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Dynamic Ice Breakup Control for the Connecticut River near Windsor, Vermont

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The Cornish-Windsor bridge is the longest covered bridge in the United States and has significant historical value. Dynamic ice breakup of the Connecticut River can threaten the bridge and cause flood damage in Windsor, Vermont. We monitored ice conditions throughout the 1985-86 winter, observed a mid-winter dynamic ice breakup, conducted controlled release tests during both open water and ice cover conditions, and analyzed more than 60 years of temperature and discharge records. River regulation presents alternatives for ice mangement that would minimize water levels during breakup. In this paper we develop the basis of a method to produce a controlled ice breakup at lower stage and discharge than occur during major natural events.

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, and significant damage from ice impacts occurred again on 14 March 1977. The water levels associated with ice damage to the bridge also caused flood damage in Windsor, Vermont.

The highest water levels on the Connecticut River near Windsor typically occur during a dynamic ice breakup, the rapid failure of a strong, intact ice cover during periods of intense runoff. There are no reports of damage of the present bridge resulting from open water floods with much higher peak discharges. The Connecticut River is regulated, and hydropower dams are located both upstream and downstream of Windsor. Donchenko (1978) observed that intensive deformation or breakup of an ice cover occur downstream of hydropower dams in response to a rapid rise in stage. He suggested that flow releases could be regulated to minimize ice breakup and jamming during the periods of ice cover formation and spring breakup. However, ice management strategies based on river regulation require a quantitative theoretical description of dynamic ice breakup.

In this paper we characterize dynamic ice breakup on the Connecticut River near Windsor, identify the critical combination of conditions that produce extreme breakup flood events, and provide data that are preliminary to quantitative predictions of ice breakup behavior. We focus on the development of a method of river regulation that produces a controlled ice breakup at lower stage and discharge than occur during major natural events. This technique would provide a quick response capability that greatly reduces the potential for ice damage and flooding. Additional ice control methods for this reach are given by Ferrick *et al.* (1988).

Background

The energy gradient of a river is a dimensionless parameter that quantifies the rate of energy dissipation in the flow. The water surface gradient is generally a good indicator of the energy gradient. River waves are long-period, shallow water waves that are a consequence of unsteady flow (Ferrick 1985). Changes in the flow release at a dam create river waves. Both the water surface and energy gradients on the front of a river wave can be significantly larger than those found during steady flow conditions, and the hydraulic forces on the ice cover are proportional to these gradients (Ferrick *et al.* 1986b).

River ice breakup occurs when the forces on the cover exceed the resistance provided by the ice strength and points of support. The possibility exists that breakup will occur at any point on the spectrum between small forces that exceed a greatly diminished ice cover resistance, characteristic of a thermal breakup, and very large forces that overcome the resistance of thick and competent ice, termed a dynamic breakup. The dynamic or thermal character of ice breakup on a river will typically span the spectrum in a period of several years. Prowse *et al.* (1988) performed prebreakup tests of in-situ ice strength on the lower Liard River in northern Canada. They reported a linear decrease in ice strength of 50% over an 18-day period, followed by a relatively mild breakup. The extent of deterioration of ice strength combined with the magnitude and rate of change in hydraulic conditions determine the character of breakup.

Dynamic ice breakup conditions produce the highest water levels, and usually the downstream movement of a single breaking front that is generally associated with the front of a river wave. While moving, the breaking front progresses rapidly, but it may stall and form 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. With an ice sheet in place, the frictional resistance of a river is increased, affecting both the steady-state stage-discharge relationship and the unsteady flow dynamics. River waves and dynamic ice breakup are intrinsically related because wave formation must occur during a dynamic breakup from the release of water in channel storage with the rapid decrease in flow resistance as the ice breaks up.

Connecticut River

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 a 35-km reach from Wilder Dam downstream (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 8,780 km^2. The White River, with a basin size of 1,820 km^2, is the primary tributary in the study reach, entering about 2 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.

