A STUDY OF DYNAMIC ICE BREAKUP ON THE CONNECTICUT RIVER NEAR WINDSOR, VERMONT

M. Ferrick, G. Lemieux, W. Demont, P. Weyrick

USA Cold Regions Research and Engineering Laboratory
72 Lyme Road, Hanover, New Hampshire 03755-1290

ABSTRACT

The Cornish-Windsor bridge is the longest covered bridge in the United States and has significant historical value. At a large peak flow, dynamic ice breakup of the Connecticut River can threaten the bridge and cause flood damage in the town of Windsor, Vermont. Throughout the 1985-86 winter we regularly monitored ice conditions, including a midwinter dynamic ice breakup on 27 January, and conducted a series of controlled release tests over the operating range of the turbines at Wilder Dam upstream. These observations were analyzed in light of more than 60 years of temperature and discharge records. Our analysis indicates that river regulation presents alternatives for ice management that would minimize the probability of bridge damage and flooding during breakup. The flow can be regulated early in the winter to promote the growth of a stable ice cover, minimizing the total ice production in the reach. In the weeks prior to breakup, sustained releases and above freezing air temperatures cause melting, weakening and gradual breakup of the ice, greatly reducing the flooding potential. Also, it is possible to produce a controlled ice breakup at lower stage and discharge than now occurs during major natural events. All of these ice control alternatives have associated power production costs.

INTRODUCTION

Initially constructed in 1796, the Cornish-Windsor covered bridge was destroyed by the Connecticut River in the spring of 1824, in 1849, and again on 3-4 March 1866 [Childs 1960]. The loss of the third bridge in 1866 was specifically attributed to ice breakup. The present structure was constructed in 1866 at a higher elevation above the river than the previous bridges. Rawson [1963] reports that ice jam floods damaged this bridge in the spring of 1925, 1929, 1936 and 1938. Significant damage occurred again on 14 March 1977 from ice impacts on the upstream side, up to a meter above the bottom of the bridge. The water levels associated with ice damage to the bridge also cause significant flood damage in the town of Windsor, Vermont.

The highest water levels on the Connecticut River near Windsor typically occur during a dynamic ice breakup. Dynamic ice breakup is the rapid failure of an ice cover that occurs during periods of intense runoff when the river is covered by intact ice. There are no reports of damage or threatened loss of the bridge at the present elevation resulting from open water floods with much higher peak discharges.

In this paper we characterize dynamic ice breakup on the Connecticut River near Windsor, identify the combination of conditions that produce extreme breakup flood events, and provide data that are preliminary to quantitative predictions of ice breakup behavior. These studies suggest methods of ice control that use the existing dams to alleviate the threats to the bridge and to the town. The essence of these methods is to minimize ice production over the winter, to melt and weaken the ice prior to breakup, and to produce a controlled ice breakup prior to an uncontrolled natural event at the minimum possible water levels. Additional studies and river monitoring are needed to optimize the river control operations, yielding maximum ice control with minimum loss of power production.

BACKGROUND

The energy in the flow of a river is coupled into an ice cover by a number of mechanisms. Dynamic ice breakup occurs when the hydrodynamic forces on the cover, related to the energy gradient of the river, exceed the resistance provided by the ice strength and points of support [Ferrick et al. 1986b]. Thick and competent ice covers have great resistance, and require high energy gradients to initiate breakup. "High energy" conditions are an extreme that produce dynamic breakups at the highest water levels. In a "high energy" dynamic breakup the downstream movement of a single breaking front is common. While moving, the breaking front progresses rapidly, but it may stall for a period of time, forming an ice jam. Jams produce water levels that are even higher than those of a moving breakup, and a sudden jam release can be destructive. Locations where the energy gradient diminishes, such as at the upstream end of impoundments of the river, are favorable for ice jam formation.

The flow of the Connecticut River in the Windsor area is controlled by Wilder Dam upstream and Bellows Falls Dam downstream. Our study has focused on the 38-km reach from Wilder Dam to a point 9 km downstream of the covered bridge (Fig. 1). The river is free-flowing over most of this reach before slowing as it enters Bellows Falls reservoir. Wilder Dam has a drainage basin of 8780 km^2. The White River, with a basin size of 1820 km^2, is the primary tributary in the study reach, entering about 3 km downstream of the dam. At an average discharge of 200 m^3/s the Connecticut River in the study reach varies between 100 and 200 m in width and has a mean depth range between 1.5 and 3.0 m. As Wilder Dam does not generally pass large quantities of ice, the uncontrolled White River is the only significant ice source at breakup external to the reach itself.

We monitored the ice conditions regularly throughout the 1985-86 winter, including a midwinter dynamic ice breakup on 27 January 1986, and conducted a series of controlled release tests over the operating range of the turbines at Wilder. For the test period, we established temporary data collection stations at regular intervals on the river to supplement the ongoing data collection at the gaging station and the dams (Fig. 1). Station 1 is located immediately upstream of Sumner Falls, a natural river control feature. Station 2 is located at the Cornish-Windsor Bridge, and station 3 is located several kilometers into the pool of Bellows Falls Dam. In addition, White River flow data are collected at a permanent gaging station at White River kilometer 11.9 (WRK 11.9).

