III-B1a

BLTERM

COLD REGIONS
SCIENCE AND ENGINEERING
Monograph III-B1a

WINTER REGIME OF RIVERS AND LAKES

Bernard Michel

April 1971

DA PROJECT 4A062112A894

CORPS OF ENGINEERS, U.S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

BREAKUP

Introduction

Ice breakup on rivers usually happens very quickly, mainly at night, and it is practically impossible to make measurements on the fast-moving water and ice. Because of this it is among the least known natural ice phenomena.

Breakup is characterized by the formation of ice jams, and numerous icy floods have been recorded. Some of these were severe; for example, the Yukon River rose 65 ft in the spring of 1930 to flood the village of Ruby.[50] Water-level rises of more than 20 ft are common when an ice jam is formed.

What is more difficult to visualize, in a river breakup, is that two processes are happening at completely different rates. One is the slow process of weakening and fracturing of the ice cover along the river course and the other is the general movement of the ice cover breaking up into ice floes in a short period of time from the source to the mouth of the river.

The equivalent processes in a lake are the gradual melting and weakening of the ice cover and the sudden breaking up, movement and accumulation of the ice remnants on the shore, caused by the wind.

River breakup

The breakup of a river has been well described.[29] It is divided into three phases, although one or two of them may not fully occur in particular cases. These phases are the pre-breakup period, the drive, and the wash.

Pre-breakup period. This period begins with the start of runoff on the watershed when solar radiation begins to melt the snow cover, even before the average daily air temperature has exceeded 32°F. The discharge of the river starts to increase, putting the ice cover under uplift pressure. With increasing discharge, the ice cover fractures at various points. In the case of a reach of low-velocity flow, this break occurs along both shores. The central part of the cover floats freely but the water floods the remaining bands of shore ice (Fig. 68). In areas of higher flow velocity, the ice cover, or parts of it, is usually attached to numerous boulders in the riverbed. The water goes up and floods most of the ice cover through numerous checker-patterned uplift cracks. Water then starts to flow on the ice itself, the snow cover quickly melts and a few pieces of fractured ice may succeed in detaching themselves and moving downstream on the remaining ice cover.

As the discharge increases, and principally because of repeated small daily flood waves,[29] the ice pieces detach themselves in the sections of rapids and accumulate at the upstream end of the stronger floating ice sheet of the low-velocity reaches. In tributaries, the daily flood wave is more important than in the main river, and the ice moves down earlier to form accumulations in front of the solid parts of the ice cover of the main river course. These first smaller accumulations, with their supporting ice covers, may be called ice-reaches. A typical ice condition at the end of the pre-breakup period is shown in Figure 69a.

