ASSESSING THE EFFECTS OF ALTERNATIVE PROJECT OPERATION ON UPSTREAM ICE CONDITIONS: AROOSTOOK RIVER AT FORT FAIRFIELD, MAINE

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ABSTRACT

Breakup ice jams in the Aroostook River have caused severe flooding in Fort Fairfield, Maine. In general, the most damaging jams halt in the area between Fort Fairfield and the international border. It has been suggested that the backwater of Tinker Dam, which extends into Fort Fairfield, contributes to the formation or stopping of ice jams in the reach between the dam and the town. This report presents the results of an investigation of the effects of river geometry on the ice regime of the Aroostook River upstream from Tinker Dam, and whether dam operations or some type of dredging might affect this regime. Our results show that present dam operations at freezeup are preferable to lowering the water level. Current gate operations are also preferable to lowering the gates at breakup when flows are greater than 283 $m^3 s^{-1}$ (10 000 $ft^3 s^{-1}$). Observed frazil deposition in the upper reaches of the pool correlates well with the location of jam stoppages. The modeled channel improvement scheme that showed the most promise for decreasing ice thickness at the critical location is to remove the island-shoal area at the McDonald Brook confluence.

INTRODUCTION

Breakup ice jams in the Aroostook River have caused severe flooding in Fort Fairfield, Maine. In general, the jams form upstream from Fort Fairfield and move downstream through town, halting in the upper reaches of the pool created by Tinker Dam. The flood of record occurred on April 16, 1994, causing damages of over $5 million. After this flood, the Federal Interagency Hazard Mitigation Team recommended a study to evaluate the effects of river geometry and dam operating regime on the ice regime of the Aroostook River near Fort Fairfield. This study was undertaken by the Cold Regions Research and Engineering Laboratory (CRREL) and the New England Division, U.S. Army Corps of Engineers (NED).

Since there is no standard approach to determining potential effects of project operations on ice transport and jam location, we used a combination of several available tools, including an open-water and ice-covered hydraulic analysis under freezeup conditions, and an equilibrium ice jam analysis. This report presents the results of our investigation.

BACKGROUND

The Aroostook River has a mild slope and a drainage area of about 5776 km^2 (2230 mi^2) at Limestone Road Bridge in Fort Fairfield (Green, 1964). As is typical of rivers in Northern Maine, ice covers form, break up, and jam annually along the Aroostook River. A review of Maine Public Service Company (MPS) ice monitoring reports since 1968 indicates that breakup of the river ice cover is usually associated with precipitation. The ice cover breaks up and begins to move first on steeper river reaches, but remains solid in slow-moving areas, such as the pools upstream from Tinker and Caribou Dams. The presence of the solid ice can slow or halt the transport of broken ice, forming jams.

Aroostook River ice jams can occur between December and May, but are most common in April. Some early season jams freeze in place, while others eventually break up and move downstream. Jams can occur simultaneously at several locations. Ice jams that form upstream from Fort Fairfield tend to move progressively downstream; in the vicinity of Fort Fairfield, jams have been known to pause at several locations between Limestone Road Bridge and Tinker Dam (see Figure 1). The jams that pause between Limestone Road Bridge and the international border cause the most flooding at Fort Fairfield.

Damaging ice jams have occurred at Fort Fairfield in at least 17 of the years between 1923 and 1994 (Acone, 1994; FEMA, 1994; and Kindervater, 1985). Eight of these events are relatively well-documented, with stage and discharge information. The peak stage at Limestone Road Bridge during the April 16, 1994 event was 112.65 m (369.6 ft), exceeding the previous peak stage (set in April 1993) by nearly 1.2 m (4 ft).