Ferrick *et al.* (1988) analyzed more than 60 years of air temperature, precipitation and discharge records for the period of November through March. The date of a dynamic ice breakup on the Connecticut River was estimated from the daily flow records. The 12 highest breakup discharge years include all years of reported bridge damage. The total number of freezing degree days evaluated for each year indicated that Connecticut River ice production in an average winter is sufficient to pose a threat at breakup. The pre-breakup temperature data do not indicate any correspondence between melting degree-days and high water levels at Windsor. A minor contribution of air temperature to ice cover decay concurs with the model studies of Greene and Outcalt (1985). They found that water temperature was the most important thermodynamic variable controlling ice thickness. The process that we term »hydrothermal melting« refers to the melting of an ice cover from the heat contained in the flowing water. The discharge-days of hydrothermal melting for the period of rising discharge generally confirm that minimum hydrothermal melting maintains the resistance to breakup of an ice cover.

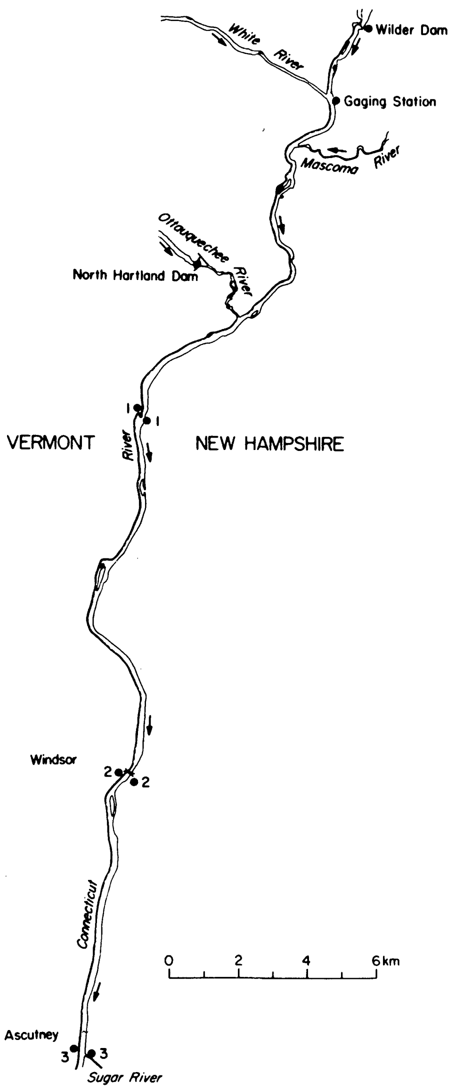

Fig. 1.
Connecticut River study reach including the major tributaries. Station 2 is located at the Cornish-Windsor covered bridge.

White River flow data are collected at a permanent gaging station at White River kilometer 11.9 (WRK 11.9). The White River is uncontrolled, and during the breakup period the flow of the Connecticut River can increase suddenly and become uncontrolled. The rate of stage increase during ice breakup at both the White River and Connecticut River gages 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 upstream. Stage recession rates of up to 1.4 m/hr have occurred in response to the release of an ice jam. Discharge has increased at breakup by a factor of 20 or more during a 24-hr period on both rivers. The largest recorded daily average Connecticut River discharge during the normal period of ice breakup was 3,260 m^3/s on 19 March 1936, a much larger event than any of the events to date that actually caused breakup.

The historical ice breakup events fall into three categories. The first group of events exhibited moderately high discharge with only gradual variations, and concurrent ice movement over a period of several days. The events in the second group each included the formation of a persistent upstream ice jam. 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 a smaller ice volume, effectively increasing the channel capacity. The third group of events includes most years of reported bridge damage and the highest water levels at Windsor, and indicates the critical 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 the combined discharge continues to rapidly increase toward a peak daily average flow in excess of 1,200 m^3/s. The Connecticut River ice run begins upstream and the entire volume of ice is involved. The channel blockage that develops combined with the high discharge causes extreme water levels.

