels no greater than the equilibrium jam curve (depending on ice conditions and supply).

It must be reiterated that calculations assuming an equilibrium ice jam generate the maximum possible water surface elevation for a given discharge. Actual water levels are most often less. Lower actual water levels can be found at locations close to the toe of the jam where the jam may not be fully developed. If there are insufficient quantities of ice to form an equilibrium jam, the actual water levels will also be lower than computed. For example, the December 1973 ice jam was known to be only about $^1/_2$ mile long, and could thus affect only a relatively short length of river.

Effect of Caribou's dam

It is possible that the dam in Caribou acts as an ice-retaining structure during breakup. If so, the supply of ice to the jam at Fort Fairfield

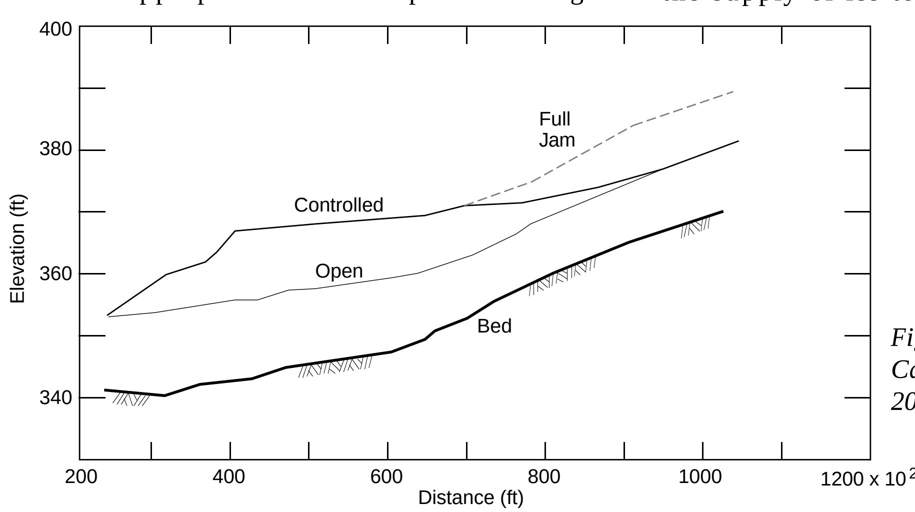


Figure 13. Possible effect of the Caribou dam as an ICS (Q = *20,000* ft^3/s*;* h_i *= 28 in.).*

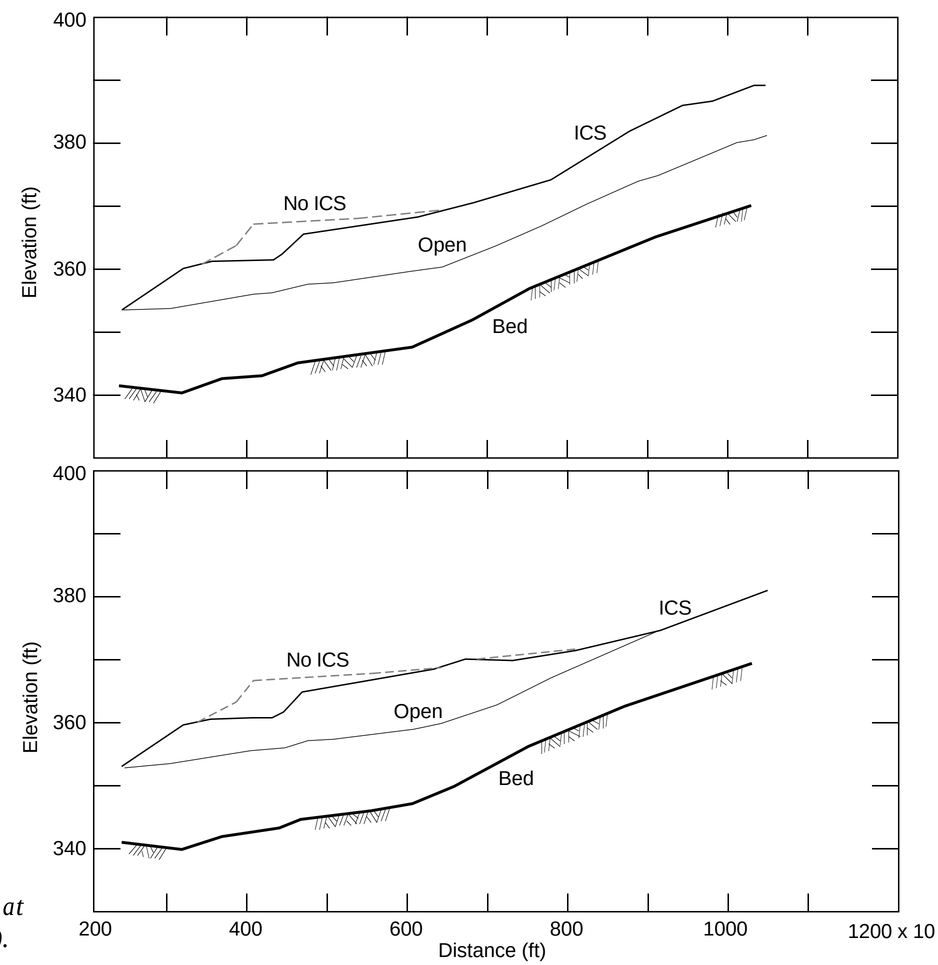
would be limited to that ice present in the river between Fort Fairfield and the dam. The HEC–2 program with ice option was run for this case, for the same discharge of 20,000 ft^3/s and with the additional assumption, supported by the field measurements and the calculations in Table 2, that the ice thickness averaged 28 in. The results of the computations are presented in Figure 13. With ice supply limited by the dam, we found that the jam should extend up to station 680, approximately, and that the jam backwater should merge with the open water surface profile at about station 950. Therefore, improvements to the dam to ensure that it acts as an ice-control structure would not be sufficient to alleviate ice jam flooding at Fort Fairfield. Additional mitigation means, upstream of Fort Fairfield and below the dam, would be required.