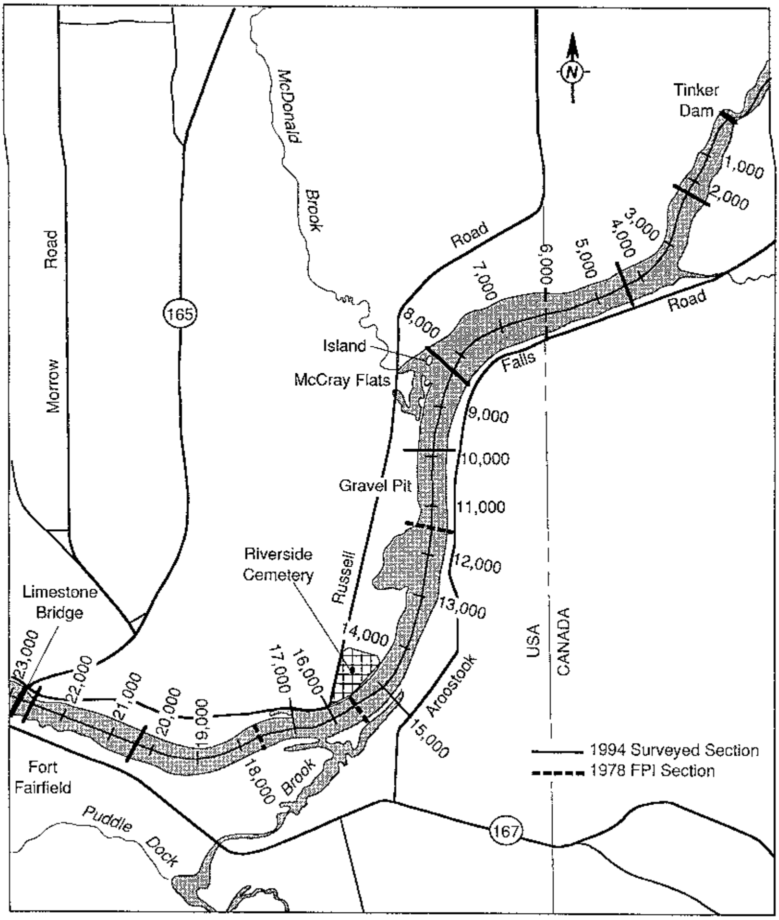

Figure 1. Map of study area. Stationing above Tinker Dam is shown in feet.

Acone (1994) estimated that the discharge during jam formation was about 792 m^3 s^{-1} (28 000 ft^3 s^{-1}).

It has been suggested that the backwater of Tinker Dam, which extends into Fort Fairfield, contributes to the formation or stopping of ice jams in the reach between the dam and the town. However, the lack of complete or reliable ice observations has prevented comparisons of the frequency, severity, and locations of ice jams before and after construction of the dam. This study investigated the effects that the geometry of the river, especially the islands, shoals, and bends between Fort Fairfield and Tinker Dam, has on spring breakup ice runs, with the goal of developing a clearer understanding of the causes of ice jam formation in that reach. In addition, we investigated the effects of different operating schemes at Tinker Dam on the upstream ice conditions.

DESCRIPTION OF THE HYDROPOWER PROJECT

The original hydropower project constructed at Aroostook Falls in 1907 consisted of the 88-m- (290-ft-) long Tinker Dam and its headworks, canal, and powerhouse with two 500-kW generating units. These were replaced in 1924 with existing units 2 and 3 (1750 kW each). An additional 4000-kW unit was installed in both 1926 and 1952, for a total installed capacity of 11 500 kW. The elevation of the main spillway crest was 104.38 m (342.45 ft) NGVD, and the normal pool at the top of flashboards was 105.75 m (346.95 ft) NGVD. In general, the flashboards remained in place throughout the winter season and failed during ice cover breakup and movement. The dam was modified in 1965 by adding two 2.9-m- (9.5-ft-) high by 38.1-m- (125-ft-) long bascule gates on the main spillway, raising the normal pool to 107.3 m (352 ft) NGVD at the top of the gates. The auxiliary gate located next to the bascule gate on the spillway is a hinge-type gate that must be lifted with a crane, and is not operated during the winter.

The bascule gates at Tinker Dam are used to regulate the headpond level. The project is normally operated with the bascule gates up and the headpond is cycled to generate power during the day and refill the pond at night. The typical drawdown is 1.2 to 1.5 m (4 to 5 ft) in the headpond during cycling. Flow through the turbines at rated capacity and 25.3 m (83 ft) of head is approximately 164 $m^3 s^{-1}$ (5800 $ft^3 s^{-1}$). As flow increases beyond this point, the bascule gates are lowered to hold the pool level at 107.3 m (352.0 ft) NGVD. According to MPS, the spillway capacity is approximately 634 $m^3 s^{-1}$ (22 400 $ft^3 s^{-1}$) with the headpond at elevation 107.3 m (352.0 ft) NGVD, the bascule gates fully lowered, and no flow through the turbines.

