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Framework for control of dynamic ice breakup by river regulation

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Cover: Dynamic and thermal ice breakup conditions representing extremes of river breakup behavior. The cover depicts these contrasting conditions at the same location on the White River at Hartford, Vermont. (Photo by M. Ferrick.)

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Framework for control of dynamic ice breakup by river regulation

Michael G. Ferrick and Nathan D. Mulherin

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In this report, we describe and classify the entire range of ice breakup behavior, from thermal to dynamic, to provide order to this complex process. The theory and model of the authors are refined, building on the concept of an intrinsic relationship between river waves and dynamic ice breakup. A force balance is developed for a common dynamic breakup behavior. Empirical criteria that quantify the resistance to breakup of an ice cover are obtained from a case study and compared with published values. Sensitivity studies of ice breakup with the completed model demonstrate insights that follow from the theory presented and the intuitive nature of the results. This framework for understanding river ice processes provides the option for ice management by river regulation, and we focus on the potential for control of ice breakup. The concept of controlled breakup involves a release of water from a dam that moves the ice downstream of locations with a high potential for damage during uncontrolled breakup. The abrupt, short-duration characteristics of the controlled release, patterned after those of unregulated river breakup, minimize both the volume of water required to cause breakup and the water levels at breakup. The open water created by the breakup collects heat that increases the rate of melting of the ice. The benefits of successful regulation include flooding prevention, minimum erosion, and decreased potential for ice damage to structures during breakup, without adverse effects on the environment.

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PREFACE

This report was prepared by Michael G. Ferrick, Hydrologist, and Nathan D. Mulherin, Research Physical Scientist, of the Snow and Ice Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding for this research was provided by CRREL Project 4A762730A4AL, *In-House Laboratory Independent Research,* Work Unit 495, *Development of a Predictive River Ice Breakup Capability,* and by DA Project 4A762730AT42, *Design, Construction and Operations Technology for Cold Regions,* Task CS, Work Unit 001, *Winter River Mechanics.*

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Introduction

The breakup of a strong and intact river ice cover at a high discharge is a dynamic process with the potential to cause significant damage. For example, Ferrick et al. (1988) concluded from a study of historical data that the highest water levels and greatest potential for damage to, or loss of, a historic covered bridge over the Connecticut River at Windsor, Vermont, is present during a dynamic ice breakup. When the ice movement occurs on the Connecticut River, the resulting channel blockage and increased hydraulic roughness, combined with a high discharge, can cause extreme water levels that threaten the bridge and cause flood damage in Windsor. However, the data indicate that the occurrence of large breakup events is predictable, with 10 of 12 recent large events occurring in a 2-1/2-week period in March, each following and in response to a significant rainfall.

Current methods used to mitigate the effects of dynamic ice breakup include blasting of ice jams that have already formed, channel excavations to prevent jam formation, construction of dams or ice retention structures to control the movement of the ice, and thermal discharges to melt ice prior to breakup. The thermal discharge method requires a source of warm water that may not be available, and the other methods may not be effective or environmentally acceptable. However, in regulated rivers the capability to manipulate the flow may be used to control both the ice formation and breakup processes. Donchenko (1978) observed that intensive deformation or breakup of an ice cover downstream of hydropower dams occurs in response to a rapid rise in river stage. He suggested that flow releases could be regulated to minimize ice breakup and jamming during the period of ice cover formation. The development of generally applicable ice management strategies based on river regulation requires a quantitative theory of dynamic ice breakup.

The primary contribution of this work is a quantitative description and subsequent demonstration of the fundamental relationship between unsteady flow and dynamic ice breakup. At breakup, the hydraulic forces on the ice cover vary widely in response to unsteady flow, and this variability cannot be neglected without careful consideration. The peak forces on the ice cover do not necessarily coincide with either the peak stage or the peak discharge. In this report we describe and classify the range of ice breakup behavior as completely as possible, consistent with our present understanding. Building on this description, we refine the theory and numerical model presented by Ferrick et al. (1986b) by developing a force balance for a common dynamic breakup behavior. We evaluate the effect on the ice cover of these forces with empirical breakup resistance criteria. These criteria are developed for a case study of the Connecticut River, using the model together with field data obtained during a dynamic breakup, and are compared with published values. The force balance can then be applied to analyze the collapse of a river ice cover, including relatively thin ice that occurs during the ice formation process and the formation and release of ice jams. An application of the completed model demonstrates the insights for interpretation of observations that follow from the theory presented, and the intuitive nature of these results.

This framework for understanding river ice processes provides the option for ice management by flow regulation. We focus on the potential for control of ice breakup on regulated rivers. Model sensitivity studies indicate that the ice cover response to a controlled release can vary greatly with ice thickness and breakup resistance.

Characteristics of ice breakup

River waves are long-period, shallow water waves that are a consequence of unsteady flow (Ferrick 1985). Flow releases at hydroelectric dams typically cause abrupt river waves that can delay or prevent the formation of an ice cover and cause ice jams, indicating an important role of these waves in ice behavior. The importance of river waves in the ice breakup process has been noted by several authors (Beltaos and Krishnappan 1982, Billfalk 1982, Doyle and Andres 1979, Henderson and Gerard 1981, Prowse et al. 1986, and Wong et al. 1985). It is widely recognized that ice jam formation and release initiates river waves, and that waves associated with sudden jam release cause ice breakup. The hydraulic forces on a river ice cover are related to the flow energy gradient, a parameter that can increase substantially on the front of a river wave. River ice breakup occurs when the forces on the cover exceed the resistance provided by the ice strength and points of support. With an ice sheet in place, the frictional resistance to the flow 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 waves form during a dynamic breakup from the release of water in channel storage with the rapid decrease in flow resistance as the ice breaks up.

Breakup may 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 over a period of years. Zachrisson (1988) reported widely differing breakup behavior in different years of the unregulated River Torneälven at the border between Finland and Sweden. High water levels occur when the ice is thick and breakup is preceded by rapid river stage increases, characteristics of dynamic ice breakup. The only condition common to mild breakups on this river is a slow increase in river stage before breakup, a characteristic of thermal events. Prowse et al. (1988) performed pre-breakup 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, determines the character of breakup. The development of abrupt, high-amplitude river waves during breakup requires significant runoff and competent ice cover.