Effects of ice-control structures upstream of Fort Fairfield

As mentioned previously, the primary objective of extending the HEC–2 data deck beyond the original, verified deck provided by NED was to assess the relative effectiveness of constructing some type of ICS.

For this study, we assumed in the computations that all the ice upstream from any control structure would be held back, thus limiting both the supply of ice reaching an ice jam in the Fort Fairfield area and the resulting water levels. The type and characteristics of the ICSs were not specified because the effects of the ICS itself on the water surface profile would be relatively small as compared to the ice effects, and they, also, would be local and would require a more accurate HEC–2 deck than the extended one used here. All computations were made for the same flow discharge of 20,000 ft^3/s.

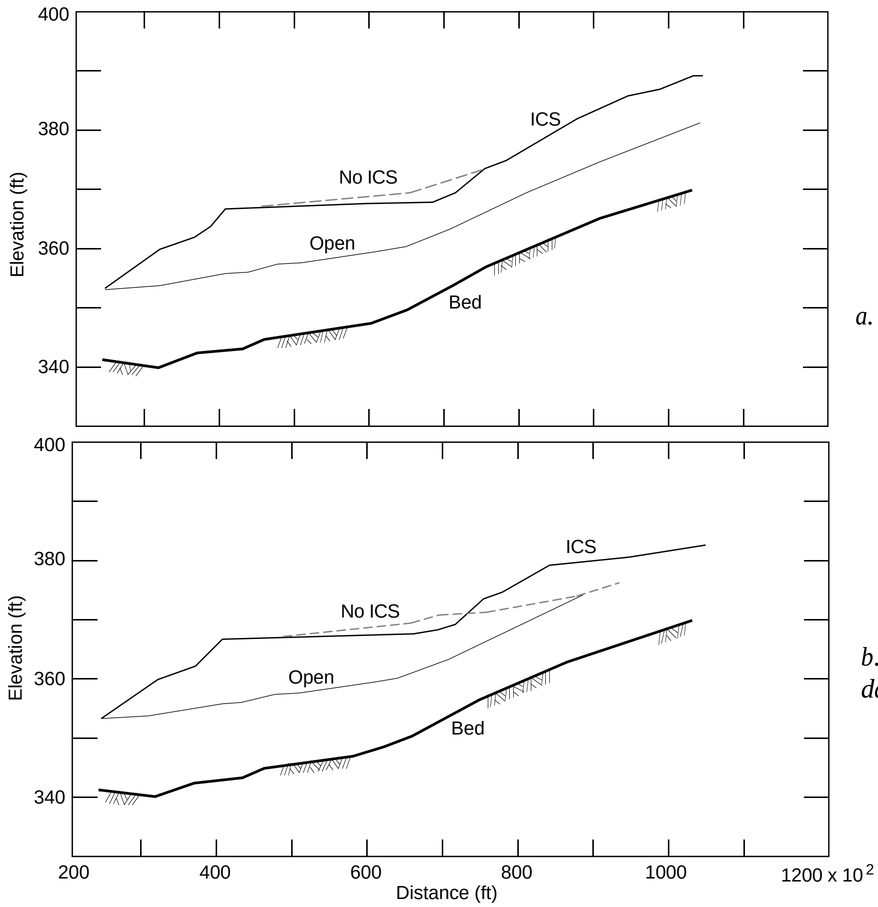
Figure 14a shows the effect of constructing an ICS at station 423+00, approximately 2000 ft upstream from the Limestone Road bridge for the case of unlimited ice supply. Figure 14b shows the effect of the same ICS when the ice supply is limited by the Caribou dam and for an ice thickness of 28 in. Both figures show that the water level is reduced by as much as 6 ft between about stations 330 and 423. Upstream of the ICS



a. Unlimited ice supply.

b. Ice supply limited by the Caribou dam (h_i = 28 in.).