Dam operations have little impact on stage when flow exceeds 799 $m^3 s^{-1}$ (28 200 $ft^3 s^{-1}$) with turbines at full capacity or 634 $m^3 s^{-1}$ (22 400 $ft^3 s^{-1}$) with no turbines running. Based on the annual open-water discharge frequency curve developed by Acone (1994), there is about an 85 percent chance that 634 $m^3 s^{-1}$ (22 400 $ft^3 s^{-1}$) will be equaled or exceeded, and a 62% chance that flow will exceed 799 $m^3 s^{-1}$ (28 200 $ft^3 s^{-1}$) in any given year. For six of the eight well-documented ice jams, the discharge was less than 634 $m^3 s^{-1}$ (22 400 $ft^3 s^{-1}$) during the jam formation period, which indicates that dam operations could potentially affect stage.

STUDY APPROACH

Our goal was to determine whether operational changes or channel improvements would improve ice transport and decrease jamming in the study reach. This required an innovative use of existing modeling capabilities in which we first performed an open-water hydraulic analysis to develop an understanding of the initial ice cover formation processes. We then assessed the likelihood of frazil deposition by applying a new deposition criterion to a standard ice-covered hydraulic analysis. Finally, we modeled equilibrium ice jam conditions and evaluated operational and channel improvement options by comparing computed ice thicknesses at an index location. Field observations were made by MPS, CRREL, and NED to guide the modeling. The model used to perform the hydraulic analyses in this study was the HEC–2 step backwater computer program (USACE, 1990), which had been used previously for an open-water flood study (USACE, 1978).

Freezeup Analysis

Open-water analyses were performed using a range of typical freezeup period discharges between 14.2 and 85 $m^3 s^{-1}$ (500 and 3000 $ft^3 s^{-1}$). The starting water surface elevation was the normal pool elevation (top of the bascule gates), or the level with the gates fully lowered. The ice-covered case for existing conditions was modeled using a smooth ice cover 0.6 m (2 ft) thick (MPS measurements in the Tinker pool showed an average ice thickness of 0.57 ± 0.1 m [1.9 ± 0.3 ft] over a 26-year period). The starting water surface elevation was normal pool with discharges of 56.6 $m^3 s^{-1}$ (2000 $ft^3 s^{-1}$), a typical early winter freezeup flow, or 85 $m^3 s^{-1}$ (3000 $ft^3 s^{-1}$), a discharge likely to occur during cycling of the pond.

Equilibrium Ice Jam Analysis

The ICETHK program (Wuebben and Gagnon, in preparation) was used in conjunction with HEC–2 to model equilibrium ice jams for the river geometry and dam gate operation scenarios summarized in Table 1. We assumed a parent ice thickness of 0.6 m (2 ft) and allowed the model to iterate until the calculated equilibrium ice jam thickness converged on a stable result. Two different operating scenarios were modeled at discharges of 283, 425, and 566 $m^3 s^{-1}$ (10 000, 15 000, and 20 000 $ft^3 s^{-1}$) by varying the starting water surface elevation at Tinker Dam. The existing operating scenario is referred to as the "gate-up" scenario. In the "gate-down" scenario, the gate was assumed

Table 1. Summary of breakup ice jam hydraulic analyses.

Discharge ($m^3 s^{-1}$)	*Initial gate position*	*Starting water surface elevation (m NGVD)*	*Channel improvement*
283	gate down	106.2	none
283	gate up	107.3	none
425	gate down	106.6	none, scheme 1, scheme 2, scheme 3
425	gate up	107.3	none, scheme 1, scheme 2, scheme 3
566	gate down	107.1	none, scheme 1, scheme 2, scheme 3
566	gate up	107.3	none, scheme 1, scheme 2, scheme 3
850	gate down	107.8	none, scheme 1, scheme 2, scheme 3
991	gate down	108.2	none

to have been totally lowered after ice cover formation, but prior to ice cover breakup, an operating alternative that has often been suggested as a potential ice control method. Higher discharges, of 850 and 991 $m^3 s^{-1}$ (30 000 and 35 000 $ft^3 s^{-1}$), were analyzed using the Tinker Dam rating curve alone, since the bascule gates would be fully lowered at these flows.