The characteristics of a dynamic ice breakup depend on the mode of failure of the ice cover. Ferrick et al. (1986b) referred to support-dominated and strength-dominated breakup behaviors as of high and low energy, respectively. A failure at the supports of an ice cover produces a sudden bank-to-bank release of the ice. This support-dominated breakup travels rapidly downstream at a speed greater than the flow velocity. The breaking front is the boundary between the intact, stationary ice cover downstream and moving ice plates upstream (Fig. 1). Fractures in the ice cover at preexisting cracks appear with the initial motion, resulting in a change from a continuous cover to ice plates. The high speed of the breaking front relative to that of the ice plates prevents ice participation in the breakup downstream. The sizes of the moving plates are reduced with time due to collisions. The rubble front separates the ice plates from the brash ice, and represents a region of ice convergence that can develop a significant thickness. Finally, open water predominates behind the ice run.

We have observed an arrest of the motion of a support-dominated breaking front at locations with reduced energy gradient, and a transition to a strength-dominated breakup. The rubble front and the breaking front are coincident in a strength-dominated dynamic breakup. This breaking front initially extends across only the high velocity portion of the channel, and the ice in more sheltered locations moves somewhat later. Brash ice from upstream interacts with the leading edge and is transported under the intact cover. At the front, relatively small pieces of ice

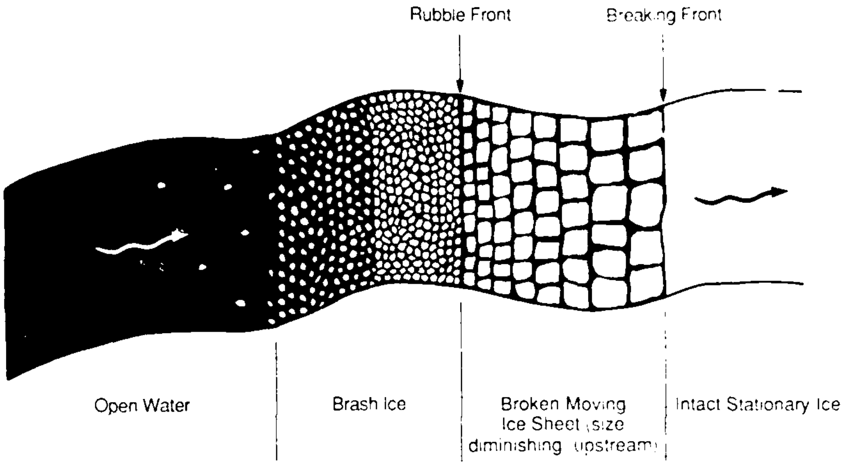

Figure 1. Overview of a support-dominated dynamic ice breakup. The breaking front travels downstream at a speed of several meters per second and is distinct from the ice rubble front. This depicts a single breaking front in a progressive breakup.

break in bending from the intact sheet. The progress of a breakup that requires the ice to fail is slower than that of a breakup characterized by support failure. Strength-dominated breakup can occur at significantly lower hydraulic forces than support-dominated breakup, and the breakup celerity is directly related to the magnitude of these forces. The breaking front speed is the velocity of the brash, indicating the importance of the interaction. If the speed of breakup is significantly lower than the river wave speed, a gradual separation develops between the wave front and the breaking front, and the moderate rate of water release from channel storage may not be sufficient to prevent wave attenuation. Both of these factors cause the hydraulic forces on the ice to diminish with time, eventually leading to a complete stall of the breaking front and the formation of an ice jam. The release of this jam initiates the next surge-stall sequence, a behavior that is characteristic of dynamic ice breakup.

The concept of *celerity matching* between the breaking front and the river wave is needed for understanding the sequencing of dynamic breakup behaviors. When these celerities are approximately equal, the hydraulic forces driving the breakup are maintained at a high level. A slowing of the breaking front relative to the wave, due to increased breakup resistance at some location, typically corresponds to a diminished force environment, and further slowing or stalling of the breakup is possible. The outcome depends on the duration of the slowing relative to the wave celerity, the displacement of the breakup from the position on the wave of the highest forces, and the magnitude of the force reduction. Sustained and rapidly moving strength-dominated breakups are possible in rivers that are steep and hydraulically rough because of the dominance of bulk waves (Ferrick 1985). The reason is that the bulk wave celerity is approximately equal to the flow velocity, and if a strength breakup has this same celerity, the matching can cause sustained movement over large distances. In mildly sloped rivers, celerity matching at the flow velocity does not occur and strength breakups at this speed are not stable.

We use the term *progressive* to indicate a dynamic breakup advance where the front of the breakup moves downstream coincident with the front of a single dominant river wave. A progressive breakup can exhibit both strength- and support-dominated failure, and surge-stall sequences. Flood water levels, scour of river banks, and damage to structures near the river are common with progressive dynamic breakups. In contrast, a *simultaneous* breakup occurs at several locations concurrently and is associated with weakened ice conditions or with hydraulic forces that are marginally adequate to produce a

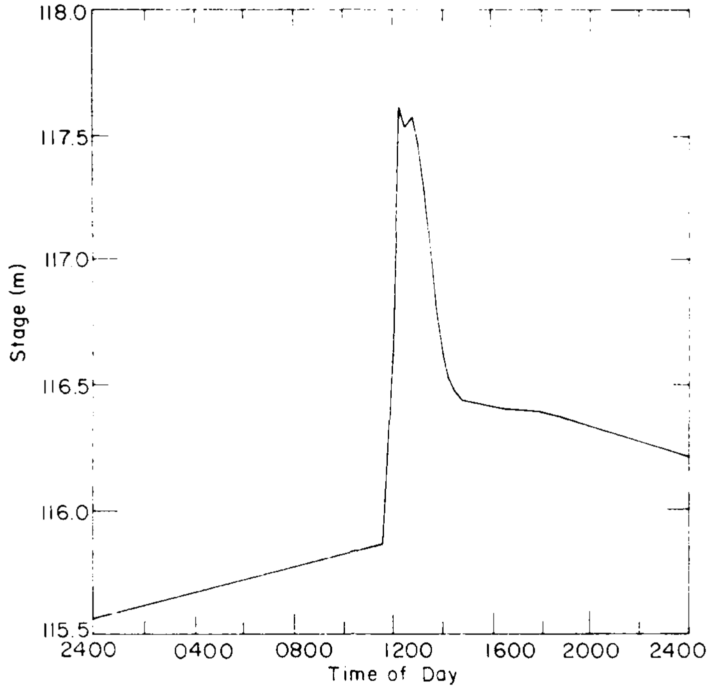

Figure 2. Stage record of a progressive ice breakup of the unregulated White River on 2 February 1988. This wave developed as a result of ice breakup upstream. The large ice forces associated with the wave front caused the breakup to move downstream with the wave.