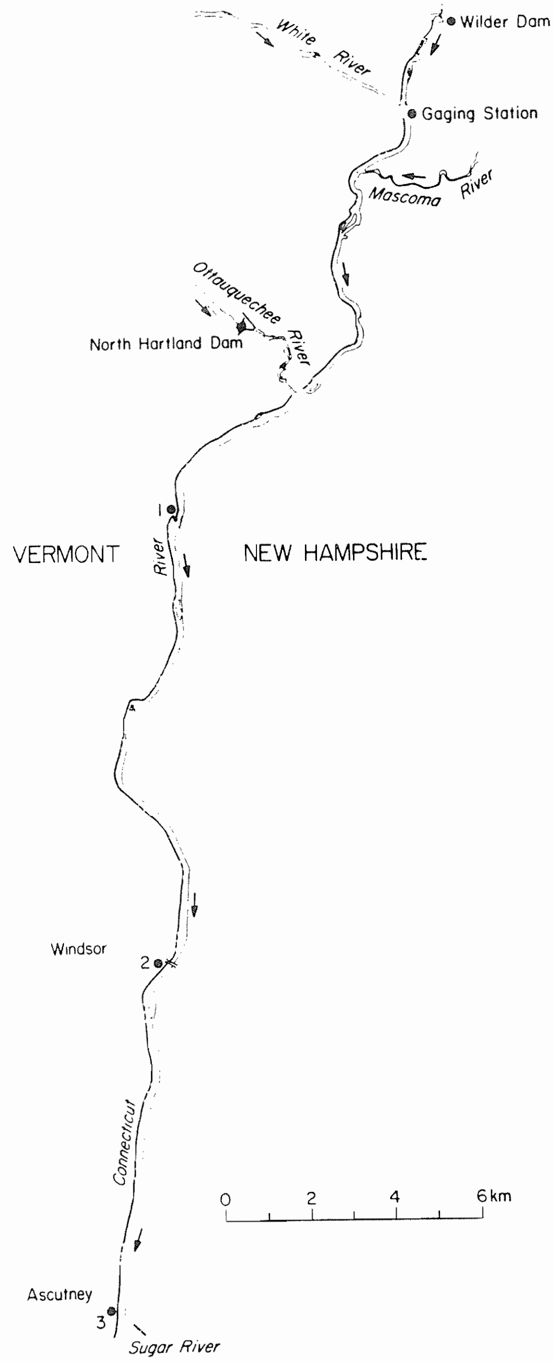


Figure 1. Connecticut River study reach including the major tributaries. Station 2 is located at the Cornish-Windsor covered bridge.

The controlled release tests provided data that describe the response of the river to a range of flow inputs, and the effect of an ice cover on this response. Additionally, these data can be used to calibrate and verify a numerical hydraulic model of the river [Ferrick et al. 1986a and 1986b], which in turn is necessary for design of a controlled ice breakup study or to analyze a natural breakup. The 1986 midwinter breakup occurred with an intact ice cover on the river. Together with the numerical model, these data and observations provide a case study that indicates an upper bound on the energy gradients that cause breakup of a well-developed and competent ice cover on the Connecticut River.

The river, ice and breakup observations from the winter of 1985-86 are most valuable for assessing the flooding/bridge damage problem when they are considered as part of a long period of records. Several parameters that affect the breakup water levels can be obtained from the historical records, including the peak breakup discharge, the accumulated subfreezing winter temperatures, the relative timing of the White River breakup, the occurrence of a prior midwinter ice breakup, and the suddenness of the onset of high discharge and warm air temperatures. The contributions of each of these parameters to the largest historical events are evaluated in this paper by using air temperature and river stage-discharge records. Knowledge of the conditions that produce the highest breakup water levels provides the foundation for the development of ice control methods.

ANALYSIS OF HISTORICAL DATA

The date of a dynamic ice breakup can be estimated from the daily flow records of a gaging station. Following a winter period of consistent low flows, the discharge increases rapidly at breakup and attains a high peak value. We obtained the peak daily average discharge and date of dynamic ice breakup, if it occurred, from 65 years of records of the Connecticut River and the White River at the gaging stations. The Connecticut River discharges were ranked and the 12 highest breakup discharge years, including all years of reported bridge damage, are given in Table 1.

Accumulated freezing degree days is a measure that allows us to compare the ice production potential of a river between years. We calculated the total number of freezing degree days at nearby Hanover, New Hampshire, for the period of November through February for 62 winters, beginning in 1924-25. These values and the relative "coldness" ranking are given in Table 1 for each high breakup discharge year and for 1985-86. Of this group only 1936, 1946, 1968 and 1977 rank among the more severely cold winters. The massive ice accumulation observed in the reach near station 2 at the end of February 1986 indicates that Connecticut River ice production in even an average winter is sufficient to pose a threat to the Cornish-Windsor Bridge at breakup.

A prior midwinter breakup of the White River with subsequent refreezing would maximize the ice supply to the reach from the primary external source. Combined with minimal midwinter ice movement on the Connecticut River, this larger ice supply increases the flood potential of the reach in the spring. Of the 12 large event years, the White River ice released on 19 and 2 January in 1929 and 1979, respectively. Also, possible or partial breakups occurred on 26 January 1938 and 7 January 1946. We conclude that this uncontrolled process contributes in some years to high water levels at spring breakup.

High air temperatures in the period immediately prior to breakup could cause significant melting of the ice cover, minimizing the flooding from a dynamic breakup. However, the pre-breakup temperature data presented in Table 1 do not indicate any correspondence between melting °C-days and high water levels at Windsor. Several high discharge events occurred without significant rainfall at Hanover, indicating nonuniform rainfall on the drainage basin and a potentially important snowmelt contribution to the flow.

The process that we term "hydrothermal melting" refers to the melting and warming of an ice cover from the heat contained in the flowing water, and the progressive failure of the weakened cover. Hydrothermal melting is most effective when daily average air temperatures are above freezing. The necessary heat is supplied more rapidly and greater forces are exerted on the ice at higher discharges. An intact ice cover with the greatest resistance to breakup exists when the discharge increases rapidly to its peak, minimizing hydrothermal melt. The discharge-days of hydrothermal melting for the period of rising discharge were computed from the daily average flow data and are given in Table 1. These data

Table 1. Historical data for years of high breakup discharge on the Connecticut River. The data are grouped according to whether or not Cornish-Windsor Bridge damage was reported.

Year	Peak flow date of breakup event	Peak Daily avg. dischage (ft^3/s)	(m^3/s)	Discharge Rank	Hydrothermal Melting (m^3/s-days)	Freezing °C days	Cold Rank	Melting °C-days through peak Q	Precip. in warm period (cm)
Reported bridge damage									
1925	12 Feb	36,000	1020	6	100	625	20	18.3	0.20
1929	24 Mar	31,100	881	11	4600	445	48	28.1	0.69
1936	13 Mar	45,100	1280	1	600	790	3	20.0	4.80
1938	25 Mar	34,800	985	8	1900	585	26	56.8	0.05
1977	14 Mar	43,100	1220	2	900	741	7	59.4	3.89
No reported bridge damage									
1927	20 Mar	34,000	963	9	3900	580	29	59.7	0.53
1945	22 Mar	40,200	1140	3	4600	712	12	50.6	2.62
1946	9 Mar	31,000	878	12	800	744	6	34.4	2.92
1964	6 Mar	35,000	991	7	400	618	23	24.7	4.14
1968	22 Mar	34,000	963	9	2100	736	8	36.7	3.73
1979	7 Mar	40,000	1130	4	1000	671	18	37.5	6.48
1981	21 Feb	38,400	1090	5	4500	565	31	43.9	1.52
1986	27 Jan	19,700	558	28	100	641	19	0.0	6.99

generally confirm that minimum hydrothermal melting of the ice and maximum water levels are compatible.