Three channel improvement schemes were selected for modeling to compare existing conditions with those that might result from removing or modifying the islands and shoals. These were evaluated for discharges of 425, 566, and 850 $m^3 s^{-1}$ (15 000, 20 000, and 30 000 $ft^3 s^{-1}$). The first channel improvement scheme assumed that the river bed was dredged to create a uniform bed slope from station 670 m (2200 ft) above Tinker Dam to Riverside Cemetery, station 4907 m (16 100 ft). The bottom width of the dredged channel was assumed to be equal to the current channel width. The second improvement scheme assumed that the channel was dredged from station 2469 m (8100 ft) to 2713 m (8900 ft) to remove the islands at the McDonald Brook confluence. The third scheme is similar to the first, but with a uniform channel bottom width of 244 m (800 ft) for all sections in the reach. The dredged cross-sections were modeled with a trapezoidal shape having side slopes of 1.5V:1H. Figure 2 shows the existing channel bed compared to the different channel improvement schemes.

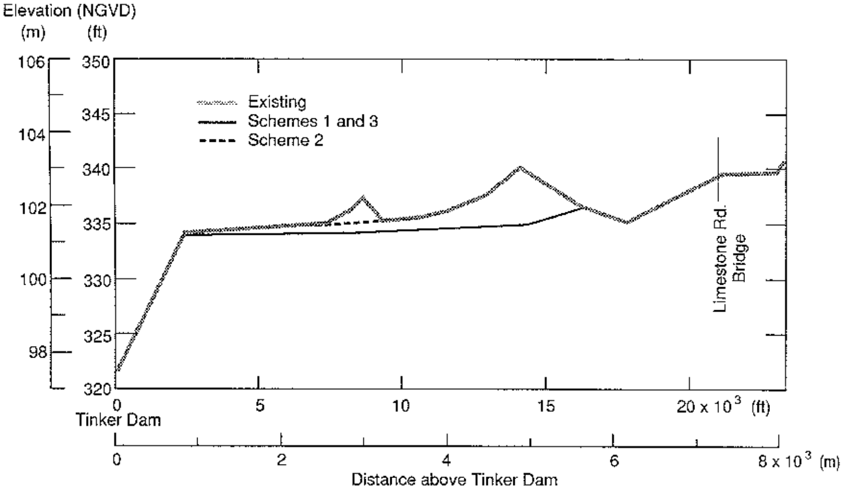

Figure 2. Minimum channel elevation in equilibrium ice jam hydraulic analyses. In scheme 1, the dredged channel retains the natural bottom width. In scheme 2, only the islands near the McDonald Brook confluence are dredged. Scheme 3 is the same as scheme 1 except the dredged channel bottom width is 244 m (800 ft).

RESULTS AND DISCUSSION

Freezeup Hydraulic Analysis

The purpose of the open-water analysis was to investigate hydraulic conditions at freezeup. In terms of ice cover formation, the most significant parameter computed by HEC–2 is the average channel Froude number at each cross section. For very low Froude numbers, we would expect ice cover formation to be dominated by heat transfer processes, such as occurs on lakes. Juxtaposition of floes into a single layer can occur at channel Froude numbers between about 0.08 and 0.13 (Ashton, 1986). At greater Froude numbers, a thicker initial ice cover resulting from shoving would be expected. Locations in which shoving, snow ice formation, or under-ice frazil deposition result in greater than normal ice thickness can have greater resistance to the breakup and movement of ice later in the season.

The open-water analysis showed that under current operating conditions, the Froude numbers in the reach between the dam and the Limestone Road Bridge are quite low, indicating that thermal processes, rather than juxtaposition or shoving, govern the initial ice cover formation. These results are confirmed by historical field observations of extremely transparent ice, which is characteristic of thermal ice growth. If the gates were to be lowered during freezeup, however, the increase in water slope and velocity results in Froude numbers greater than 0.08 at several locations. The locations where high Froude numbers suggest that shoving might occur include near Limestone Road Bridge, the bend near the cemetery, and just upstream from the McDonald Brook confluence near McCray's Flats, all of which are reported to be ice jam locations. The open-water analyses indicate that operating with the gate down during freezeup could exacerbate jamming in these locations; therefore, the current operating scheme is preferred.

The combination of very low air temperatures and turbulent open water areas allows frazil ice production in the Aroostook River throughout the winter season. Historical measurements made by MPS in the Canadian (downstream) portion of the Tinker Dam pool showed no frazil deposits. In February 1995, we observed loose frazil at station 4343 m (14 250 ft), 0.23 m (0.75 ft) of relatively dense frazil at station 4877 m (16 000 ft), and 0.88 m (2.9 ft) of very dense frazil at station 5182 m (17 000 ft), near the upstream end of Riverside Cemetery (Figure 3). There was no frazil measured at station 6858 m (22 500 ft). The increased ice thickness resulting from frazil deposition could provide additional resistance to the downstream movement of ice at breakup, resulting in ice stoppages. Therefore, predicting the locations of frazil deposition may aid in predicting the locations of breakup ice jamming.