breakup. Simultaneous breakups can be classified as thermal, dynamic, or somewhere in between, depending on the strength and thickness of the ice cover, and the amplitude and steepness of the waves associated with the breaking fronts.

A progressive breakup can be initiated in uncontrolled rivers by a simultaneous breakup in the upland portion of a basin. Sharp-fronted river waves that develop in unregulated rivers can cause a progressive dynamic breakup over great distances, with few stalls of relatively short duration. Other important characteristics of these waves are significant stage increase, short duration of the high water levels, and a large contrast in discharge between the initial and peak flow conditions. Figure 2 presents stage data from a progressive breakup on 2 February 1988 of the unregulated White River in Vermont. Ice breakup occurred at this gaging station immediately following the arrival of the wave. This record does not exhibit abrupt rises and falls characteristic of ice jamming. The sharp-fronted, high-amplitude and short-duration features of this river wave are all characteristic of a progressive ice breakup.

The characteristics of dynamic ice breakup on regulated rivers are distinct from those of uncontrolled rivers in several respects. Because of main stem and tributary storage, flow increases are more gradual during a flood than for a comparable uncontrolled river. Sharp-fronted river waves cannot form in an impoundment, and if wave formation occurs upstream or in a tributary, attenuation is rapid after reaching a pool. Without an abrupt wave front, the development of sufficient stress on the ice cover to cause breakup requires locally high water levels. Also, the flow in mainstream backwater reaches occurs at greatly reduced energy gradients, corresponding to large stress reductions and an increased ability of the ice cover to resist and slow the progress of an ice breakup. Together these factors typically prevent the formation of a single breaking front, resulting in the development of breakup segments in reaches between dams.

Theory of dynamic ice breakup

Ferrick et al. (1986b) presented a theory of dynamic ice breakup that is the basis for our analysis. Briefly, they proposed that the river flow causes hydraulic forces on the ice cover that are resisted by the ice strength and points of support. The primary hydraulic forces on the ice result from the shear stress of the flowing water and the streamwise component of the weight of the cover. A good approximation of the applied hydraulic force per unit length of ice sheet is

$$f_h = BS_f(\gamma R + \gamma_i t_i) \qquad (1)$$

where S_f = flow energy gradient
B = river width (m)
γ and γ_i = specific weights of water and ice (N/m^3), respectively
R = hydraulic radius of the channel (m)
t_i = ice thickness (m).

The applied force varies linearly with the energy gradient of the river. In low- to-moderate gradient rivers, the energy gradient can increase by 100% or more on the front of a river wave relative to the natural stream gradient. In steep, shallow rivers like the White River, the increasing gradient at the front of the wave is accompanied by large increases in the hydraulic radius, and the combined effect produces a large increase in the force on the ice cover. A positive feedback exists between river waves and ice breakup. Ice breakup generates unsteady flow, and unsteady flow increases the hydraulic forces on the stationary ice cover, potentially leading to additional breakup. A basic requirement of an analysis of dynamic breakup is the capability to quantify this interaction.

An analysis of ice breakup also requires the development of criteria that indicate the initiation of breakup. Bolotnikov (1982) developed a condition based on the theory of elasticity for the bending failure of an ice cover due to river wave movement. The equations given for both the flexural strength and the breakup resistance of the ice cover vary linearly with ice thickness, and flexural strength is the critical parameter that determines breakup resistance. We have estimated the hydraulic forces at failure of river ice covers and have found them to result in distributed stresses more than an order of magnitude below the commonly used measures of ice strength. Similarly, Beltaos (1985) calculated hydraulic forces for a Thames River breakup that were also much less than the usual measures of ice strength. We conclude that dynamic breakup occurs either as a result of a failure of the support of the cover or due to locally high forces that result from ice interaction and exceed ice strength.

The ice sheet transfers the applied forces to the banks and through points of ice grounding to the stream bed. The support provided to a river ice cover by the bed generally decreases with increasing flow depth, and the primary supports are at the banks. The hinge cracks present at the banks are continuous, and the forces on the ice must be transferred across these cracks. Prior to breakup the applied forces are in equilibrium with the reactions at every location. The primary resistance to ice motion frequently relies on crack irregularity and the interlocking along the crack that results. When two surfaces touch at a relatively small number of locations, the resistance to motion is proportional to the actual area of contact, which varies with location and is not generally known. It would be reasonable to assume that the contact area, like the surface area of the crack, increases linearly with ice thickness. Local failures of the ice at contact points are required to initiate motion. However, the stresses required to cause the failure of the support and the motion of the ice cover depend on several parameters and are currently unknown.

At locations where the geometry of the river does not permit movement along the hinge cracks or when the hydraulic forces are inadequate to cause support failure, a different dynamic breakup behavior is observed. In these ice strength-dominated cases, locally high ice forces that overcome the flexural strength of the ice are necessary for a breakup to proceed. The underturning of floating ice blocks is one of the processes of interaction between brash and an intact cover that produces these high forces. Daly (in prep.) developed a moment balance equation and found that for any given ice thickness and depth the tendency for block underturning increases with the Froude number. Local ice failure would be expected in the part of the cross section with the highest Froude number. Other ice interaction processes are expected to respond similarly to flow conditions.