Figure 68. *Water, shore ice and rapids.*

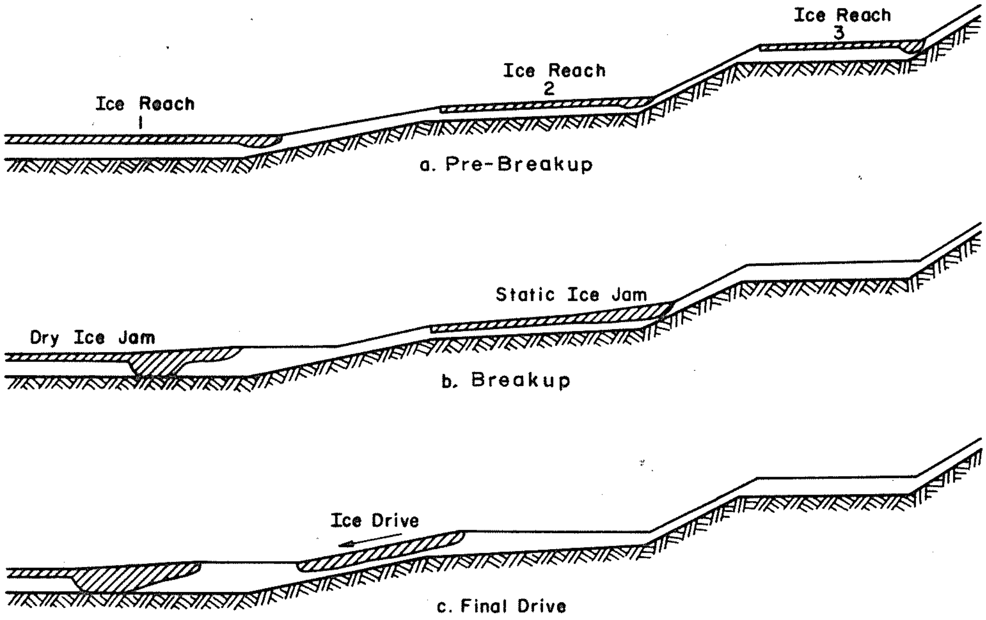


Figure 69. *Typical breakup on a river stretch.*

The drive. The causative mechanism of these first ice-reaches is essentially a mechanical process of destruction by the action of hydrodynamic forces acting on the ice cover. At the end of this first phase, the ice cover in zones of low-velocity flow is still amply strong and well preserved from melting by solar radiations because of the snow cover or the snow-ice surfaces on top of it.

The next movement of the ice cover depends on the possible combinations of river discharge and strength of the ice sheet. Let us first suppose, as an extreme case, that there is little snow on the watershed, that it melts slowly and that there is no precipitation during the melt period. The river discharge will not increase sensibly, so it will not develop strong forces on the solid ice sheet of an ice-reach and the ice will slowly disintegrate in place until it becomes weak enough to be gently pushed through by the water. No appreciable drive will occur.

But let us now look at the opposite case, much closer to what usually occurs at breakup. There is rain or intensive melt on the watershed, the discharge increases considerably and the tangential friction forces of water under the ice-reach become high enough for it to become unstable. The frontal accumulation breaks through the ice sheet and one complete reach is destroyed and moves downstream (Fig. 69 b).

This moving ice pack then gets to the following ice-reach downstream, which may not have moved at the same time. The ice accumulates in front of this stable reach and a jam of unconsolidated ice floes forms at its upstream end. Depending on the site and the discharge conditions, this jam may be stable enough to stay in place. Ice jams may form at various sites along the river with increasing discharge, each jam being stopped by a more resistant jam priming site, in a lower reach.

Finally, with ever-increasing discharge and the ice cover weakening by thermal effects, one of the bigger jams gives way and its impact carries all others along its course, freeing the river of ice in a matter of hours (Fig. 69 c). This general ice movement makes a grinding noise that can be heard well in advance of its coming. The ice accumulation moving down pushes on the parts of the ice cover that are still solid and breaks them into very large floes, which are rammed on the banks with a tremendous force[155] to form heaps of ice. Some of these floes are projected into the air, then fall back and break. As they move downstream the floes are continually rotated, overridden, underridden, turned over, and broken up by impact with adjacent ones. Between the floes are smaller blocks and accumulations of remaining snow or frazil slush.

Because most river breakups occur when there is still a strong ice cover, the determining factor is usually the river discharge. The advent of rain while the runoff is rapid because of frozen ground is a major factor affecting a general ice breakup.

The wash. After the breakup, vertical walls of ice of smooth, masonry-like form are left along the shore (Fig. 70). They attest to the shearing action of the ice pack and the maximum levels attained by the ice. Experience shows[29] that, after the drive, the spring flood comes and cleans the ice floes left over on the banks and bordering lowlands.

Figure 70. Sheared ice walls.

Lake breakup

The melting and breakup of lake ice has been well studied and we will repeat here the accurate description of them by G.P. Williams.[153]

The ice first starts to melt on the shore because it is thinner there and because more heat comes from the adjoining ground surface. A free water surface appears along the shoreline leaving the main body of ice floating free. At that time the ice cover still has considerable strength.