In the past, frazil ice deposition has been predicted using a critical deposition veloc-

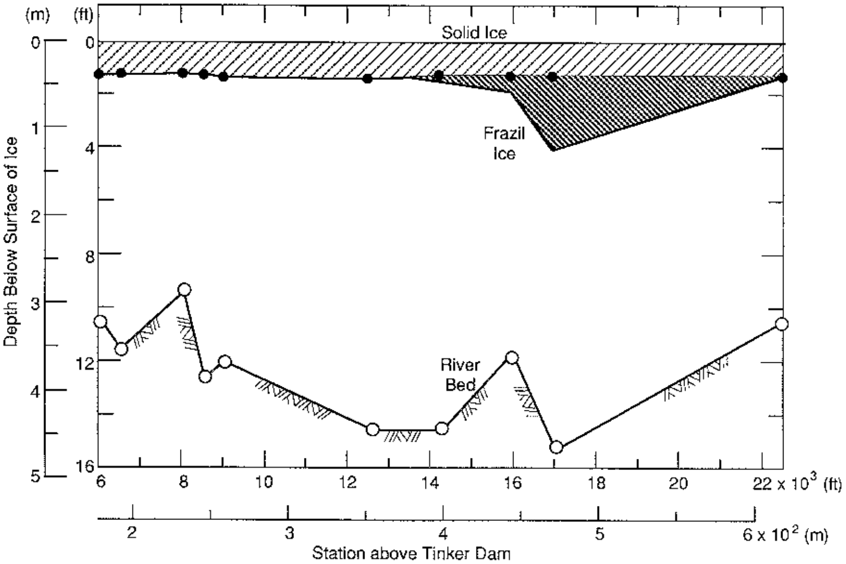

Figure 3. Ice thickness measurements made February 22, 1995. Snow ice and thermally grown ice are combined as solid ice, and zero is the top of the solid ice.

ity approach in which frazil deposits are thought to accumulate from upstream to downstream, beginning with the most upstream location where the average cross-sectional flow velocity is less than some critical deposition velocity. Frazil will deposit at that location until the critical velocity has been reached, at which point any additional frazil will be transported downstream, where the process begins again. Michel and Drouin (1981) reported critical velocities between 0.5 and 1 m/s for two reaches of the LaGrande River in Quebec. If the lower critical velocity criterion were to be applied to the Aroostook River at Fort Fairfield, the ice-covered hydraulic analyses indicate that for discharges below about 56.6 $m^3 s^{-1}$ (2000 $ft^3 s^{-1}$), frazil would deposit at every cross-section in the study reach beginning at station 9780 m (32 090 ft) and progressing downstream. At 141 $m^3 s^{-1}$ (5000 $ft^3 s^{-1}$), deposits would start upstream from the Limestone Road Bridge, below station 8845 m (29 020 ft), and progress downstream.

Our field observations suggest that the critical velocity criterion does not adequately describe the frazil deposition process at Fort Fairfield. Recently, Shen and Wang (1995) proposed a new method to analyze frazil transport based on the concepts of bed load transport. We, in turn, used this method as a frazil deposition criterion. When we applied the new criterion to hydraulic parameters computed by HEC–2 for 56.6 $m^3 s^{-1}$ (2000 $ft^3 s^{-1}$), deposition was predicted downstream from station 5425 m (17 800 ft), while frazil ice would remain in transport above that point. Our field data fit this deposition criterion quite well, with transport at station 6858 m (22 500 ft), and a thick, dense deposit at station 5182 m (17 000 ft). At a discharge of 141 $m^3 s^{-1}$ (5000 $ft^3 s^{-1}$), frazil ice would theoretically remain in transport until station 2594 m (8510 ft), near the McDonald Brook confluence. This deposition location also coincides with a known jam stopping site.

Using the results of the ice-covered analysis, we would predict frazil deposition in the Tinker Dam pool somewhere between stations 2594 and 5425 m (8510 and 17 800 ft) under normal winter conditions. At lower flows, the frazil will tend to deposit toward the upstream end of this reach, while at higher flows such as those experienced during cycling operations, deposition will not begin until the lower end of this reach. The presence of the frazil deposits appears to be quite closely correlated to the location of ice stoppages that result in ice jam flooding at Fort Fairfield. A regular program of ice thickness measurements throughout this reach could be useful both in characterizing frazil deposition and in designing measures to mitigate or avoid the effects of deposition.