The energy gradient and Froude number are closely related parameters. Both parameters vary with time during the passage of a river wave, and using Chezy's equation the relationship can be expressed as

$$S_f = \frac{V^2}{C_*^2 g \frac{Y}{k}} = \frac{F^2}{(C_*^2/k)} \tag{2}$$

where F = Froude number
C_* = dimensionless conveyance coefficient
V and Y = average velocity (m/s) and depth (m) in a cross section, respectively
g = acceleration due to gravity (m/s^2); k relates the depth and hydraulic radius of wide channels
k = 1 for open water conditions or
k = 2 if the channel is ice covered.

Ferrick et al. (1986a,b) studied a controlled ice strength-dominated breakup and noted that downstream progress occurred only during periods of high energy gradient. Therefore, we conclude that a parameterization of this breakup behavior could be expressed as a function of either the energy gradient or the Froude number.

Dynamic ice breakup model

A one-dimensional unsteady-flow hydraulic model is the basis of the ice breakup model. The open-channel flow continuity and momentum equations are solved using a Preissmann or four-point implicit finite-difference method (Cunge et al. 1980). We select a spatial and a temporal resolution, supply a geometric description of the river (bed slope, channel width, ice thickness), and calibrate the hydraulic roughness. A stationary ice cover increases the resistance to flow of the channel relative to open water. When an ice cover is present, the channel roughness parameter represents a composite of the bed and the ice, flow depth is measured from the bed to the underside of the ice, and the cross-sectional area of the channel is determined using this depth. If ice breakup occurs, the ice is assumed to move at the water velocity, and flow resistance conditions return to those of open water.

In the model, breakup is evaluated in discrete reaches that are set by the spatial resolution. The ratio of the spatial to temporal resolution is the grid celerity c_g, the minimum speed of the breakup in the model. Because of the feedback between flow dynamics and ice breakup, this ratio must be less than or equal to the breaking front speed observed in the river, c_b. Otherwise, an artificially high rate of water release from storage, as the ice breaks upstream, would cause a more extensive model breakup downstream than would occur in the river. The speed of the breaking front can be used to define a breakup Courant number C as

$$C = \frac{c_b \Delta t}{\Delta x} = \frac{c_b}{c_g}. \tag{3}$$

The breaking front speed is limited by the dynamic wave celerity $c = V + \sqrt{gY}$ at the wave front. The dynamic wave celerity appears in the usual definition of the Courant number C_r,

$$C_r = \frac{c \Delta t}{\Delta x} = \frac{c}{c_g}. \tag{4}$$

Finally, we obtain a pair of conditions from the relationships between c_g, c_b and c that govern the Courant numbers,

$$1 \le C \le C_r. \tag{5}$$

An implicit model is required in order to obtain both a stable numerical solution and the correct rate of water release from storage when the Courant numbers exceed 1. In the case of a strength-dominated breakup where $c_b << c$, eq 5 requires the use of a large C_r.

Available theory and data are not adequate to quantitatively model the failure of an ice cover during strength-dominated dynamic breakup conditions. However, data from the Connecticut River (Ferrick et al. 1988) are adequate for an initial evaluation of support-dominated breakup on that river. We compute the hydraulic forces per unit length of ice cover f_h at each model section using eq 1. A force balance written for the ice cover in the longitudinal direction yields

$$F_n \, dL = df \tag{6}$$

where F_n = $f_h - 2\tau t_i$, the difference between the applied forces and the bank reactions per unit length (N/m)
dL = length increment in the longitudinal direction (m)

df = change in the force transmitted downstream through the ice cover corresponding to the distance dL (N)

τ = stress transmitted to the bank across each shore crack (Pa)

τ_m = maximum allowable stress corresponding to failure of the ice cover support (Pa), $\tau \leq \tau_m$.

The calculation of F_n in eq 6 assumes equal reactions at both banks to balance f_h, and assumes that these forces are applied over an area of a unit length times the ice thickness. An ice cover is stable when the forces and reactions are in balance and $F_n = 0$. As the hydraulic forces on the ice increase, τ reaches an upper limit and F_n becomes positive, indicating increasing forces with distance downstream. Continued ice cover stability requires additional support to counteract the local force imbalance. Ice breakup at a model section occurs when τ exceeds τ_m, an empirically determined failure condition that characterizes the breakup resistance of a given river reach. The capability to model ice breakup in regulated rivers presents several options for ice management, including control of breakup by flow regulation. The remainder of this discussion develops a case study of controlled breakup on the Connecticut River.

Control of Connecticut River ice breakup

The flow of the Connecticut River in our study reach (Fig. 3) is controlled by Wilder Dam upstream and Bellows Falls Dam downstream. The Connecticut River is free-flowing downstream of Wilder Dam, with an average bed slope of 0.00037. At an average discharge of 200 m^3/s the Connecticut River varies between 100 and 200 m in width and has a mean depth range between 1.5 and 3.0 m. The uncontrolled White River is the primary tributary in the reach, entering about 2 km downstream of the dam. The location of the head of the Bellows Falls pool varies with the headwater elevation at the dam and the ice conditions, but it is generally near data station 2 at Windsor. As Wilder Dam does not generally pass large quantities of ice, the White River is the only significant ice source at breakup external to the study reach area. Because of large hourly fluctuations in the flow release at Wilder Dam, the 14-km reach between the dam and station 1 is largely free of stable ice cover. However, a short sinuous reach near the confluence with the Mascoma River generally develops a stable ice cover that is resistant to breakup. A continuous stable ice cover occurs in the 54-km reach between station 1 and Bellows Falls Dam.

In extreme dynamic breakup events the White River rises abruptly to a high peak and deposits large quantities of ice in the Connecticut. Meanwhile, the ice on the Connecticut River is competent and intact, and the combined discharge continues to increase rapidly toward a peak daily average flow in excess of 1200 m^3/s. Under these conditions the river is out of control and the probability of bridge damage or loss and flooding at Windsor is high. The river regulation concept applied to the Connecticut River involves an abrupt flow release from Wilder Dam, patterned after the breakup behavior of unregulated rivers, with a minimum initial flow and a minimum Bellows Falls pool elevation. If the release has a sufficient peak discharge and duration, the ice cover in the reach upstream of station 3 will break up. These controlled conditions, put into effect days in advance of the White River ice release and uncontrolled flows, ensure that minimum volumes of ice and water are involved in the breakup, minimizing the potential for ice and related flood damage. The open water created by the late winter or early spring breakup then becomes a heat source that collects and delivers heat to rapidly melt the ice accumulation downstream of station 2. This method of controlled ice breakup would not produce ice breaking forces farther downstream because of wave attenuation in the Bellows Falls pool.