Because the Connecticut River is controlled and because it exhibits sudden uncontrolled flow increases, daily average discharges do not provide the information necessary to adequately compare ice breakup in different years. For example, the instantaneous flow peak at the gage on 27 January 1986 of greater than 926 m^3/s is at least 66% greater than the daily average discharge. Further understanding of ice dynamics from the historical record requires hourly or more frequent resolution of the data.

In this paper we will summarize the detailed White River and Connecticut River gage records. A more complete chronology is included in Ferrick et al. [1987]. During ice breakup the rate of stage increase at each gage has frequently approached 2.0 m/hr. These high rates are associated with ice jam formation immediately downstream of the gage, or with ice breakup and jam release upstream. Stage recession rates of up to 1.4 m/hr have occurred in response to the release of an ice jam downstream. Discharge increases at breakup by a factor of 20 or more during a 24-hr period have occurred on both rivers. An abrupt rise of the White River at the gage to a peak discharge greater than 300 m^3/s, sustained for several hours, indicates a complete breakup of the ice cover downstream to the confluence at an average speed of more than 1 m/s.

The events listed in Table 1 fall into three general categories of ice breakup behavior. The first group of events (1927, 1929, 1945, 1968, 1981) exhibited moderately high discharge with only gradual variations, and concurrent ice movement for several days. A simultaneous breakup at several locations that extends over days characterizes a reduced energy gradient breakup behavior. Hydrothermal melting is effective under these conditions and makes an important contribution to the breakup. The product of flow and duration exceeded 2000 m^3/s-days in each event, indicating significant potential for hydrothermal melting. The breakup was in an advanced stage when the peak discharge occurred, and water levels were generally moderate. The high water levels associated with bridge damage do not readily follow from the available data for 1929. However, the probable White River ice breakup in January 1929 distinguishes this event from the others in the group, and could explain the apparent contradiction.

The events in the second group (1946, 1964, 1979) each included the formation of a persistent upstream ice jam. The eventual release of the White River ice jam in 1964 produced the highest water levels since at least the 1920's at White River Junction, Vermont [Lehman 1986], and two spans of a three-span bridge over the White River were destroyed. This short-duration, extremely high flow input was not supplemented by a rising Connecticut River and experienced significant attenuation prior to arriving at Windsor. In 1946 and 1979 ice jams near the Connecticut River gaging station persisted for about 35 and 48 hr, respectively. The delay of the ice from the White River and the upstream reach of the Connecticut River provided an opportunity for breakup downstream to proceed with less ice volume, effectively increasing the channel capacity. Therefore, the breakup at Windsor developed lower water levels than would have occurred if a single breaking front had advanced rapidly downstream.

The third group of events (1925, 1936, 1938, 1977) includes most years of reported bridge damage and the highest water levels at Windsor. In each case an abrupt White River rise deposited large quantities of competent ice in the Connecticut River. The intact ice on the Connecticut River then began to fail as the discharge continued to increase rapidly, and the breakup traveled downstream. The largest quantities of competent ice together with a high peak discharge produce the highest river levels at breakup. The largest recorded daily average Connecticut River discharge during the normal period of ice breakup was 3260 m^3/s on 19 March 1936, a much larger event than any of the events to date that actually caused breakup.

WINTER 1985-86 OBSERVATIONS

We regularly observed the ice conditions on the Connecticut River study reach throughout the winter of 1985-86. During December and January a generating unit at Wilder Dam was out of service, limiting releases to a maximum of 142 m^3/s. An ice jam commonly forms over the winter in the reach near station 2. However, restricted peak flows limited the energy gradients near station 2, producing a uniform ice sheet. During normal two-unit flow releases, the reach above station 1 is predominantly free of stable ice. The reduced unsteadiness of the flow during this period allowed the development of an ice cover of maximum extent, reducing the open water area below the dam, the heat loss from the river, and consequently, the total ice production in the reach.

The ice breakup on 27 January cleared the reach of ice from Wilder Dam to a point 2 km downstream of station 2. Following the breakup, a second ice sheet with uniform initial thickness formed near station 2. However, by the end of February, a massive jam had developed at this location; surface relief of 1.5 m indicated that the accumulation rested on the river bed at several places. The available freezing-degree-days were nearly equal during the development of the January ice sheet and February ice jam. However, the ice jam experienced much higher Wilder flow releases and a backwater effect from Bellows Falls Dam that was not present during the formation of the uniform sheet.

The February ice jam at station 2 was not desirable because it blocked much of the channel and restricted the flow. The primary cause of the jam formation, evident from the ground and from low-altitude aerial photographs, was shoving and piling of thin ice.

Mechanisms that contributed to the ice jam development were the increased ice supply from daily formation and breakup of thin ice upstream of station 1, and maximum open water area causing increased ice production. Ice deposition in the jam was initially favored by its location at the head of the backwater, and later by the channel blockage that developed.

An ice cover that has developed sufficient thickness can be very stable, as evidenced by the high January discharge prior to breakup. After the breakup we found large grounded ice floes exceeding 0.20 m in thickness at station 1 that were remnants of the upstream ice cover. Ice of this thickness is resistant to breakup at normal flow conditions. These observations support the relationship between minimum ice production and flow control during the period of ice cover formation.

Controlled Release Tests

Each abrupt flow release from a dam creates a long-period river wave that undergoes changes as it travels downstream. Wave celerity in a free-flowing river is the translation speed of a release in the downstream direction. The purpose of the controlled release tests on the Connecticut River was to obtain a comprehensive data set including the low flow hydraulic gradient and wave celerity between stations, and the rate of stage increase, the wave front steepness, and the wave amplitude at several stations. These data are then used in several ways: to compare flow releases with different peak discharges and rates of increase to the peak discharge; to determine the effects of the ice cover on river response; to compare the response of different reaches and locations, especially noting changes with distance downstream; and finally, to compare the response of the Connecticut River with other rivers having different characteristics. This analysis provides us with an improved understanding of the parameters affecting the response of the river. These data also enable the calibration and verification of numerical models, providing additional testing of ice breakup theory with the goal of controlling ice breakup.

We conducted these tests on the Connecticut River on 15 October 1985 during open water conditions, and on 26-28 February 1986 when ice was present in the river. A flow release schedule for each test day was specified for Wilder Dam (Table 2), while the discharge at Bellows Falls Dam was varied as required to maintain a constant headwater elevation. The schedules vary the rate of rise and the peak flow, and examine river response to successive releases spaced 2 hr apart. The mean discharge of the White River is also given in Table 2 for each test day.