Controlled Release Tests

For the controlled release tests on the Connecticut River we established temporary data collection stations at regular intervals, to supplement the ongoing data collection at the gaging stations and the dams (Fig. 1). These data are used in several ways: (1) to compare flow releases with different peak discharges and rates of increase to the peak discharge; (2) to determine the effects of the ice cover on river response; (3) to compare the response of different reaches and locations, especially noting changes with distance downstream; and (4) to compare the response of the Connecticut River with other rivers having different characteristics. These data enable the calibration and verification of numerical models, and together with data characterizing ice breakup, allow testing of existing breakup theory and the potential for controlling breakup.

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 in the reach near station 2; however, restricted peak flows produced a uniform ice sheet. During normal two-unit flow releases, the reach upstream of station 1 is predominantly free of stable ice. The reduced unsteadiness and peak discharge during this period allowed the development of an ice cover of maximum extent upstream. The ice breakup on 27 January cleared the reach of ice from Wilder Dam to a point 2 km downstream of station 2. However, by the end of

Table 1 – Controlled flow release test schedules at Wilder Dam, mean discharge of the White River during the monitoring period, and base flow of the Connecticut River at Bellows Fall Dam. A release pattern number identifies each test schedule.

Release pattern number:	1	1	2	3	3
	Discharge (m^3/s)				
Time	15 Oct.	26 Feb.	27 Feb.	28 Feb.	16 Oct.
0000-0700	21	21	21	21	22
0700-0800	85	85	142	21	283
0800-0900	170	170	142	283	283
0900-1000	255	255	21	283	283
1000-1100	255	255	21	283	283
1100-1200	255	255	142	283	283
1200-1300	21	21	142	283	22
1300-1700	21	21	21	21	22
1700-2400	open	open	open	open	open
Mean discharge					
White River(m^3/s)	27	22	19	19	43
Connecticut River at Bellows Falls Dam (m^3/s)	75	59	55	54	134

February, a massive jam had developed near station 2. 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 energy gradients with two-unit Wilder flow releases. The primary cause of the jam formation was shoving and piling of thin ice. The daily formation and breakup of thin ice upstream of station 1, and the resulting open water area increased ice production.

We conducted the Connecticut River tests on 15 October 1985 and 16 October 1987 during open water conditions, and on 26-28 February 1986 with ice present in the river. A flow release schedule for each test day was specified for Wilder Dam (Table 1), while the discharge at Bellows Falls Dam was varied as required to maintain a constant headwater elevation. The mean discharge of the White River and the base flow of the Connecticut River at Bellows Falls Dam given in Table 1 quantify the relative local inflows to the reach. The open water tests had significantly higher inflows than the winter tests.

The ice regime was not changed substantially over the course of the winter test. 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 caused the growth of large expanses of thin ice that was repeatedly broken, transported and deposited downstream of station 1 by the scheduled Wilder Dam release. 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 ice sheet farther downstream averaged about 0.5 m thick and was unchanged over the test.

Stage hydrographs relative to mean sea level (msl) measured during the fall and winter tests are presented in Fig. 2. The headwater elevation at the Bellows Falls Dam averaged 88.50 m above msl for the open water test on 15 October, and 88.27 m above msl for all remaining tests. A much larger stage response occurred at all stations, with two-unit, compared to single-unit, Wilder Dam releases, and the disparity increased with distance downstream. Also, the rates of stage increase with time downstream of station 1 followed this same trend, reflecting relative water surface and energy gradients. A general increase in stage is evident at the downstream stations during ice cover conditions. Although the mean winter Bellows Falls headwater was 0.23 m lower than that of the initial open water test, the ice caused low flow stage increases of 1.4 m and 2.0 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 and a significant upstream extension of the Bellows Falls pool as a result of the ice cover.