The Connecticut River regulation required to control ice breakup in this reach includes the 93.3-km reach between McIndoe Falls Dam upstream and Wilder Dam, and the 68.2-km reach between Wilder Dam and Bellows Falls Dam. Regulation of the river above Wilder Dam is necessary because the available storage in the reservoir is inadequate to produce a controlled breakup of the study reach. A temporal resolution of 0.5 hr was used in all simulations, and the uniform spatial resolutions used were 3220 m between McIndoe Falls and Wilder dams, and 2440 m between Wilder and Bellows Falls dams. The relatively fine spatial resolution below Wilder Dam yields a grid celerity of half the observed speed of breakup. Calibration of hydraulic roughness of the McIndoe Falls–Wilder segment of the model was achieved by comparison with steady-flow water surface profile data. The Wilder–Bellows Falls model segment was cali-

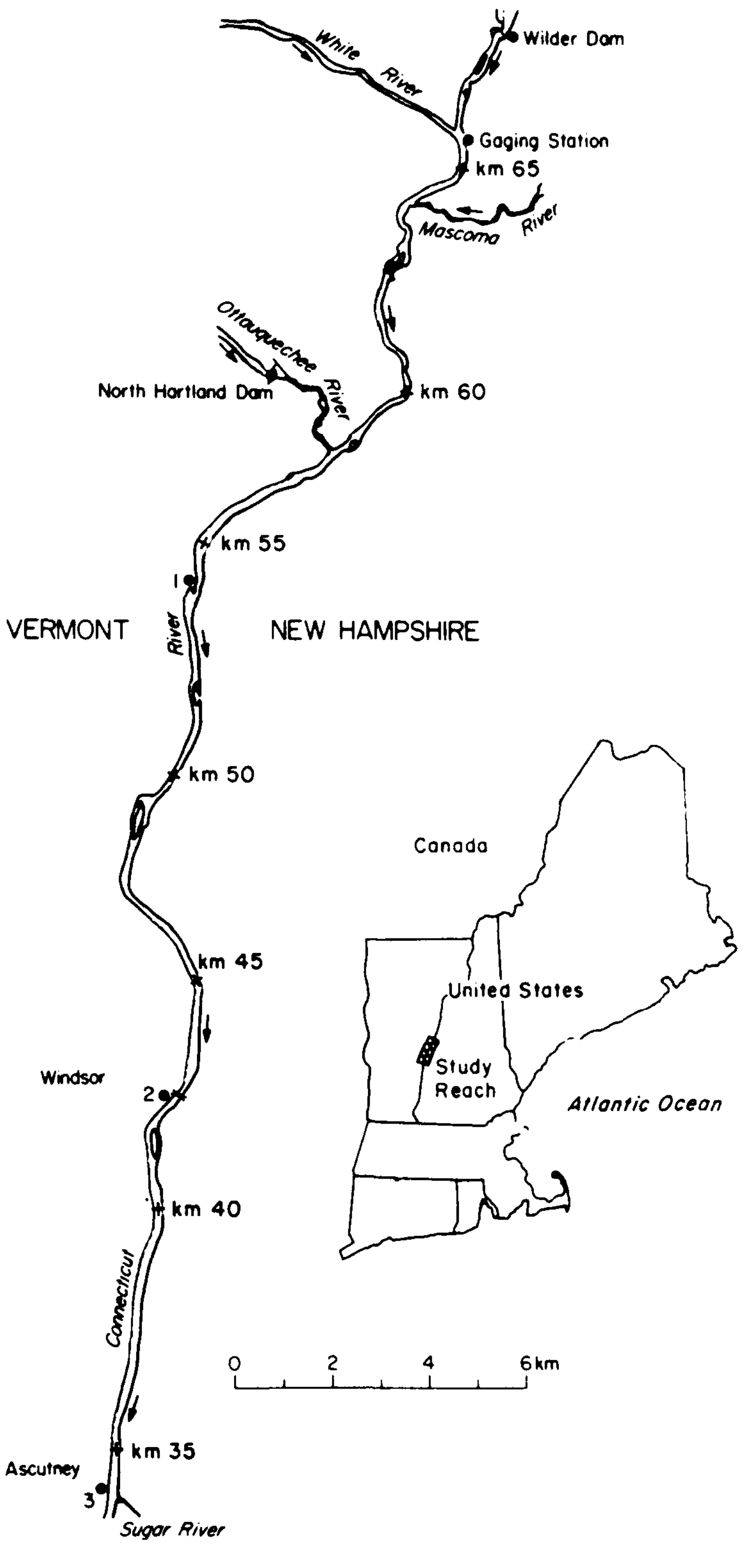

Figure 3. This reach of the Connecticut River is the focus of the ice breakup study, although a significantly longer reach is considered in the model simulations. Data collection stations 1, 2, and 3 are indicated, and the kilometer points measure distance upstream of Bellows Falls Dam. The location of the primary damages at ice breakup is near station 2.

brated with data from the open-water and ice-covered unsteady flow test conditions reported by Ferrick et al. (1988).

Development of empirical breakup criteria

The rapidly moving support-dominated dynamic ice breakup depicted in Figure 1 accurately represents the behavior of the Connecticut River in the study reach. Because a theory that describes the support failure of a river ice cover is not available, we sought empirical failure criteria. The approach taken was to apply the model to simulate the dynamic ice breakup of 27 January 1986 reported by Ferrick et al. (1988). The river flow conditions were known at the dams and for the primary tributaries, and the ice breakup behavior was observed. Ice thickness data prior to breakup were not available, and uniform thickness was assumed. The thicknesses of ice blocks observed at station 2 were about 0.3 m. Because the breakup occurred in midwinter, the ice was extremely hard and characterized by instantaneous 100-m-long fractures resulting from collisions between large ice floes and a blunt bridge pier.