The ice regime of the river in our study reach was not changed substantially over the course of the winter test (Fig. 2). The few areas of solid shorefast ice that existed in sheltered bends of the river upstream of station 1 remained. Low overnight temperatures prior to each test day of -12°, -17° and -22°C, respectively, caused the growth of large expanses of thin ice in this largely open water reach. This ice was repeatedly broken, transported and deposited downstream of station 1 by the scheduled Wilder Dam release, while the more permanent shorefast ice remained intact. The ice conditions in the 2-km reach downstream of station 1 became more highly fragmented over the duration of the test and the quantity of ice increased as a result of the supply from upstream. The surface appearance of the ice farther downstream was unchanged over the test. Accumulations of broken sheet ice near station 2 were several meters thick. The sheet ice thickness in sheltered areas near the right bank at station 2 was 0.56 m, and at station 3 the ice was solid and relatively uniform with a thickness of 0.53 m.

Stage hydrographs measured during the fall and winter tests are presented in Figure 3. A much larger stage response occurs at all stations with two-unit compared to single-unit Wilder Dam releases, and the disparity increases with distance downstream. The general increase in stage is evident at the downstream stations during ice cover conditions. The ice caused low flow stage increases of 0.46 m and 0.91 m at stations 2 and 3, respectively. The common water surface drawdowns at stations 2 and 3 early in each winter test day and the small stage difference between these stations indicate continuous backwater.

The hydraulic gradients at low discharge presented in Table 3 were obtained for the reaches between measurement locations. The kilometer positions of the measurement locations listed in the table are based on a local system with distance increasing upstream from Bellows Falls Dam. Upstream of station 1 the winter gradient is somewhat greater than the open water gradient because of the spotty presence of ice. The river downstream of station 3 was completely ice covered and that gradient was significantly larger than it was during open water. This increased winter gradient downstream caused the head of the Bellows Falls backwater to shift from an open water location of between 1 and 2 km downstream of station 2 to an ice-affected location upstream of station 2. As a result, the overall hydraulic gradient between stations 2 and 3 is reduced in winter. Because the winter stage increase at station 2 was approximately equal to the ice thickness, the extent of backwater above station 2 was probably less than 1 km. The increased winter gradient between 1 and 2 is accommodated by flooding the lower portion of "Sumner Falls" rapids, downstream of station 1.

Wave celerity is obtained by timing the initial stage increase between measurement locations. The relatively small quantity of ice upstream of station 1 on the morning of each test day did not affect wave celerity (Table 3). Farther downstream, where a complete and stable ice cover existed, wave celerity was reduced by as much as a factor of 2 relative to open water conditions. Consistent wave celerity reduction on the Hudson River in the presence of ice was also measured by Ferrick et al. [1986a]. They measured celerities in flat, pooled reaches that were significantly greater than those in sloped and freely flowing reaches, and celerity increases with increasing peak discharge. These same slope and peak discharge tendencies also occurred on the Connecticut River and can be noted in Table 3.

Table 2. Controlled flow release test schedules at Wilder Dam, and mean discharge of the White River during the monitoring period. A release pattern number identifies each test schedule.

Release pattern number:	#1	#1	#2	#3
	Discharge (m^3/s)			
Time	15 Oct	26 Feb	27 Feb	28 Feb
0000-0700	21	21	21	21
0700-0800	85	85	142	21
0800-0900	170	170	142	283
0900-1000	255	255	21	283
1000-1100	255	255	21	283
1100-1200	255	255	142	283
1200-1300	21	21	142	283
1300-1700	21	21	21	21
1700-2400	open	open	open	open
White River mean discharge (m^3/s)	27	22	19	19