Williams[153] states: "During the second stage of melting there is melt of the snow and of the snow ice on the floating ice. The melt water flows along drainage patterns on the surface and it drains to the open water at the shore-line or to holes that appear to develop preferentially along old thermal cracks. When the melt water drains away, the surface has a porous, white and crumbly structure which reflects solar radiation and retards internal melting. As the melt season progresses some melt water accumulates beneath the ice surface. A typical ice-cover profile will then consist of a shallow, porous surface layer 2 to 3 inches thick, a layer of water-logged ice several inches thick and then solid unmelted ice extending to the water.

"In the final stages, the underlying entrapped water layers result in darkened surface ice and most of the incoming solar radiation is absorbed."

Figure 71 shows large patches of this darkened ice. "When the ice cover reaches this advanced stage of melt it is ripe for breaking by wind and currents and is unsafe for over-ice transportation. The currents created by strong winds will break up the ice cover and induce circulation that brings the warmer subsurface water to the ice. This can cause rapid weakening and melting and indeed, the final disappearance of ice covers has occurred so quickly at times that early observers believed the ice actually sank.[14]

Figure 71. Dark ice on a lake.

Forecasting

From the description of the breakup that has just been given it is clear that no general method can predict these phenomena because, contrary to freeze-up, they depend only partly on the heat exchange with the atmosphere.

To illustrate the fact that the mechanical breaking of ice in rivers and lakes by wind and currents is sometimes more important than its melting, the breakup records for several lakes, rivers and salt water harbors in Canada were analyzed by Williams[150] (Fig. 72): "The number of days from the time the ice thickness was last measured, in the spring, to the time it was completely cleared was related to the total ice thickness at the time of the last measurement. The comparison shows the great variation in the rate at which ice disappears from different bodies of water. The lower limit, where the ice melt is due entirely to the heat from the atmosphere, is about 1 in./day. This is less than one tenth the upper limit where the ice is cleared from a river or harbour largely by wind and current effects."

Except for sheltered lakes where atmospheric heat exchanges are dominant[150] the prediction of breakup in rivers and lakes may be attempted only with a multiple correlation analysis of precipitation, wind and heat exchange.

As for freeze-up, however, it is also possible to determine the average date of breakup for various regions and prepare a map of isopleths of breakup dates. This was done for Canada[20] (Fig. 73). Because there is a considerable difference in time, when the comparison is made between rivers and lakes in the same area, it was found more convenient to take only the date of a break in ice along the shore in the case of a lake. Indeed this depends very much on heat exchange conditions only.