Equilibrium Ice Jam Analysis

A one-dimensional, steady state model such as HEC–2 will not precisely model a dynamic breakup ice jam that includes several successive shoving events such as occur at Fort Fairfield. However, it can provide us with information that may be used to indirectly analyze the situation. To assess the suitability of HEC–2 for this study, we compared computed stages at the Limestone Road Bridge with observed stages. According to Acone (1994), most of the ice jams that affected Fort Fairfield failed at discharges below 708 $m^3 s^{-1}$ (25 000 $ft^3 s^{-1}$), and two-thirds failed at discharges less than 566 $m^3 s^{-1}$ (20 000 $ft^3 s^{-1}$), with the exception of the April 1976 ice jam. Figure 4 indicates that the stages computed using HEC–2 are reasonable for typical breakup discharges in the study area, less than about 850 $m^3 s^{-1}$ (30 000 $ft^3 s^{-1}$).

The severity of ice jam flooding in Fort Fairfield appears to be related to the amount of time that the jam remains in place, allowing river stage to increase. If we assume that thicker ice accumulations would withstand larger forces from upstream and stay in place longer than thinner ice accumulations, jam thickness may prove to be a useful index of ice jam severity. Our model results show that thickening always begins about 2591 m (8500 ft) upstream from Tinker Dam, near the McDonald Brook confluence. The initial thickening coincides with the island-delta formation at the mouth of the brook, a known jam stopping point. The greatest thickening occurs about 3048 m (10 000 ft) upstream from the dam in the area known as McCray's Flats, near the downstream end of the gravel pits on the left bank of the river. Rather than compare the various schemes on the

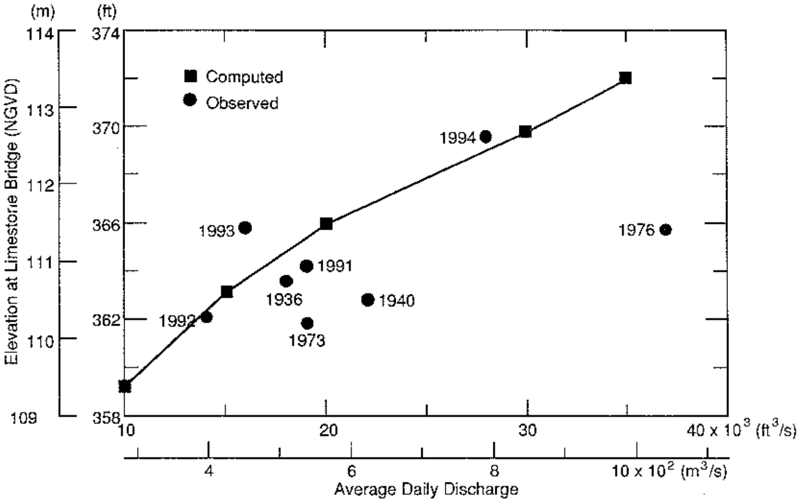

Figure 4. Comparison of observed stage at Limestone Road Bridge during selected ice events (●) and estimated stage resulting from equilibrium ice jam (■).