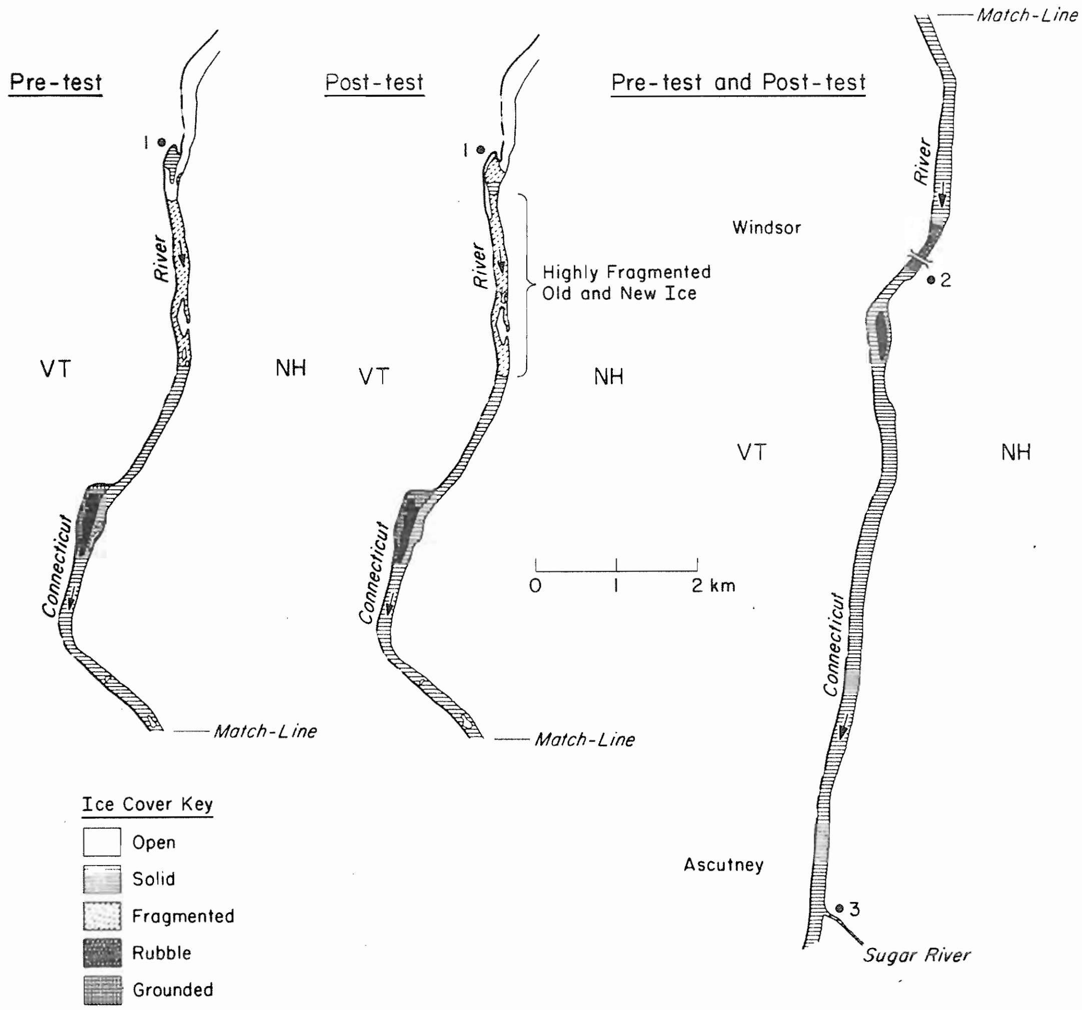
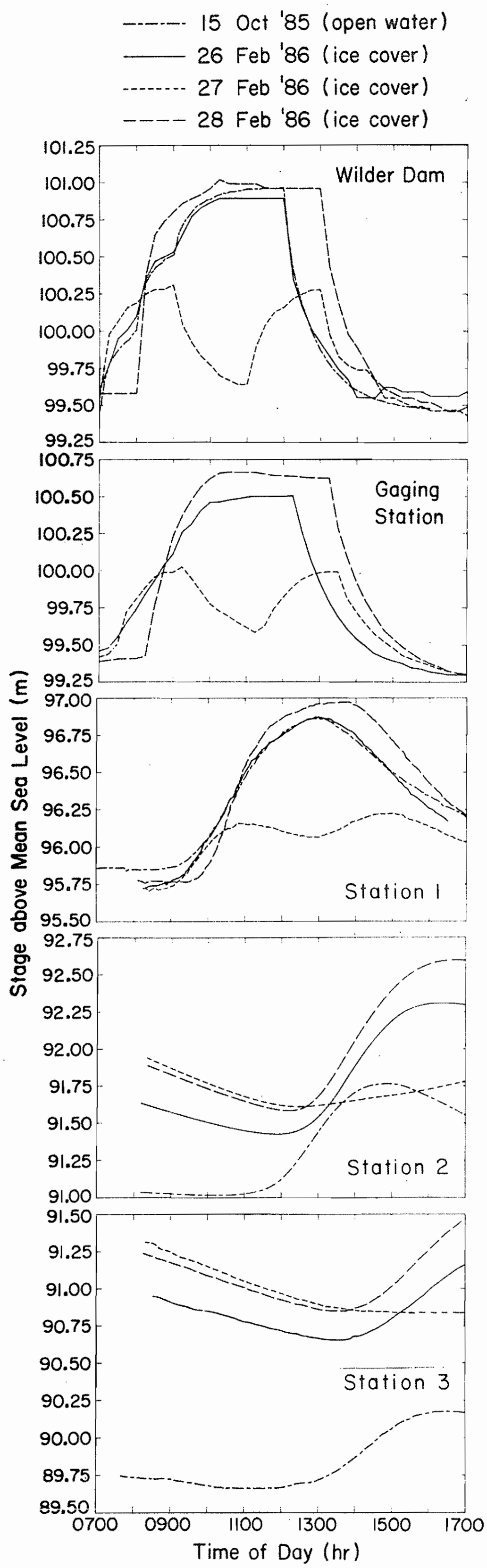


Figure 2. Ice conditions in the reach between stations 1 and 3 both prior to and following the winter test. The ice cover between stations 2 and 3 remained unchanged over the period of the test.

On the Hudson River, the ice cover caused a significant reduction in the maximum rate of stage increase relative to open water conditions [Ferrick et al. 1986a]. However, the ice cover on the Connecticut River did not affect this rate at the ice-affected stations, 2 and 3 (Table 4). The most likely explanation for the different effects of the ice on the increasing stage in these rivers is a difference in wave type. The increased frictional resistance to flow from the ice cover causes increased attenuation of dynamic waves (Hudson) [Ferrick 1987], but decreases attenuation of bulk waves (Connecticut) [Ferrick 1985]. Higher rates of stage increase with higher peak discharge, and a reduction in these rates with downstream distance occurs in both rivers.

The wave front steepness estimates presented in Table 5 are obtained from the rate of stage increase and wave celerity data. Estimated wave steepness increases with peak discharge and generally decreases with distance downstream. In some cases wave steepness increased with the bed slope of the river. The presence of an ice cover caused steepness to increase significantly relative to open water. Following the rate of stage increase data, the ice cover effects on wave steepness in the Connecticut River are opposite those reported by Ferrick et al. [1986a] for the Hudson River.

Wave amplitude is the stage increase at a given location obtained from measurements immediately prior to wave arrival and at the wave peak. Wave amplitude and amplitude attenuation are a reflection of the channel capacity, a function of the geometric and



hydraulic characteristics of the river. Wave amplitude (Table 6) increases with peak discharge, and decreases with distance downstream as a result of attenuation. With ice in the river the flow resistance is increased, causing higher wave amplitudes relative to identical open water flow conditions.

January 1986 Ice Breakup

The ice breakup that occurred on 27 January is a natural starting point for an analysis of breakup dynamics. The air temperatures in the week prior to breakup were seasonally cold, totaling 61 freezing °C-days. Because of the cold temperatures the ice in the reach between stations 1 and 2 was strong, with thicknesses ranging between 0.3 and 0.5 m. A rainfall on 26-27 January of more than 5 cm provided the source of the inflow that eventually led to the breakup.

River stage and discharge data at Wilder Dam, and at the Connecticut gaging stations, are presented in Figures 4 and 5, respectively, for 27 January. The flow release at Wilder increased throughout the day, attaining a peak of more than 10 times the initial flow. The elevation of the headwater at Bellows Falls Dam was held constant at 87.97 m above mean sea level (msl), the minimum pool of the normal operation range.

Knowledge of the energy gradient at breakup is essential for ice management. The energy gradient varies with stage, discharge, and ice conditions, and can be greatly affected by breakup. The water surface gradient is generally a good indicator of the flow energy gradient. Unfortunately, water surface elevation data in the reach downstream of station 1, where the primary ice breakup occurred, are not available. Therefore, the energy gradient at station 2 will be estimated based on limited on-site data and known upstream flow conditions.

Steady flow open water data yield a Manning's roughness coefficient of 0.03 for the reach between stations 1 and 2. Variable ice roughness and thickness, and sparsity of data introduce uncertainty into a combined ice-bed roughness determination.

Figure 3. Measured stage during the fall and winter tests as a function of time at several locations in the study reach.

Table 3. Wave celerity variations with release discharge and cover condition, and comparison of low discharge hydraulic gradients by reach and cover condition.