The failure condition at each section in the model was adjusted, and the modeled breakup wave amplitude and subsidence, breaking front progression and speed, and ice jam location were compared with observations. The basic character of the observed breakup was reproduced by the model, with breakup stresses on each hinge crack exceeding 1.68 kPa at most locations and 1.87 kPa in more resistant reaches. An increased resistance to breakup may have been caused by greater ice thickness in reaches typically subjected to larger hydraulic forces. These stress criteria are a measure of ice resistance to breakup. We assigned the stress criteria of this initial simulation an ice resistance of 1.0. The results of this simulation compared with field data in Table 1 indicate good agreement except for the breakup celerity. Pariset et al. (1966) developed a dimensionless stability diagram for granular river ice covers. Their results, guided significantly by data, indicate that the value of the dimensionless parameter $X = (B/Yk)S_f$ must be less than 2.8×10^{-3} for an ice cover to resist breakup at any ice thickness to depth ratio. Consistent with intuition, the 1.0 resistance case has $X = 7.4\times10^{-3}$ at station 2 immediately prior to breakup, representing a significantly greater resistance to movement than exhibited by granular ice covers.

These celerity and stability data imply that the specified 1.0 breakup stress criteria may be somewhat high. Therefore, the breakup stress and ice thickness were varied for the same flow conditions to both improve the breakup celerity agreement and determine the sensitivity of the simulation to these parameters. The 0.9 and 0.8 ice resistance values listed in Table 1 indicate 10% and 20% uniform reductions in the stress required at breakup. A reduction of either ice resistance or ice thickness causes an increased breakup celerity. Of those attempted, the 0.9 resistance, 0.30-m thickness case yields the best agreement with the available data. The base flow

Table 1. Comparison of observed and simulated characteristics of Connecticut River ice breakup near station 2 on 27 January 1986. Wave amplitude and subsidence are based on river stage 1 hr prior to and 1 hr after the peak at breakup, respectively. The mean energy gradient S_f and the mean stress at breakup were determined for model sections between stations 1 and 2. Ice jam location is the distance above Bellows Falls Dam.

Case (ice resistance, ice thickness) (m)	*Wave amplitude (m)*	*Wave subsidence (m)*	*Average celerity of breakup (m/s)*	*Mean S_f ($\times 10^3$)*	*Mean breakup stress (kPa)*	*Ice jam location (km)*	*Breakup character*
Field data	0.3	0.3	2.7			40.0	Progressive
1.0, 0.30	0.33	0.26	1.35	0.399	1.80	39.0	Progressive
1.0, 0.23	0.16	0.52		0.362	1.98	17.0	Simultaneous
0.9, 0.30	0.27	0.19	2.71	0.377	1.64	39.0	Progressive
0. 8, 0.30	0.16	0.09		0.362	1.54	26.8	Simultaneous

in the river exceeded 610 m^3/s in the study reach prior to breakup. The modeled peak breakup discharge at station 2 averaged 860 m^3/s with only minor variations between the simulations, a significant increase in discharge considering the small increase in river stage (Table 1). The breakup in the reach upstream of km 39.0 of the 0.30-m ice thickness occurred at an increased average stress with increasing ice resistance conditions. In this reach the mean energy gradient at breakup also increased with ice resistance, marginally exceeding the mean stream bed gradient of 0.00036 by up to 11%. Without high gradients, eq 1 indicates that large flow depths and high river stage must occur to produce the high forces needed for a dynamic breakup, and very high water was observed.

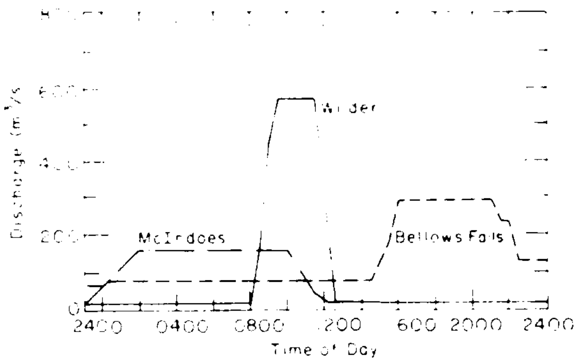

Figure 4. Example release hydrographs of Connecticut River dams for a controlled ice breakup experiment.

Design of controlled ice breakup experiment

The design of the Connecticut River ice breakup experiment had to satisfy several constraints. The regulated flows must comply with environmental regulations on the operation of the river system. Pool fluctuations required by the test are confined to the ranges of normal operation, and minimum flow releases are maintained. The loss of hydroelectric power production and other effects on normal river operations are minimized if the water requirements of the breakup are small. Together, these considerations require that the hydraulic forces are sufficient to cause breakup at a significantly lower river stage and smaller total water volume than occur in major natural events. The flood control and ice damage control objectives are ensured by the small volume of the release and by excluding the ice upstream and in the White River from participating in the breakup. Excluding the ice contributions from the tributaries places a constraint on the timing of the regulation. The need to prevent additional ice formation following the breakup requires a net heat flux into the river, and places an additional constraint on timing.

Our design of a controlled ice breakup on a regulated river simulates the behavior of an unregulated river. An abrupt and relatively large short-duration increase in flow provides a contrasting condition to a low-flow initial state and produces large forces on the ice cover. Proposed ice breakup flow releases at the three Connecticut River dams are given in Figure 4; Wilder is the only dam with scheduled releases that exceed turbine capacity. The water level in the Wilder impoundment must initially be near the top of its operating range to provide the capacity to supply the release. The release from McIndoe Falls Dam is timed with the Wilder release to maintain the Wilder pool in its normal operating range, slow the drawdown near the dam, and keep the segment of the impoundment experiencing rapid drawdown to a minimum. The Bellows Falls headwater elevation is set initially at the bottom of its operating range to move the head of the impoundment downstream, increasing the forces attainable downstream of station 2 and the extent of the breakup. The turbine capacity at Bellows Falls Dam is sufficient to maintain that elevation with only minor variations. Storage dams on a pair of tributaries above (Ompompanoosuc River) and below (Ottauquechee River) Wilder Dam are operated to minimize drawdown and enhance the breakup, respectively.