Figure 14. Effects of an ICS at station 423 (Q = 20,000 ft^3/s).



a. Unlimited ice supply.

b. Ice supply limited by Caribou dam (h_i *= 28 in.).*

Figure 15. Effects of an ICS at Haley Island ($Q = 2000\ ft^3/s$*).*

the water level is initially reduced by about 2 ft, but at about station 630 it goes back to the level without the ICS.

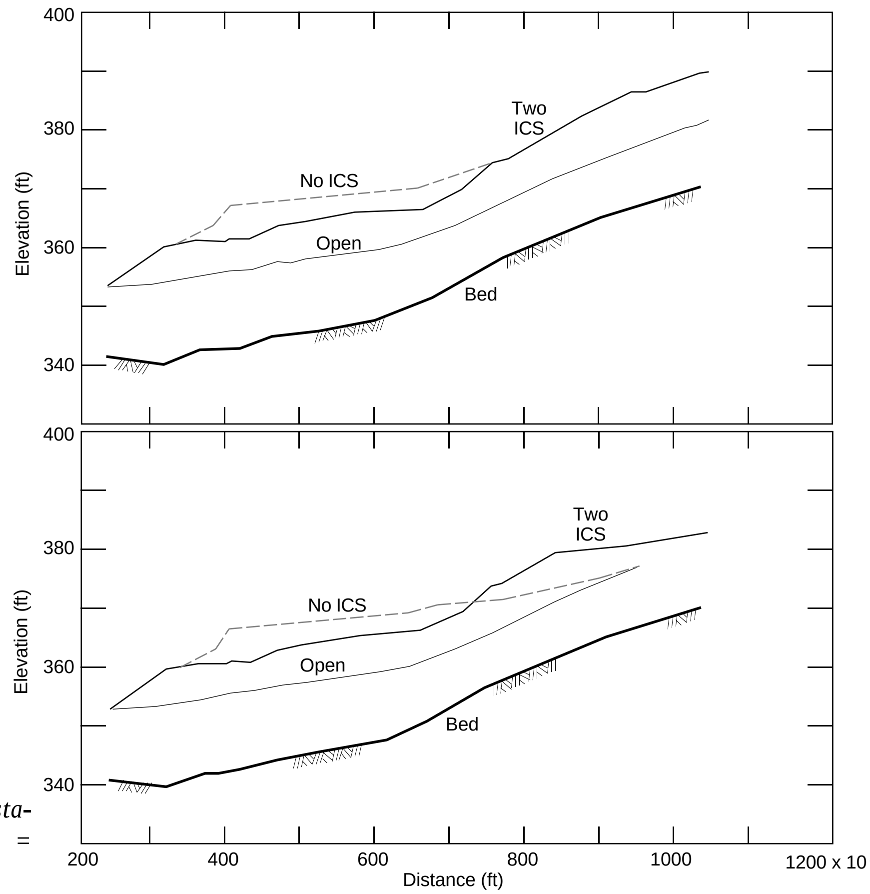
The effects of an ICS at station 656 in the vicinity of Haley Island are shown in Figure 15 for the two cases of unlimited ice supply and ice supply limited by the Caribou dam. The figures show no discernible effect of the ICS on the water level below station 500, and a maximum drop of about 3 ft in the water level at the ICS location. For the case of unlimited ice supply, the water level upstream of the ICS goes back to the full jam value at about station 740. On the other hand, if the Caribou dam indeed limits the downstream ice supply, the ICS at Haley Island leads to an increase in upstream water level (Fig. 15b) because it retains all the ice between Haley Island and the dam.

Finally, the effects of installing ICSs both at station 423 and at Haley Island are shown in Figure 16a for unlimited ice supply and in Figure 16b for ice supply limited by the Caribou dam. The combined effect of both structures is to reduce the water levels in the reach from about station 330 to the Haley Island structure by an average of approximately 3 ft and as much as 6 ft between the Limestone Road bridge and the structure at station 423. In the case of limited ice supply (Fig. 16b), the Haley Island structure would again lead to increased upstream water levels, since it would create a local jam by holding the ice between the structure and the Caribou dam that would otherwise have passed downstream.