		Low discharge hydraulic gradient ($x10^3$)		Celerity (m/s)				
				#1	#2		#2	#3
Location	(km)	open	ice	open	ice	ratio	ice	ice
Wilder	70.0							
		0.035	0.039		3.42		3.10	4.33
Gaging Sta.	66.1			2.34		1.00		
		0.30	0.32		2.09		2.02	2.38
Sta. 1	54.7							
		0.23	0.30	1.61	0.97	1.66	0.88	1.17
Sta. 2	43.1							
		0.16	0.097	2.67	1.33	2.01	1.33	1.48
Sta. 3	35.1							
		0.032	0.068	9.75	---	--	--	4.50
Bellows Falls	0.0							

Table 4. Variations in the maximum rate of stage increase with release discharge and cover condition.

		Max. rate of Stage Increase (m/min)				
		#1	#1		#2	#3
Location	(km)	open	ice	ratio	ice	ice
Wilder	70.0	0.024	0.022	1.09	0.036	0.054
Gaging Sta.	66.1	---	0.010	---	0.011	0.022
Sta. 1	54.7	0.0083	0.0083	1.00	0.0058	0.016
Sta. 2	43.1	0.0063	0.0065	0.97	0.00088	0.0077
Sta. 3	35.1	0.0037	0.0036	1.03	0.00000	0.0042

Table 5. Variations in the estimated wave front steepness with release discharge and cover condition.

		Estimated Wave Front Steepness (m/m x 10^3)				
		#1	#1		#2	#3
Location	(km)	open	ice	ratio	ice	ice
Wilder	70.0	0.12	0.11	1.1	0.19	0.21
Gaging Sta.	66.1	---	0.049	---	0.059	0.085
Sta. 1	54.7	0.066	0.066	1.0	0.048	0.11
Sta. 2	43.1	0.065	0.11	0.59	0.017	0.11
Sta. 3	35.1	0.023	0.045	0.51	0.000	0.047

Table 6. Wave amplitude variations with release discharge and cover condition.

		Wave Amplitude (m)				
		#1	#1		#2	#3
Location	(km)	open	ice	ratio	ice	ice
Wilder	70.0	1.52	1.46	1.04	0.88	1.52
Gaging Sta.	66.1	--	1.16	--	0.68	1.36
Sta. 1	54.7	1.01	1.10	0.92	0.51	1.20
Sta. 2	43.1	0.75	0.88	0.85	0.17†	1.01
Sta. 3	35.1	0.51	0.50†	--	0.00	0.60†

†Stage rising beyond measurement period.

With an estimated mean ice thickness we obtained a combined roughness for the February test that is comparable to the open water value. At 1400 hr, prior to breakup at station 2, the estimated discharge, river width and mean depth beneath the ice were 740 m^3/s, 150 m and 4.0 m, respectively, yielding a mean flow velocity of 1.23 m/s. The corresponding energy gradient estimate is 0.54×10^{-3}, and the dynamic wave celerity is 7.5 m/s. The increased flow resistance from the static ice cover increased the flow depth by 1 m relative to open water, effectively holding this volume in storage.

The stage decrease between 1300 and 1400 hr at the gaging station with steady flow conditions at Wilder and from the White River indicates an ice release downstream of the gage. This release was timed properly to have initiated the downstream breakup. The breakup began upstream and progressed rapidly downstream as a single feature with no ice source external to the reach itself. As the breakup progressed into the Bellows Falls backwater the energy gradient diminished and, at about 2 km downstream of station 2, became insufficient to sustain the ice breakup. The fragmented ice visible from station 2 was motionless at 1530 hr, coincident with the peak stage at that location. A rapid stage subsidence of 0.3 m by 1600 hr indicated the short-duration characteristic of the river wave resulting from the breakup of the reach. The stage peak at station 2 attained in this event was 95.11 m above msl, corresponding to 3.71 m of freeboard at the Cornish-Windsor Bridge.

The speed of the breaking front cannot be greater than the dynamic wave celerity. The flow resistance decreases rapidly as the ice begins to move. Ice moving at the flow velocity causes negligible resistance to the flow. If the acceleration of the ice plates is instantaneous, the stored water is released at the speed of the breaking front. This maximum contribution to the river wave yields an upper bound on the energy gradient. The breaking front speed, estimated at 5 m/s near station 2, and the peak gradients that develop are related. The rapid movement of the front indicates that large energy gradient increases were not necessary to initiate breakup [Ferrick et al., 1986b].

The second stage of the breakup event was caused by the river wave from the breakup of the White River. At 1615 hr a large wave from ice breakup upstream passed the gaging station at WRK 11.9. Observations of the ice sheet in the lower 3 km of the White River revealed intact ice at 1700 hr. The flow in the Connecticut River at the gaging station began increasing at 1800 hr in response to the rising White River. The White River ice run accompanied by sharply increasing flow arrived at the gage at 1945 hr, followed closely by the peak discharge at 2000 hr. The speed of the breakup in the lower White River averaged 1 m/s, requiring just over 3 hr to progress the 11.9 km from the gage to the Connecticut River confluence. The speed of the wave front was constrained by the velocity of the water which in turn was limited by the presence of the ice. The relatively steep bed slope (0.0013), the modest initial flow with an abrupt transition to a high peak flow, and the high roughness of the ice covered channel caused the relatively low bulk wave celerity.