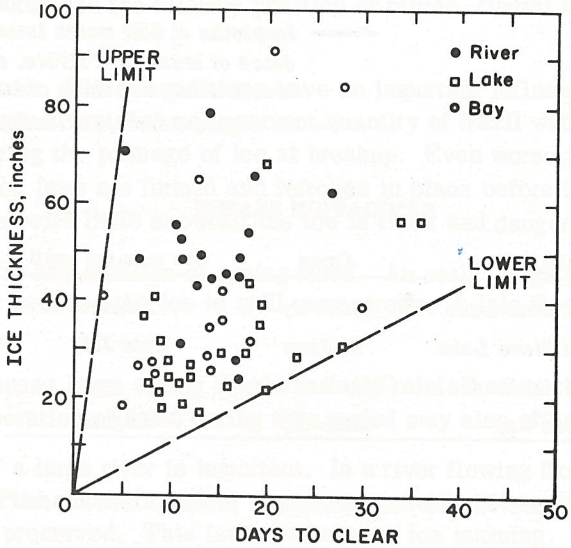
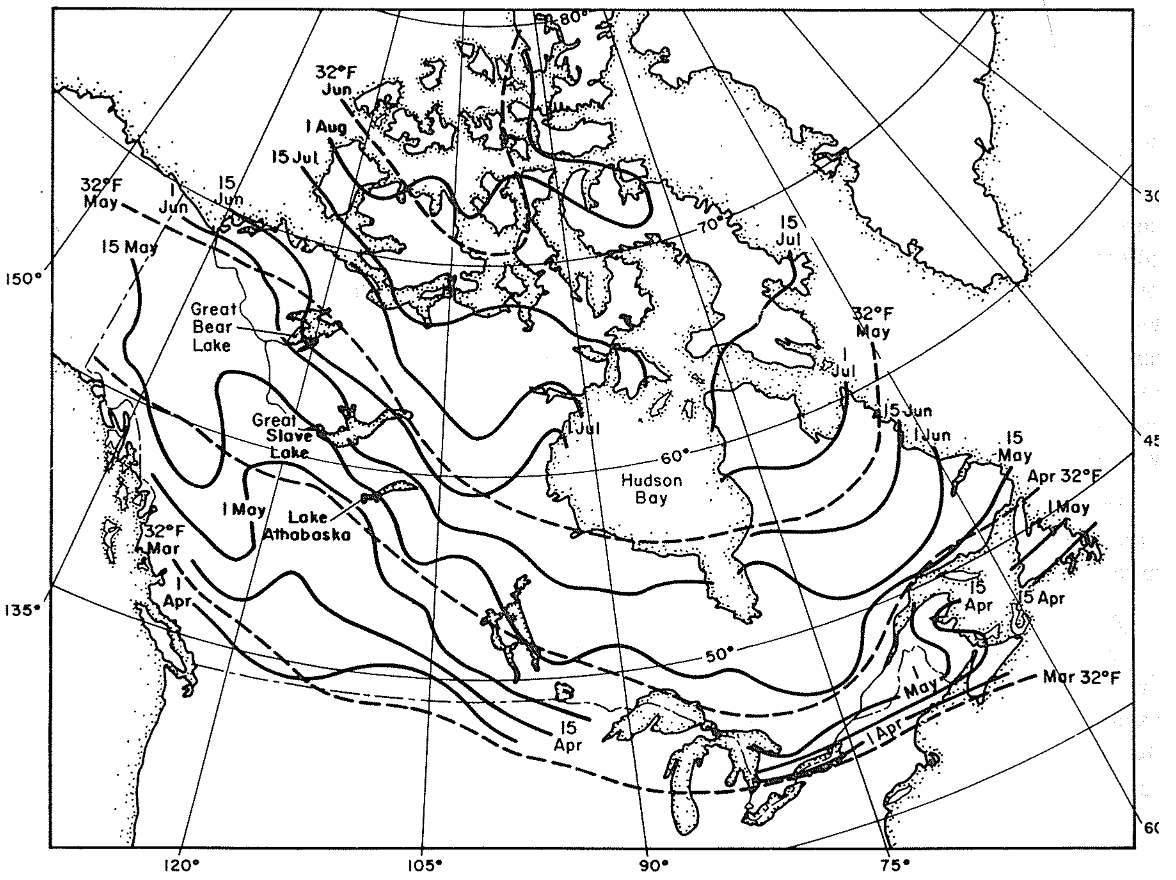


Figure 72. Number of days for ice to disappear and ice thickness at time of last measurement. [150]



— Isopleths at half month intervals give the average dates of breakup of rivers, and the appearance of breaks along the shore of lakes.

— — — 32 degree Fahrenheit isotherm for month shown.

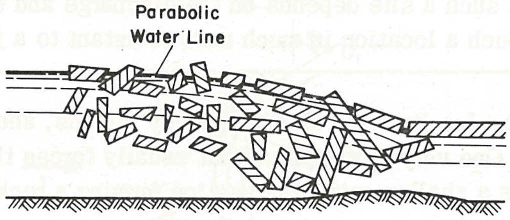
NAVIGATION SEASON

Lake or bay	Open	Ice remains until
Great Bear Lake	*Mid July*	*August*
Great Slave Lake	*15 June*	*Late July*
Lake Athabaska	*1st wk. June*	
Hudson Bay	*Mid July*	*August*

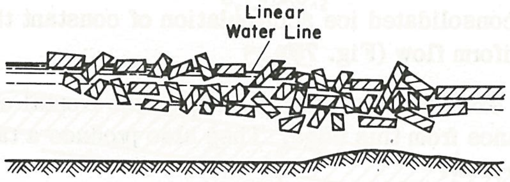
Figure 73. Average dates of breakup in Canada.[20]

Factors affecting ice jams

There are essentially two types of ice jam[29] that can form on a river stretch: the simple ice jam and the dry ice jam (Fig. 74). The simple ice jam is caused by the regular accumulation of ice floes in front of a solid ice cover. It is of uniform shape and the water flows freely underneath the accumulation. It is stable in a static manner, and produces a regular increase in water level along its length. It is destroyed by an increase in river discharge or by the impact of furth oncoming ice floes. This type of ice jam occurs frequently. It is accessible to computation and prediction.



a. Dry Ice Jam



b. Simple Ice Jam

Figure 74. Types of ice jams.