The hydraulic gradients at low discharge presented in Table 2 were obtained for the reaches between measurement locations. The change in river stage of 2.2 m across the rapids immediately downstream of station 1 is nearly constant over the normal range of open water flow conditions, and was not included in the calculation of the hydraulic gradients. 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 was somewhat larger 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 at about 2 km downstream of station 2 to an ice-affected location approximately 3 km upstream of station 2. As a result, the overall hydraulic gradient between stations 2 and 3 was reduced. Conversely, a 0.23-m reduction of the Bellows Falls headwater between the open water tests shifted the head of the backwater downstream. The open water data (Fig. 2) at station 3 reveal that the lower headwater elevation increased both the wave amplitude and the rate of stage increase, corresponding to an increased energy gradient of 0.20×10^{-3} between stations 2 and 3. The backwater at station 2 reduced the winter gradient between stations 1 and 2 relative to that during ice-free conditions.

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 2). Higher open water celerities relative to those in winter were caused by higher local inflows and higher

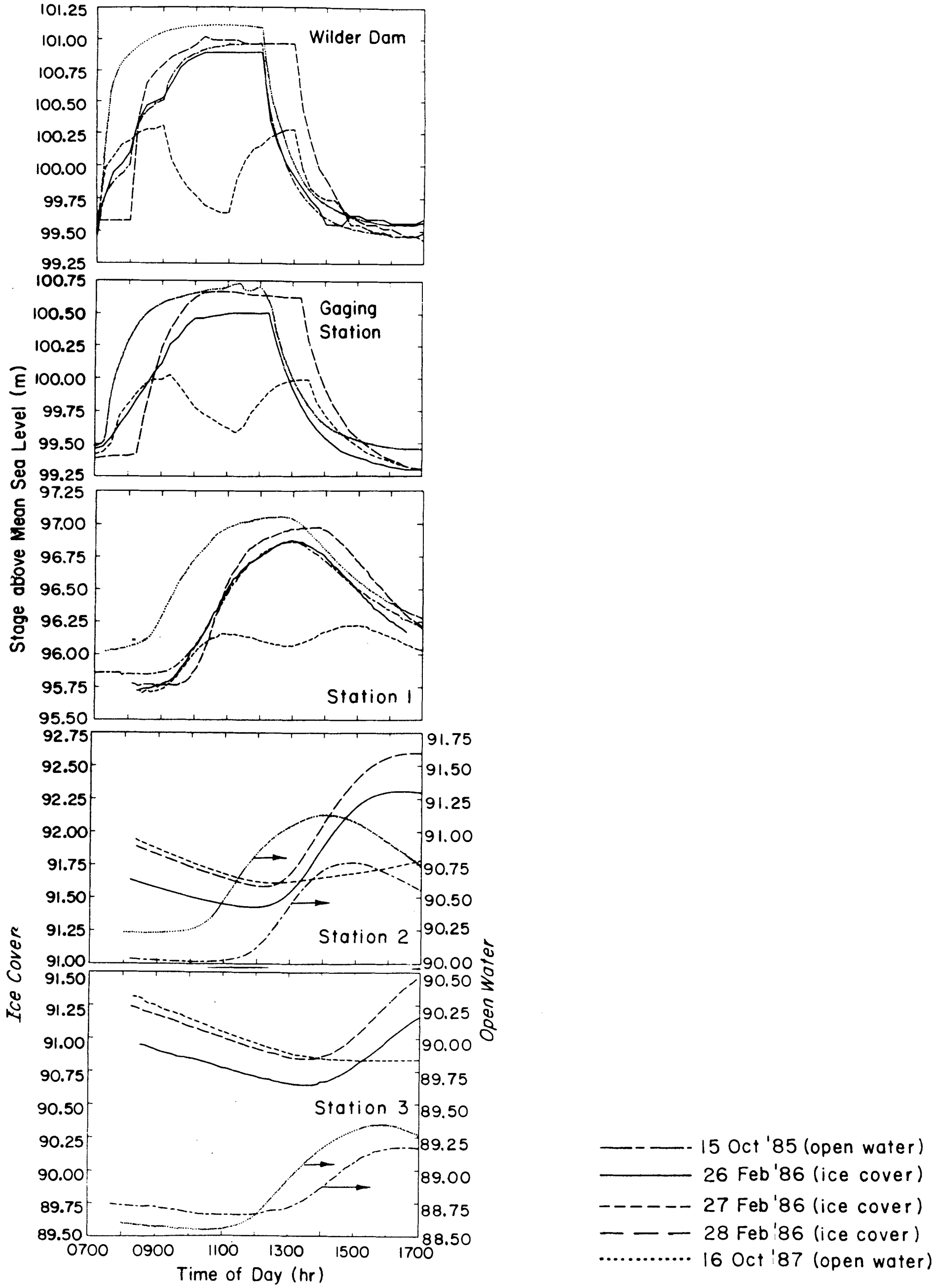

Fig. 2. Measured stage during the fall and winter tests as a function of time at several locations in the study reach. The stage data at stations 2 and 3 required separate vertical scales to present both the ice cover and the open water results.

Table 2 – 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	1		2	3	3	
Location	(km)	open	ice	open	ice	ratio	ice	open	ice	ratio
Wilder	68.2									
Gaging Sta.	65.6	0.014	0.056	2.23	2.23	1.00	2.02	2.82	2.49	1.13
Sta. 1	54.1	0.30	0.32	2.13	1.99	1.07	2.04	2.94	2.55	1.15
Sta. 2	42.6	0.31	0.25	1.43	1.01	1.41	0.88	1.87	1.18	1.59
Sta.3	34.2	0.15	0.093	2.03	1.35	1.51	1.19	2.26	1.52	1.48
Bellows Falls	0.0	0.004	0.070	3.24	---	---	---	3.26	2.26	1.44

