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EFFECTS OF CLIMATE ON RIVER ICE JAMS

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Abstract

River ice jams have major social, economic and ecological impacts throughout Canada. River ice processes in general, and ice breakup and jamming in particular, are governed by the flow hydrograph, the thickness of the winter ice cover, and the stream morphology. These factors are directly or indirectly influenced by climate, and particularly by temperature and precipitation. Consequently, there is concern over the potential impacts of changing climatic conditions on the ice regime, and, thence, on stream ecology and local economy. The limited evidence that is available to date indicates that the duration of the ice season is changing, in step with small but perceptible temperature increases during the past one hundred years. However, very little work on changes to the ice breakup regime has been done. Using the predicted greenhouse-gas effects on Canadian climate, it is possible to identify general trends in ice jamming severity and related socio-economic and ecological concerns. The most conspicuous trend is the increased incidence of winter breakups, caused by rainfall events that would ordinarily have been mere snowstorms. Detailed impacts at specified locations may include a variety of changes, both detrimental and beneficial, but are difficult to predict due to limitations in circulation modelling and in river ice science. Research needs are discussed and pertinent river ice studies identified.

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INTRODUCTION

Ice jamming is a common occurrence in Canadian rivers and has a multitude of socio-economic impacts such as flooding, damage to private property and infrastructure, interference with navigation, and inhibition of hydropower generation. Ice jams attain thicknesses of several metres and have highly irregular undersides. To pass the river flow, the water level has to rise drastically in order to accommodate both the large additional resistance created by this new boundary and the keel of the jam, itself being a large part of the thickness. Serious flooding is often the result, even where the discharge is modest relative to that of open-water floods. Unlike the latter, which can usually be anticipated days or even months in advance, ice-jam flooding is sudden and allows little time in which to plan and implement mitigation measures or to evacuate local residents. The release of an ice jam is also a matter of concern because a large volume of water is able to come out of storage at once, creating a surge. This phenomenon is qualitatively similar to a dam-break, though not as pronounced. Ice-jam surges are characterized by very rapid stage increases downstream and very high flow velocities (5 m/s is not uncommon), capable of substantial bank erosion and bed scour. Major damage happens within minutes of the arrival of the surge.

The total tangible annual cost of ice jams to the Canadian economy has been estimated as $ 60 million (Gerard and Davar, 1995), comparable to the 100 million estimated for the United States (Carlson et al, 1989). A much greater amount is attributed to missed hydro-electricity production opportunities because of inadequate understanding of river ice processes in general (Raban, 1995). In New Brunswick, where detailed damage records are available, it has been found that ice jams cause a third of all flood events but appear to be more destructive than open-water floods because they are responsible for two-thirds of all flood damages (Humes and Dublin, 1988).

Equally important is the strong relationship between river ice and aquatic ecosystems, in terms of both habitat and life cycle (Prowse and Gridley, 1993). River ice jams and the surges caused upon their release, can have many detrimental impacts on aquatic life, such as habitat degradation or loss, species stress or mortality, deposition of fines and deterioration of spawning grounds. But ice jams also have beneficial ecological effects, such as the replenishment of floodplains with essential nutrients and sediment for the sustenance of many aquatic, terrestrial and avian species. For instance, the Mackenzie, Peace-Athabasca and Slave River deltas are wildlife havens that depend on ice-jam flooding for revitalization (Peace-Athabasca Delta Project, 1973; Marsh and Hey, 1989).

This paper reviews current understanding of breakup and jamming phenomena in rivers, and identifies the dominant climatic factors involved. Evidence of changing ice regime in world rivers is reviewed briefly. Though limited, it suggests that ice phenomena are responding perceptibly to the relatively small changes in local climatic conditions that have been experienced in the past one hundred years or so. It is difficult, at present, to predict specific impacts of global warming on the ice regime of northern rivers. However, certain general trends can be anticipated, raising a number of potential concerns. To investigate and quantify such concerns, both atmospheric and river ice science need to be improved. Specific weaknesses are identified, and research needs discussed.