A dry ice jam is formed by the jamming of ice floes at an obstacle which may be an existing ice accumulation or bed irregularity. The ice completely blocks the whole flow section down to the river bottom. The water has to flow by infiltration through the ice plug and its level increases rapidly upstream. The jam is essentially unstable and it will go out when the upstream water level increases sufficiently. It is practically unpredictable.

The main factors affecting the formation of ice jams are the previous winter conditions, the water discharge at breakup and the relative position of rapids, fluvial transitions or other hydraulic features.

Winter ice conditions. Winter conditions have an important influence on breakup.[67] Ice formation may happen in such a way that an important quantity of frazil will be formed and deposited under the cover, hindering the passage of ice at breakup. Even worse is the case of a winter breakup when partial ice jams are formed and refrozen in place before the real breakup occurs. In a long, very cold winter with little snowfall the ice is thick and dangerous at breakup time.

Precocity, intensity and duration of spring flood. An early, large spring flood will cause the highest jams in a river because the ice is still very strong. A late flood will more easily move the decayed ice sheet.

One factor that causes large spring floods is early rainfall when there is a quick runoff on frozen ground. The operation of dams during that period may also affect ice jams.

The orientation of a large river is important. In a river flowing from south to north, the flood coming from melting in the southern part of the watershed will get to the northern area where the ice cover is still well preserved. This favors extensive ice jamming.

The torrential-fluvial transition. The hydraulic feature most likely to give rise to an ice jam is the upstream end of a fluvial flow reach at the foot of a rapid. At such a section the downstream ice cover is usually strong, with shore leads only, and resistant to ice thrust. Furthermore, there is often an underwater frazil accumulation increasing the resistance of the cover. The broken-up ice floes can accumulate to considerable length and depth in the low velocity area until the head created by the water flow is adequate to shear through and move the pack ice. The importance of a jam that can be formed at such a site depends on the discharge and the total quantity of ice can be fed to that point. Such a location is much more resistant to a jam if the channel is al crooked.

Hydraulic singularities. Ice jams are also caused by islands, shoals, narrows, sharp ber bridge piers or abutments. One very likely place that usually forces the ice pack to become g ed and form a dry ice jam is a shallow widening section forming a rocky ridge at the end of a river pool.

Stability of an idealized ice jam

Let us consider an unconsolidated ice accumulation of constant thickness h in a rectang channel of width B with uniform flow (Fig. 75).

The flow and the wind exert a hydrodynamic force on the frontal edge of the cover of p_0 l unit width, at a short distance from this edge. They also produce a tangential force τ per uni area in the direction of the flow.

The problem of the distribution of the stresses in such an ice accumulation is then simil to the one of a two-dimensional grain elevator with a top load.[28,85,92] Both materials are grar where the unit force τ takes the place of the weight of the grain. The stress distribution in a elevator has been studied for a long time. A theory that verifies well the measurements is th of Caquot,[21] which assumes that part of the total thrust is transmitted to the edges by an arcl action of the material. Because of the constant loading, this system consists of parabolic ar that correspond to the directions of the principal stresses in the material.