Table 3 – 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	3	
Location	(km)	open	ice	ratio	ice	open	ice	ratio
Wilder	68.2	0.023	0.020	1.13	0.031	0.059	0.053	1.11
Gaging Sta.	65.6	---	0.0091	---	0.011	0.026	0.024	1.11
Sta. 1	54.1	0.0069	0.0079	0.88	0.0053	0.0087	0.012	0.74
Sta. 2	42.6	0.0060	0.0062	0.97	0.00087	0.0065	0.0068	0.96
Sta. 3	34.2	0.0034	0.0034	1.00	0.00000	0.0046	0.0040	1.14

initial releases. Farther downstream, where a complete and stable ice cover existed, wave celerity was reduced substantially relative to open water conditions. Consistent wave celerity reduction in the presence of ice was also measured on the Hudson River by Ferrick et al. (1986a). Celerities in flat, pooled reaches that were significantly greater than those in sloped and freely flowing reaches, and celerity increases with increasing peak discharge were common to both rivers.

The rate of stage increase at a given location varies continuously during the passage of a river wave. Table 3 presents maximum rates of stage increase for 15-minute periods at the measurement locations on the Connecticut River. Upstream of station 1 the higher base flow present during the open water tests caused a greater reduction with distance of the maximum rate of stage increase than in winter. However, the permanent ice cover downstream of station 1 reversed this comparison. The significant reduction of the maximum rate of stage increase due to the ice cover was also reported by Ferrick *et al.* (1986a) for the Hudson River.

Table 4 – Wave amplitude variations with release discharge and cover condition.

		Wave Amplitude (m)						
		1	1		2	3	3	
Location	(km)	open	ice	ratio	ice	open	ice	ratio
Wilder	68.2	1.50	1.29	1.16	0.79	1.58	1.40	1.13
Gaging Sta.	65.6	---	1.05	---	0.61	1.21	1.26	0.96
Sta. 1	54.1	1.01	1.11	0.91	0.49	1.03	1.19	0.87
Sta. 2	42.6	0.75	0.88	0.85	0.17†	0.86	1.01	0.85
Sta. 3	34.2	0.51	0.51†	---	0.00	0.79	0.60†	---

†Stage rising beyond measurement period.

Higher rates of stage increase with higher peak discharge, and a reduction in these rates with downstream distance occurred in both rivers.