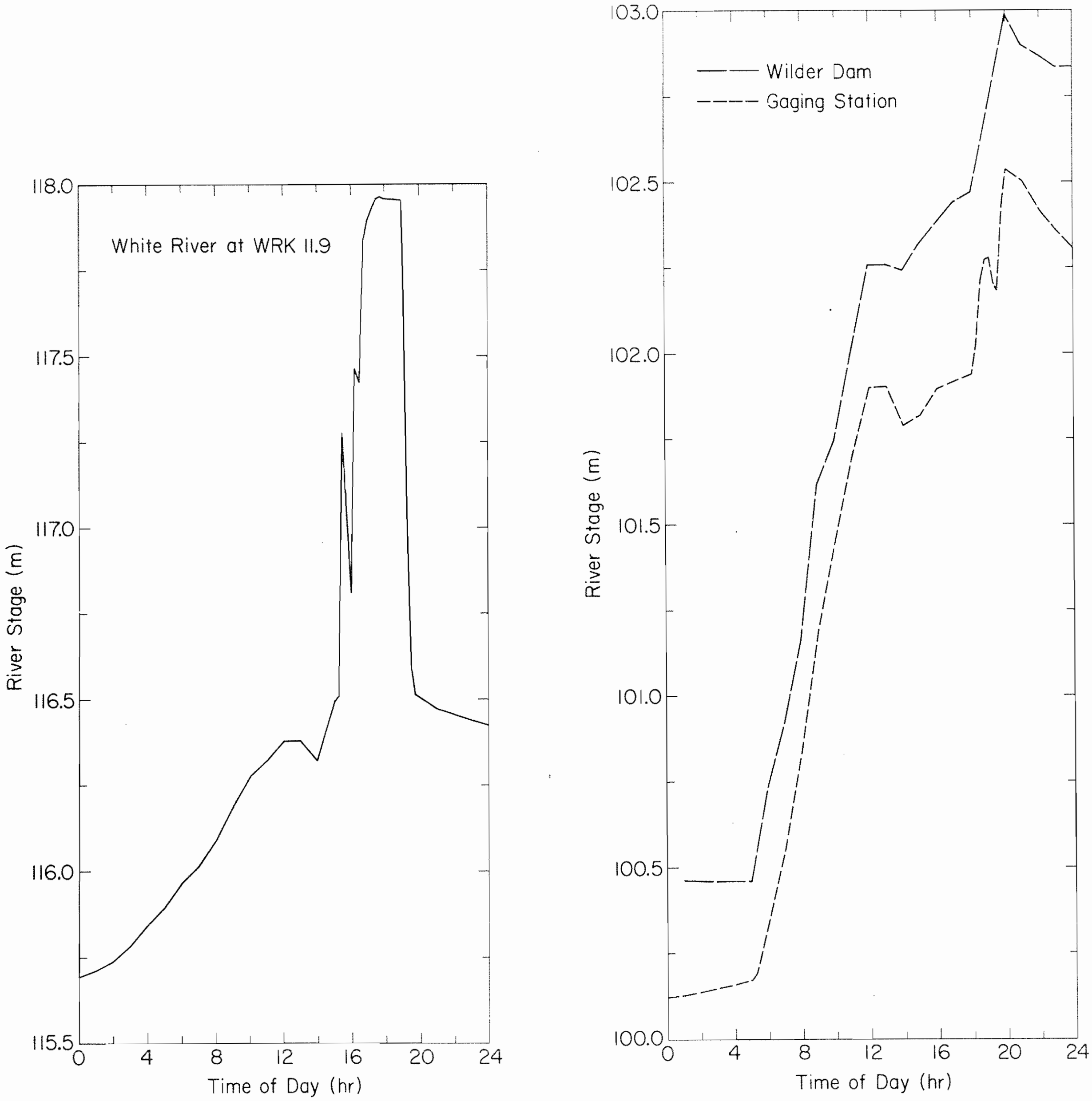


Figure 4. River stage variations with time for 27 January 1986 at the White River gage WRK 11.9, the Connecticut River gage and the tailwater at Wilder Dam.

The stage-discharge relationship at a gaging station is developed during relatively steady flow conditions. However, during a dynamic breakup the flow is rapidly varied, and the rating curve would significantly underpredict the discharge. This reasoning is supported by continuity considerations between the White River inflow, Wilder Dam release and the Connecticut River gage discharge. The 310-m^3/s flow increase at WRK 11.9 was sustained for 2 hr. At the confluence the peak inflow should have been even higher and/or the duration longer with the additional water release from storage during the complete breakup of the lower White River. In contrast, the gage showed a peak flow increase of only 220 m^3/s above the Wilder discharge that was sustained for less than 1 hr before subsiding (Fig. 4).

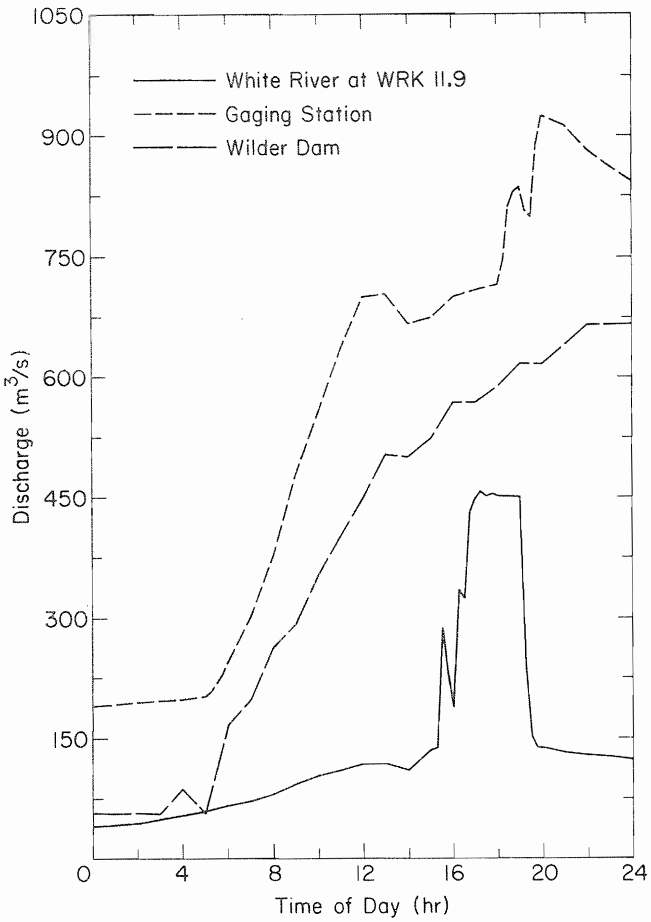


Figure 5. River flow variations with time for 27 January 1986 for the tailwater at Wilder Dam and estimates based on the rating tables for the gages on the White and Connecticut Rivers.

With the arrival at Windsor of the breakup wave from the White River the energy gradient increased, causing the ice jam to release and travel about 16 km farther downstream into the Bellows Falls backwater. Wave movement and corresponding changes in energy gradient are much faster than the velocity of ice floes in relatively deep open water. Moving ice downstream of Windsor was observed several hours before the ice from the White River could have arrived. The subsequent ice jam, again caused by an insufficient energy gradient, was about 16 km long including the White River ice deposited at the head of the jam upstream.

CONNECTICUT RIVER ICE CONTROL

The highest water levels on the Connecticut River near Windsor, Vermont, occur with the following sequence of ice breakup events. The White River rises abruptly to a high peak, depositing large quantities of ice in the Connecticut River. Meanwhile, the ice on the Connecticut River is competent and intact, and its own discharge continues to rapidly increase toward a peak daily average flow in excess of 1200 m^3/s. A successful ice control strategy must reliably disrupt this combination of events.