If we consider an element of this system limited by axial planes (Fig. 75), one of the pri stresses is σ_{n1}, which is a constant all along the arch, and the other is the normal stress σ_y the y direction. From considerations of the conjugate stress relationships at equilibrium in g ular media we have for "filling" conditions:

$$\sigma_{n2} = K_\alpha \; \sigma_x \qquad (90$$

where $K_\alpha = \tan^2 (45° - \alpha/2)$ is the coefficient of active thrust for an element of obliquity α. limiting condition of equilibrium will be attained for the highest value of α at the wall, where $\alpha = \psi$, ψ being the angle of friction of the material with the wall. We then have:

$$\sigma_r = \sigma_{n1} \cos\psi \, K_\psi \; . \qquad (91$$

It is now possible to write the equation of equilibrium along the x axis for an arch eleme of the system:

$$\tau \; B \; dx - d\sigma_{n1} \; Bh - 2 \; \sigma_r \; \sin\psi \; hdx = 0 \quad . \qquad (92$$

With eq 2, this gives

$$\frac{d\sigma_{n1}}{dx} + \frac{\sin 2\psi \;\; K_\psi}{B} \; \sigma_{n1} - \frac{\tau}{h} = 0 \qquad (93$$

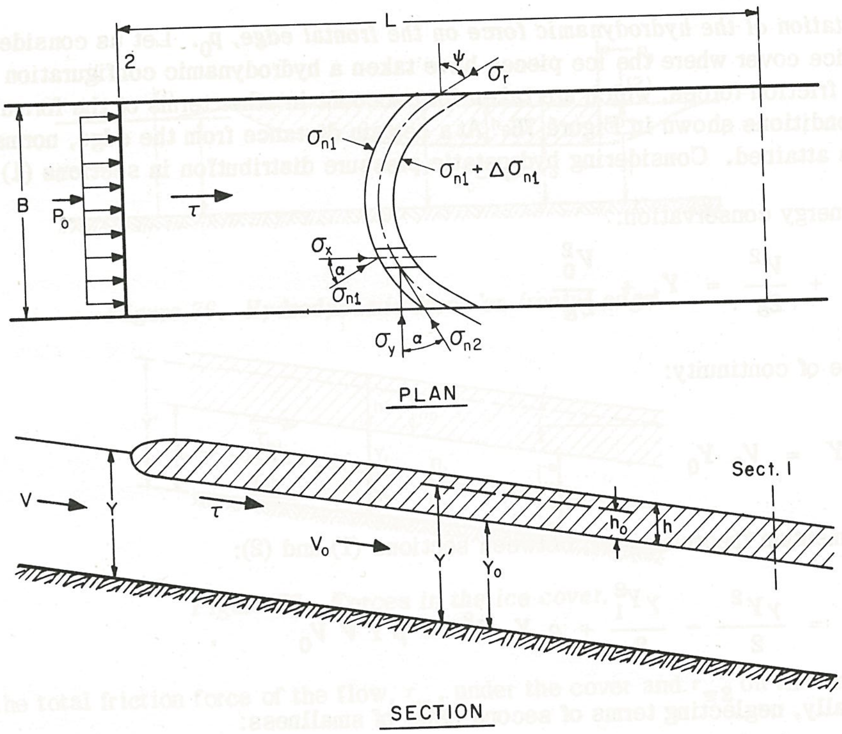


Figure 75. General stress distribution in an unconsolidated ice cover.

whose solution is, with $\sigma_{n1} h = p_0$ for $x = 0$:

$$T' = \sigma_{n1} Bh = p_0 B e^{-\xi x/B} + \frac{\tau B^2}{\xi}\left[1 - e^{-\xi x/B}\right] \qquad (94)$$

where T' is the total thrust exerted on an arch at a distance x from the edge, and:

$$\xi = \sin 2\psi \tan^2 (45° - \psi/2)$$

There is an important practical advantage in the application of this method. If the angle of friction of ice on the shores varies from 15° to 30° the coefficient ξ varies very little. By taking a value:

$$\xi = 0.3$$

the error is less than 4% in that range. This is very useful in the case of ice floes where this angle has not been measured but it most probably lies in that range, as for many other granular materials.

With these numerical values we can now write the final formulas:

$$\left.\begin{aligned} T &= T_\infty \left[1 - a\, e^{-0.3x/B}\right] \\ T_\infty &= 3.3\tau B^2 \\ a &= 1 - \frac{p_0}{3.3\,\tau B} \end{aligned}\right\} \qquad (95)$$