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 4) 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 air temperatures in the week prior to the ice breakup that occurred on 27 January were seasonally cold, totaling 61 freezing degree-days and the ice in the reach was strong, with thicknesses ranging between 0.3 and 0.4 m. A rainfall on 26-27 January of more than 6 cm provided the source of the inflow that eventually led to the breakup. River stage data at Wilder Dam, and at the Connecticut River and White River gaging stations, are presented in Fig. 3 for 27 January. The elevation of the headwater at Bellows Falls Dam was held constant at 87.97 m above msl, the minimum pool of the normal operation range. The flow release at Wilder increased throughout the day, attaining a peak of more than 10 times the initial flow.

The stage decrease between 1300 and 1400 hr at the gaging station with steady flow conditions at Wilder and from the White River indicated an ice release downstream of the gage that was timed properly to have initiated the breakup. With wave arrival at station 2 the entire ice sheet was forced downstream. Behind the breaking front, which we define as the location of initial ice motion, the ice sheet was transformed into a mosaic of plates with initial size and shape determined by the pattern of preexisting fractures. These observations indicate that the critical

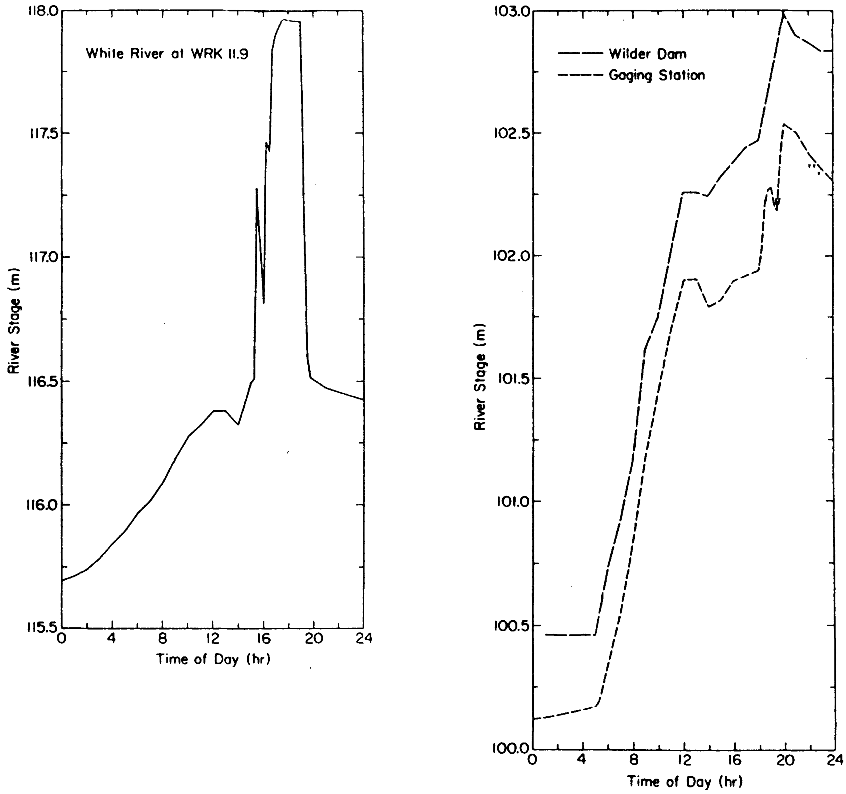

Fig. 3. River stage variations with time for 27 January 1986 at the White River gage WRK 11.9, the Connecticut River gage and the tailwater at Wilder Dam.

component of ice resistance to breakup was support rather than ice strength. The breaking front moved ahead of the ice plates that were not directly involved in the breakup. The motion of large plates immediately behind the breaking front was restricted, while farther upstream the smaller brash moved freely. The difference between these speeds resulted in a zone of ice convergence and a rapid transition from plates to ice rubble. This ice rubble front followed the breaking front at station 2 by a distance of about 2 km. As the river wave progressed into the Bellows Falls backwater, the energy gradient diminished and became insufficient to sustain the ice breakup at km 40. The fragmented ice at station 2 became motionless coincident with the peak stage. A rapid stage subsidence of 0.3 m in 30 minutes indicated the short-duration characteristic of the wave resulting from the breakup of the reach.