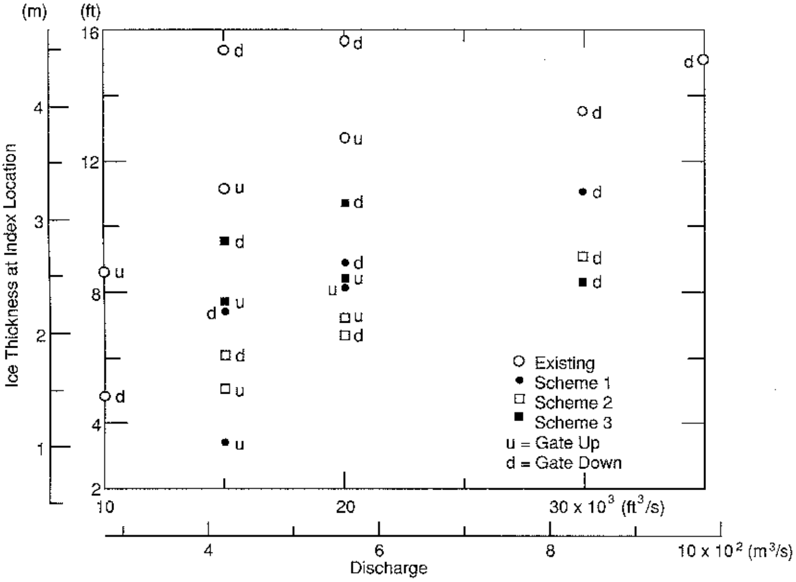

Figure 5. Average computed ice thickness at the index location. The letter u refers to a "gate up" starting condition; d refers to a "gate down" starting condition. In scheme 1, the channel bed is dredged to a trapezoidal shape, retaining the natural bottom width. In scheme 2, only the islands at McDonald Brook are dredged. Scheme 3 is the same as scheme 1 except the dredged channel bottom width is 244 m (800 ft).

basis of the computed water stage at one location (Limestone Road Bridge), we chose to compare them using the computed equilibrium ice jam thickness at McCray's Flats, reasoning that thinner ice here would be less resistant to upstream forces and would fail sooner than thicker ice, potentially reducing flood levels in Fort Fairfield.

Figure 5 presents the mean equilibrium ice jam thickness at the index location (stations 3045 and 3048 m [9990 and 10 000 ft]), for each of the alternatives given in Table 1. The model predicts that the thickest ice jams will occur at discharges of 425 to 566 $m^3 s^{-1}$ (15 000 to 20 000 $ft^3 s^{-1}$) with the existing river channel geometry when the Tinker Dam gates are lowered prior to jamming. The situation is improved slightly under the current ("gate up") operating scenario.

Scheme 2, dredging the island between about stations 2469 and 2713 m (8100 and 8900 ft) appears to show the most promise in reducing ice jam thickness at the index location. Dredging the entire reach from the Riverside Cemetery to Tinker Dam (schemes 1 and 3) also reduces equilibrium ice jam accumulations. However, environmental impacts and the costs of a major dredging operation make it a less desirable option than scheme 2. It is also important to note that dredging is often only a temporary solution in movable-bed rivers. Hydraulic conditions in the Tinker Dam pond may have caused the present sediment deposition. Without measurements or observations prior to construction, it is difficult to predict the longevity of dredging, or the effects of dredging on frazil deposition and the downstream movement of ice. At best, the ice accumulations in the area will be thinner, resulting in the jams failing at lower discharges and lower upstream river stages.

CONCLUSIONS

Our study approach allowed us to characterize ice cover formation in the study reach, identify potential jam stopping points, and evaluate the possible effects of operational and channel improvement alternatives. We modeled open-water freezeup conditions using current Tinker Dam operating procedures and confirmed past observations that the river freezes into a smooth ice sheet in the study reach. Lowering the bascule gates during freezeup could result in a thicker, rougher initial ice cover due to increased water slope and velocity. This would be undesirable because of the potential for increased resistance to breakup of the thicker ice. Therefore, our results suggest that the gates at Tinker Dam should be left up during initial ice cover formation.

When we applied Shen and Wang's frazil deposition criterion to the results of the ice cover analysis, we found that frazil ice deposition should occur near the Riverside Cemetery at the mean daily winter flow of about 56.6 $m^3 s^{-1}$ (2000 $ft^3 s^{-1}$). At the higher flows that occur during pond cycling, the model predicted frazil deposition farther downstream, near the islands at McDonald Brook. The deposition near the cemetery, confirmed by field observations, could be a significant factor in determining the location of jam stoppages in the reach of river immediately below Fort Fairfield. The town of Fort Fairfield should initiate a monitoring program to obtain further information on frazil deposition. This information may provide some insight into the process of frazil deposition, which in turn might aid in the prediction of ice jam locations in a given year.

Based on our equilibrium ice jam analysis with the existing river geometry, the current gate operating procedure at Tinker Dam appears to be preferable to lowering the gates just prior to jamming. The model indicates that for flows above 283 $m^3 s^{-1}$ (10 000 $ft^3 s^{-1}$), dropping the bascule gates results in a thicker equilibrium ice jam accumulation at McCray's Flats than does the gate-up case. Since this is a known ice jam stopping point, a thicker ice accumulation is undesirable because it could increase resistance to downstream movement of the jam, possibly resulting in higher, more persistent flood levels in town. The model indicates that dredging the river could be an improvement over current river geometry. Scheme 2, dredging only the island-shoal area of the river at stations 2469 to 2713 m (8100 to 8900 ft), seems to result in the greatest reduction in ice jam thickness and should be investigated further.