The predictable timing of a dynamic ice breakup works to the advantage of any ice control method. The data in Table 1 indicate that 10 of the 12 largest breakup events occurred in a 2-1/2 week period in March. All of these events closely follow and occur in response to a significant rainfall. With river regulation the available methods of ice control are to 1) minimize ice production over the winter, 2) reduce the quantity of ice prior to breakup, and 3) disrupt the natural White River-Connecticut River breakup sequence, reduce the peak breakup discharge, and minimize the river stage during breakup.

Minimizing Ice Production

The total ice production of a river can be minimized by river regulation during the period of ice growth. The basic concept is that by enabling a uniform ice cover to develop with the maximum possible areal extent, the water is insulated from midwinter air temperatures. The test and observational data indicate that a single-unit maximum steady discharge should be sustained until the maximum ice cover extent develops with thicknesses generally greater than 20 cm. The thickness requirement ensures that the cover will not readily break up when normal operations resume. This method avoids ice jamming during freezeup that is caused by repeated shoving and breakup of immature ice cover, and minimizes the total production of ice by minimizing the surface area of open water. The process is repeated if a midwinter ice breakup occurs.

Hydrothermal Melting

Another method of ice control is to melt, weaken and gradually break up the ice prior to the natural event. The historical data suggest that high water levels are avoided when sustained moderate discharge and moderating above-freezing air temperatures produce significant hydrothermal melting and weakening of the ice cover. If we assume adiabatic melting of the ice by heat contained in the water, the product of water volume and temperature needed to melt all the ice in the study reach above station 2 is 6.9×10^7 m^3-°C. With a constant water temperature of 0.2°C at the upstream edge of the ice sheet, a release of 280 m^3/s for 14 days would be required. However, water temperature increases with the area of open water, greatly reducing the necessary volume of water. We recommend a sustained continuous discharge of at least 280 m^3/s from Wilder Dam for between 7 and 10 days with minimum Bellows Falls headwater elevation, coordinated with daily average air temperatures of 0°C or higher in late February and early March. If the available water is insufficient for a continuous release, hydrothermal melting can be optimized by coordinating releases with maximum solar insolation and air temperature. Sufficient lead time usually exists to greatly reduce the quantity of ice in the river at the time of breakup.

Controlled Ice Breakup

Controlled ice cover breakup is a method that disrupts the critical combination of events that causes breakup flooding and can be implemented on the relatively short notice of a 1- to 2-day weather forecast. The concept is to cause the Connecticut River to break up prior to the natural event at a lower stage and discharge, and in advance of the White River breakup. Another benefit is that the early release of water from upstream creates storage and reduces the eventual peak discharge. Both the observed breakup on 27 January 1986 and the analysis of the historical records clearly indicate the flood reduction advantage of separating the White River and Connecticut River breakups. Precise release patterns from Wilder Dam that will produce a controlled breakup have not yet been developed, but guidance is available from the conditions of the January 1986 event. Abrupt releases of several hours in duration provide maximum energy gradients and ice breaking capability with a minimum volume of water released and at minimum river stage. Lowering the Bellows Falls headwater from the winter test elevation of 88.27 m to 87.35 m above msl would shift the head of the pool downstream near its open water location. The minimum possible Bellows Falls headwater elevation increases the attainable energy gradients downstream from station 2, limiting the size of the upstream release needed for effective ice breaking. This method of ice control for the Windsor area would not change the ice breakup behavior in the lower 30 km of the Bellows Falls pool. From that location upstream, the controlled breakup would occur earlier, and at a reduced stage and discharge, than the natural event. Additional laboratory modeling and field testing are necessary before attempting a controlled ice breakup.

CONCLUSIONS

The potential exists for a much larger breakup event than has occurred in the historical record. Three basic methods have been identified that use river regulation to minimize the probability of flooding and damage or loss of the Cornish-Windsor bridge during ice breakup on the Connecticut River. The use of all these methods, to the largest extent possible, would produce minimum river stage during the period; however, all have associated power production costs. Controlled Connecticut River ice breakup is the alternative for ice management that provides the most flexible response capability. Additional development, including field testing of this method, is needed before it can be used with confidence.

ACKNOWLEDGMENTS

Larry Gatto, Nancy Perron, Ron Farr, Sharon Borland, Steve Perkins, Gordon Gooch, Ed Foltyn and Jim Wuebben, all of CRREL, assisted with field data collection. Ron Liston and Bob Demars, of CRREL, provided aerial photographic coverage of the reach prior to and following the winter field test. Howard McLaren of the New England Power company arranged the river control for the field tests and provided flow release and water surface elevation data for Wilder and Bellows Falls Dams. The cooperation of the New England Power Company in these tests is gratefully acknowledged. Glenn King of CRREL provided meteorological data, and James Linney and Mike Coakley of the U.S. Geological Survey provided data from the gaging stations. Darryl Calkins and Steve Daly, of CRREL, provided technical reviews, and Ed Wright, of CRREL, edited the manuscript. Donna Harp, of CRREL, provided accurate and rapid typing of the manuscript.

References

Childs, W.H., A History of the town of Cornish, New Hampshire, Vol. 1, Rumford Press, Concord, NH, 1960.

Ferrick, M.G., "River wave response to the friction-inertia balance," Hydraulic Engineering, Proceedings of the 1987 National Conference on Hydraulic Engineering, ASCE, New York, pp. 764-769, Aug. 1987.

Ferrick, M., G. Lemieux, W. Demont and P. Weyrick, "A study of dynamic ice breakup on the Connecticut River near Windsor, Vermont," CRREL Report, in preparation, 1987.

Ferrick, M., G. Lemieux, N. Mulherin and W. Demont, "Controlled river ice cover breakup, part 1. Hudson River field experiments," Proceedings of the IAHR Symposium on Ice 1986, Vol. III, Iowa City, Iowa, 1986a.

Ferrick, M., G. Lemieux, N. Mulherin and W. Demont, "Controlled river ice cover breakup, part 2. Theory and numerical model studies," Proceedings of the IAHR Symposium on Ice 1986, Vol. III, Iowa City, Iowa, 1986b.

Ferrick, M.G., "Analysis of river wave types," Water Resources Research, Vol. 21, pp. 209-220, Feb. 1985.

Lehman, R.W., Personal communication, Town Manager, Hartford, Vermont, 1986.

Rawson, B.E., A History of the town of Cornish, New Hampshire, Vol. 3, Courier Printing, Littleton, NH, 1963.