The controlled breakup of Connecticut River ice of any thickness and resistance is possible with a sufficient release volume. However, the usable volume severely limits the release and causes an uncertain outcome that is dependent on the properties of the ice cover. A sequence of design simulations were run for the Figure 4 flow releases with a range of ice thickness and resistance parameters. In all cases, based on observation in past winters, ice covers were assumed to be present in a 2.4-km reach below the White River confluence and from station 1 continuously to Bellows Falls Dam. A summary of important characteristics of these simulations is presented in Table 2. As a measure of conservatism the breakup ice stress of the resistant sections in the 1.0 resistance case was increased to

Table 2. Design simulations of Connecticut River ice breakup. Wave amplitude and peak discharge are at station 2. Average breakup celerity, energy gradient S_f, and breakup stress were determined for model sections between stations 1 and 2. Ice accumulation location is the distance above Bellows Falls Dam.

Case (ice resistance, ice thickness) (m)	*Peak discharge (m^3/s)*	*Wave amplitude (m)*	*Average celerity of breakup (or peak stress) (m/s)*	*Mean breakup or peak S_f ($\times 10^{3}$)*	*Mean breakup or peak stress (Pa)*	*Ice accumulation location (km)*	*Breakup character*
1.0,0.21	725	1.84	2.26	0.713	2.69	26.8	Progressive
1.0,0.30	761	2.01	1.80	0.676	2.11	34.1	Progressive
1.0,0.40	501	1.97	(2.26)	0.577	1.50		Non-breakup
0.9,0.30	746	2.04	1.80	0.717	2.11	26.8	Progressive
0.9,0.34	746	2.04	1.80	0.717	1.92	34.1	Progressive
0.9,0.36	741	1.97		0.600	1.81	31.7	Simultaneous
0.9,0.40	501	1.97	(2.26)	0.577	1.50		Non-breakup
0.8,0.40	746	2.04	1.80	0.717	1.73	34.1	Progressive
0.8,0.46	501	1.97	(2.26)	0.577	1.35	—	Non-breakup

2.01 kPa. The standard ice stress criterion of 1.68 kPa for this case was retained from the January 1986 results. As before, the 0.9 and 0.8 resistance parameters correspond to multipliers that reduce the breakup ice stress at each section in the model.

The simulation results indicated that ice breakup would occur only between Wilder Dam and the location given in Table 2. An ice breakup above Wilder was not predicted in any of these cases. The computed peak flow velocity, depth and discharge at all locations in the reach were less than or equal to those that occurred in the January 1986 breakup, a relatively small event in the historical record (Ferrick et al. 1988). The wave amplitude at station 2 was nearly the same for all cases. However, there was a large difference in peak discharge between the progressive breakup and non-breakup cases. The resistance of the ice cover to breakup for a given case is characterized by the product of the resistance parameter and the ice thickness, corresponding to an applied hydraulic force per unit length. The 0.21-m ice thickness case was the least resistant to breakup, with an average breakup celerity between stations 1 and 2 that was equal to the celerity of the peak stress in the non-breakup cases. The average celerity of the other progressive breakups was 1.8 m/s in each case. The simultaneous breakup was the most resistant case in which breakup occurred, and represents a borderline condition between the breakup and non-breakup regimes. This case exhibited late and concurrent breakup at several locations. The average of the peak energy gradients at model sections between stations 1 and 2 was much larger in all of these design simulations than in the January 1986 breakup (Tables 1 and 2). These high gradients provide the high stresses on the ice sheet at the relatively low river stages required in a controlled breakup. The progressive breakup gradients were significantly larger and the simultaneous breakup gradients marginally larger than the non-breakup gradients.

The flow data are identical for the cases that did not generate an ice breakup. The breakup cases exhibit minor differences in stage-time and discharge-time response, with the simultaneous breakup case the most distinctive of the group. The progressive breakup and non-breakup cases, compared in Figure 5, reveal several important differences that result from the interaction of the ice breakup and the river wave. Without ice breakup, the wave amplitude, the peak dis-