ACKNOWLEDGMENTS

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DISCUSSION

Terry Prowse,
National Hydrology Research Institute:
Could you please elaborate on the hydrometeorological conditions that precipitate breakup in your study area - both for the dominant spring breakups and the midwinter breakup that occurred in 1973?

Reply: Ice covers form, break up, and jam annually along the Aroostook River. We know from Maine Public Service Company (MPS) ice monitoring reports that, at least since 1968, breakup of the river ice cover is usually associated with precipitation. Ice breaks up and moves on the steeper river reaches, but can slow or jam in slow-moving areas, such as the pools upstream from Tinker and Caribou Dams. Little is known of early and mid-season jams except that some early season jams freeze in place, while others eventually break up and move downstream. This is partly due to lack of close monitoring, but also because the reported frequency of jams, 17 of the years between 1923 and 1994, is small enough that it is difficult to detect significant differences in jam causation between years. Only eight of these events are relatively well-documented, with stage and discharge information, and meteorological information dates to 1939.

Two ice jams occurred in the Aroostook River Basin during 1973, one in April and another in December. The April 30, 1973 ice jam occurred after a sharp rise in discharge caused by a rainfall event of 7.6 cm (3 inches) that fell on a substantial snowpack. It is theorized that the snowpack insulated the ice cover, decreasing the normal deterioration that might be expected at such a late date. This event caused significant damages throughout the St. John River Basin, including flooding at Washburn and Caribou, ME upstream from Fort Fairfield. However, no specific ice, stage, or discharge information was located for Fort Fairfield. The December 24, 1973 jam was quite unusual in that occurred so early in the season. This jam was associated with rainfall (3.3 cm or 1.3 inches on December 20 and 21) and snowfall (7.6 cm or 3inches on December 20), combined with warm temperatures of up to 12°C (54°F).

Rick Carson,
Acres International Ltd.:
I understand that an ice breaker was used in a trial program. Was it successful, and will it be used in the future?

Reply: The town of Fort Fairfield contracted with Normrock Industries of Canada for the services of the Amphibex amphibious ice breaker in March 1995. The Amphibex can break thin ice using its backhoe. Thicker ice is broken as the machine pulls itself onto the ice with the backhoe, causing the ice to fail under the weight of the machine in a manner similar to the breaking of ice beneath the bow of an icebreaker. Two crews operated around the clock for 55 hours on March 25-27 to form a channel in the ice about 12 m (40 feet) wide and extending about 5.2 km (3.2 miles) upstream from the international border to the Limestone Road Bridge. Estimated ice thickness ranged from 35.6 cm (14 inches) to a maximum of 76 cm (30 inches) beneath the Limestone Road Bridge. The ice breaking operation cost $15,800 (US).

No damaging ice jam occurred in 1995. However, because the test took place rather late in the ice jam season, and the ice cover had deteriorated substantially, there is no way to predict the success of the ice breaking under normal ice conditions. On March 10, MPS observers making their usual end-of-season measurements in Tinker Pond downstream from the border found no clear ice at all, only slush and deteriorated ice resembling snow ice. This level of deterioration was noted only one other year in the period 1968 to 1995. This was in March 1977, when there was no damaging ice jam recorded at Fort Fairfield, Washburn, or Masardis. In addition, the fact that the river ice cover experienced what was essentially a thermal meltout in early April rather than the usual ice cover breakup and movement prevented us from making observations that might have provided information on the effects of the operation on ice jamming in Fort Fairfield. If the goal of the operation was to create a man-made open channel in the upper portion of the Tinker Dam impoundment, then the operation should be considered a success. It will probably be repeated in the future.

David Andres,
Trillium Engineering and Hydrographics, Inc.:
I am a little concerend about the dramatic variation in ice thickness along the reach. Is this an artifact of not allowing the ice thickness to vary according to non-uniform theory (of the ice) or is it due to not choosing the optimal locations of the cross-sections?

Reply: The variation in ice thickness may appear quite dramatic in part because of the distorted scales used, as is common practice in presenting hydraulic and ice profiles. The variation in ice thickness is probably a combination of using a one-D steady state hydraulic model and equilibrium ice jam theory to model a dynamic jam situation along with cross-sections that may have been less than optimal. The number of cross-sections was limited, as always, by cost. We did, however, obtain nine new cross-sections in October 1994 (three in New Brunswick and six in Maine) to supplement the 1978 Flood Plain Information Study survey information.