We again emphasize that in developing Figures 13 through 16 we assumed that the jams would be fully developed, a conservative assumption, and that ice volumes would correspond to a before-breakup ice cover thickness of 28 in. Depending on the actual thickness of ice formed in a given year and, especially, the extent of ice decay before breakup, the actual ice volumes, ice jam length and resulting water levels may be less.

CONCLUSIONS AND RECOMMENDATIONS

In spite of the very mild ice breakup conditions in April 1992, our 1991–92 winter field ob-



a. Unlimited ice supply.

b. Ice supply limited by Caribou dam (h_i = *28 in.).*

Figure 16. Effects of ICSs at both station 423 and Haley Island (Q = *20,000* ft^3/s*).*

servations of ice formation and breakup in the St. John River basin provided an initial understanding of the ice processes particular to the St. John River and its main tributaries.

From these observations, complemented with available information on the extremely severe ice events of spring 1991, we propose alternative ice-control methods in several general areas along the St. John River and the Aroostook River to alleviate ice jam flooding. These methods need to be further analyzed to determine whether they can be economically and environmentally justified by NED and the state of Maine. Such analysis must consider that the implementation of any ice-control technique will benefit all downstream sites and not only the area in the immediate site of the project.

On the basis of the limited information gathered during this reconnaissance study, we can only recommend that, at a minimum, the following general sites and ice mitigation methods be further analyzed.

Upper St. John River

1. Ice motion detection systems at Nine Mile and at the confluence of the Big Black River. It is estimated that the former system would give an advanced warning of up to 24 hours to the town of Dickey and 24 to 48 hours to Fort Kent, while the latter system would give up to 12- to 36-hours of advanced warning respectively.

2. Ice control structures downstream of the Priestly bridge. Either a 6- to 8-ft high weir similar to the Oil Creek or Cazenovia Creek ICS, or a series of rock-filled cribs connected by modified ice booms could be built. It is estimated that such an ICS would alleviate all ice damage from the 500-year event at all locations downstream from the structure.

3. Ice control structure downstream of Big Black River confluence.

4. St. Clair Island area excavation upstream from Dickey. The anticipated benefits are similar to an ICS at the Priestly bridge.

Aroostook River

1. An ice control structure located approximately 2000 ft upstream from the Limestone Road bridge. Such an ICS, especially when complemented by another one in the vicinity of

Haley Island, would likely prevent all major ice jam floodings at Fort Fairfield.

2. Bypass channel. Dredge an existing channel at Crouseville to improve its flow capacity and reduce flooding.

3. Ice motion detector. Install detectors at the DCP sites in Masardis or Washburn, or both, which could provide up to 48 hours advanced warning to the town of Fort Fairfield.

The one season of field observations over such a vast area was insufficient to allow us to precisely identify both sites and corresponding specific ice control methods. The most important information still lacking is the amount of ice that reaches the flood-prone areas during a quick, troublesome breakup. For example, we are still uncertain whether a significant amount of ice currently passes over the Caribou dam and contributes to the severity of the jam at Fort Fairfield. If it does, then an ICS immediately upstream of the Caribou dam would help alleviate the ice jam at Fort Fairfield, while the structure proposed upstream of Fort Fairfield in the vicinity of Haley Island may or may not be necessary or justified. If not, and all the ice that causes problems at Fort Fairfield originates downstream from the Caribou dam, then no structure at the dam should be considered. In that case only an ICS within 5 miles of Fort Fairfield would be considered. At a minimum, an additional year of field investigations would be required beyond this reconnaissance study to ensure that proper locations and designs of any ICSs or proposed stream alterations considered are determined.

Whether any of the above ice control or protection measures are deemed justifiable or not, an early breakup warning network must be considered along both the upper Aroostook River and the upper St. John to enhance the existing early warning system provided by the National Weather Service and St. John River Flood Forecast Center. This network would consist of ice movement sensors located at the suggested locations and would prove invaluable by providing warning and verification that a breakup is in process and ice jam flooding is probable.

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Ice jams occur almost every year on the Aroostook and St. John rivers in northern Maine. While most of these jams cause minor flooding or no flooding at all, ice jams have caused severe flooding six times in the last 20 years. In 1991 ice jams on the St. John River caused damage estimated at $14 million. This report reviews field observations of the ice regime on the rivers and discusses possible mitigation measures—ice retention structures, channel modifications and early warning systems. In addition, since the 1991 ice jam caused water levels to rise so quickly that people were stranded in their homes, the development and installation of an ice jam motion detection system is described. To aid in early warning, a system to predict the potential for ice jams and their severity that is based on a correlation of hydro-meteorological data with the ice regime is presented.

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