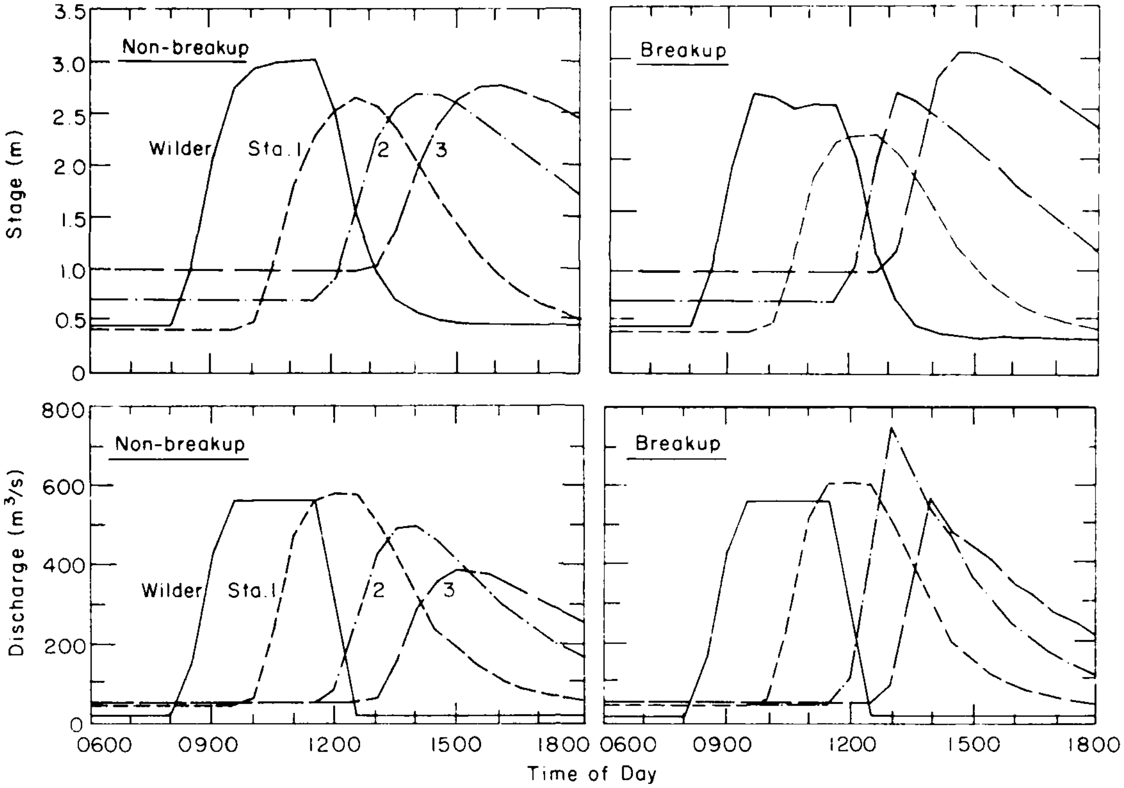

Figure 5. Comparison of computed stage and discharge during ice breakup and non-breakup simulations at four locations below Wilder Dam.

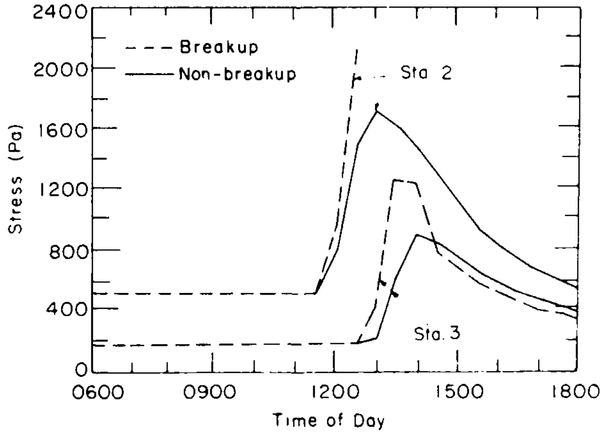

Figure 6. Comparison of hinge crack stresses on a 0.4-m-thick ice cover at stations 2 and 3. All conditions of these two cases are identical except for a reduction in the resistance of the supports that allowed the breakup. In this case the breakup progressed downstream beyond station 2 before stalling about a kilometer upstream of station 3.

charge and the rates of stage and discharge increase on the wave front all diminish with distance downstream, demonstrating significant attenuation of a large and abrupt river wave in 20 to 30 km. In contrast, ice breakup increases the wave amplitude at stations 2 and 3, and creates more peaked hydrographs that have a higher or only marginally reduced maximum discharge relative to upstream locations. The stage and discharge increases on the wave front have a much higher rate and occur earlier at these stations as a result of ice breakup. All of these tendencies emphasize the importance of the release of water from channel storage during breakup to counteract wave attenuation.

Hinge crack stresses at stations 2 and 3 are compared in Figure 6 for a breakup case and a non-breakup case. All conditions of these cases are identical except for a reduction in the resistance of the ice cover supports that allowed the breakup. At the lower resistance the ice cover at station 2 breaks up, but the breakup stalls just over a kilometer upstream of station 3. In both cases the peak stress at each station occurred about 0.5 hr prior to the peak discharge and about 1 hr prior to the peak stage. The breakup causes the stresses at both stations to increase earlier and attain significantly, higher peak values than without breakup. The short duration of the high stress condition caused by the short-duration release and the rapid attenuation of the peak stress immediately downstream of the stall prevent the formation of a significant ice jam.

Conclusions

River ice breakup is complex, exhibiting wide variations in behavior from a thermal breakup at low forces, resulting from a large decrease in ice strength, to a dynamic breakup of thick and competent ice at very high forces. The mode of failure of an ice cover in a dynamic breakup is determined by geometric and hydraulic conditions, varying between strength-dominated and support-dominated failure at different locations in a river. Support-failure, strength-failure, and ice jamming represent a continuum of dynamic ice breakup behavior. These processes typically occur in sequence, giving dynamic breakup a surge-stall character. The development of abrupt, high-amplitude river waves during a breakup on an unregulated river requires significant runoff and competent ice cover. Regulated rivers respond differently at breakup than unregulated rivers because the control structures change both the hydraulic conditions and the ice conditions.

The fundamental component of the theory presented is the intrinsic relationship between unsteady flow and ice breakup for dynamic breakup conditions with a rapidly moving breaking front. A dynamic ice breakup model that treats support-dominated failure was developed and applied to the Connecticut River. Data from a dynamic breakup were used to obtain empirical criteria for the failure of the support of the ice cover. The relationship between river waves and ice breakup was observed in field data from the White River and was demonstrated in the model simulations of the Connecticut River. The simulations also indicate that the breakup response of a river changes from progressive to simultaneous and then to non-breakup conditions for the same initial wave by increasing the ice thickness or breakup resistance. These results identify the need for an in-situ index test of ice cover resistance. Further refinement and verification of our theory of ice breakup would be achieved most readily by conducting controlled breakup field experiments. A high spatial density of stage-time records and ice observations with known boundary conditions are needed for several cases to adequately characterize both strength-dominated and support-dominated dynamic breakups.

Our theory of dynamic breakup provides the framework for implementing controlled breakup and minimizing potential ice-related damages on regulated rivers. Control of ice breakup by river regulation uses existing dams, requires a relatively small volume of water, and is environmentally sound. The concept is to remove the ice cover from upstream of locations with a high damage potential during breakup, and to enhance the rate of melting of the ice. The rapid stage increase and short-duration characteristics of a controlled breakup are patterned after those of unregulated rivers. Because of the short duration of the release, the ice forces at the downstream extent of the breakup rapidly diminish, preventing the formation of a significant ice jam. The involvement of a limited ice volume and the low initial river stage and discharge distinguish this event from uncontrolled breakup events on regulated rivers. Once developed for a river system, controlled ice breakup can be implemented on relatively short notice and only when needed.

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