Continuous hinge cracks in the cover were present along each bank prior to breakup. The banks provide the primary support for the ice in the Connecticut River, and the hydraulic forces on the cover must be transferred across these cracks. The energy gradient as a function of time is needed to determine the hydraulic forces on the ice cover that led to breakup. However, sufficient data to characterize the gradient are not available. Ferrick and Mulherin (1988) studied this breakup using a numerical model together with data collected at station 2, known stage and discharge conditions at the dams, and known tributary inflows. Steady-flow open water data yield a Manning's roughness coefficient of 0.02 for the reach, and with an estimated mean ice thickness the combined ice-bed roughness for the February test is comparable to the open water value. The simulations of Ferrick and Mulherin (1988) indicate that at 1400 hr, prior to breakup at station 2, the discharge, river width, mean depth and velocity beneath the ice were about 635 m^3/s, 150 m, 3.9 m and 1.35 m/s, respectively. Following from these values are a dynamic wave celerity in the downstream direction of 7.5 m/s, an energy gradient of 0.36×10^{-3} that is equal to the stream bed gradient, and stresses on the hinge cracks of 1,540 Pa. The increased resistance from the static ice cover increased the depth by 1 m relative to open water, effectively holding this volume in storage.

Our observations and the ice breakup theory of Ferrick *et al.* (1986b) indicate that the speed of the breaking front cannot be greater than the dynamic wave celerity. If the acceleration of the ice plates is instantaneous, the stored water is released at the speed of the breaking front, yielding a maximum contribution to the energy gradient. The breaking front speed, estimated at 5 m/s near station 2, indicates that large energy gradient increases were not necessary to initiate breakup (Ferrick *et al.* 1986b). Results of the numerical model study indicate an energy gradient of 0.39×10^{-3} and hinge crack stresses of 1,700 Pa at station 2 immediately prior to breakup. Both the energy gradient and the mean ice thickness are significantly greater than those of the midwinter Hudson River breakup reported by Ferrick *et al.* (1986a).

The second stage of the breakup event was caused by the river wave from the breakup of the White River. The White River ice run accompanied by sharply increasing flow arrived at the Connecticut River gage at 1945 hr, with the peak stage at 2000 hr. The ice jam at Windsor released in response and traveled 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. The subsequent ice jam was about 16 km long, including the White River ice deposited at the head. The post-breakup arrival of the White River ice in this event was similar to the historical events that were characterized by persistent upstream ice jams.

Connecticut River Ice Breakup Control

The potential exists for a much larger ice breakup event on the Connecticut River than has occurred in the historical record. The predictable timing of dynamic ice breakup is an advantage of a control method. The data indicate that 10 of the 12 largest breakup events occurred in a 2-½-week period in March. All of these events closely follow and occur in response to a significant rainfall. Controlled ice cover breakup disrupts the critical combination of breakup events 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 that is used to cause the breakup also creates storage capacity 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 are developed by Ferrick and Mulherin (1988) using both the test data and the data from 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 shifts the head of the pool downstream toward its open water location, increases the attainable energy gradients downstream from station 2, and limits the size of the upstream release needed for effective ice breaking. Controlled ice breakup in the Windsor area would not change the breakup behavior in the lower 30 km of the Bellows Falls pool. From that location upstream, the controlled breakup would occur earlier than with current operations, and at a reduced stage and discharge. Releases designed to produce hydrothermal melting would be initiated immediately following this breakup. The input of heat to the river is proportional to the area of open water (Marsh and Prowse 1987). The combination of high roughness of the ice accumulation downstream and the large area of open water upstream yields the highest possible rate of melt. A successful field trial of the breakup plan is required before this ice management option can be used. However, once developed and tested, controlled ice breakup has important advantages including implementation on relatively short notice, allowing it to be used only when needed.

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