ICE BREAKUP PROCESSES AND ICE JAMS

General

Ice jams occur during both the freeze-up and the breakup periods. Because of the much higher flows that usually prevail during breakup, freeze-up jams have, as a rule, a lesser potential for damages to structures and habitat than do breakup ones. Hence, we will concentrate on breakup jamming in this paper, even though freeze-up jamming is known to pose many additional problems, especially with respect to hydro-power generation.

The breakup of river ice is triggered by mild weather and encompasses a variety of processes associated with thermal deterioration, initial fracture, movement, fragmentation, transport, jamming, and final clearance of the ice. Though several or all of these processes may be occurring simultaneously within a given reach, it is convenient to visualize the breakup period as a succession of distinct phases such as *pre-breakup, onset, drive, wash.* During the pre-breakup phase, the ice cover becomes more susceptible to fracture and movement via thermally induced reductions in thickness and strength. At the same time, the warming weather brings about increased flow discharges, due to snowmelt or rainfall or both. The rising water levels fracture the ice cover and reduce its attachment to the river banks while the increased flow velocities cause it to move and break down into relatively small blocks. This is the onset of breakup, and is followed by the drive, that is, the transport of ice blocks and slabs by the current. The onset is governed by many factors, including channel morphology which is highly variable along the river. It is thus typical to find reaches where breakup has started alternating with reaches where the winter ice cover has not yet moved.

Invariably, this situation leads to jamming because ice blocks moving down the river in one reach encounter stationary ice cover and begin to pile up behind it, initiating a jam. Ice jams can stay in place for a few minutes or for many days; they can be a few hundred metres or many kilometres long. Even with moderate river flows, jams of substantial length can cause very high water levels, several metres above the corresponding open-water flow stages, as illustrated in Fig. 1 (Beltaos and Burrell, 1992). The flow rating curve, applicable to open water conditions is also shown for comparison. The difference between an observed ice-influenced stage and the open-water stage for the same discharge is called the *backwater*. The "equilibrium-jam" curve is seen to provide an upper bound to the data points, consistent with theoretical concepts (Beltaos, 1995a). The sheet-ice-cover curve represents the stage that prevails shortly before breakup is initiated, when the ice cover is still intact but its underside has already been roughened somewhat by heat transfer from the water. Both the stage and backwater due to an ice jam are seen in Figure 1 to increase with discharge so that the severity of breakup is compounded by the fact that the spring runoff is often associated with the annual peak flow.

When a jam lets go, a large amount of water comes out of storage in short time, producing a *surge*. The water level drops very quickly upstream, but rises rapidly downstream, of the jam, while water speeds increase to extreme values. Intact ice cover may be broken up and carried by the surge or, if still very competent, it may stay in place and initiate another jam. In this manner, more and more ice is broken up and carried down the river, until the final jam releases. This is the start of the wash, or final clearance of ice.

Types of Breakup Events

Depending on hydro-meteorological conditions, the severity of a breakup event can vary between two extremes, those of the *thermal* or *overmature* breakup and the *premature* breakup. The former type occurs when mild weather is accompanied by low runoff, due to lack of rain and slow melt. The ice cover deteriorates in place and eventually disintegrates under the limited forces applied by the modest current. Ice jamming is minimal, if any, and water levels remain low. Typically, a thermal event would be represented in Fig. 1 by a data point that plots near the sheet-ice curve. Premature breakup on the other hand, is associated with rapid runoff, usually due to a combination of rapid melt and heavy rain. The hydrodynamic forces are sufficient to lift and break segments of the ice cover before significant thermal deterioration can occur. Ice jams are now the most persistent because they are held in place by sheet ice that retains its strength and thickness. This is aggravated by the high river flows caused by the intense runoff, rendering premature events the most severe in terms of flooding and damages. Usually, a breakup event falls somewhere between these two extremes, and involves a combination of thermal effects and mechanical fracture of the ice. Herein, the term *mechanical* breakup will be used to denote all non-thermal events because they are at least partly governed by the mechanical properties of the ice cover.

In the colder parts of Canada such as the Prairies or Territories, we are most familiar with a single event, the *spring breakup,* triggered by snowmelt. In more moderate regions, however, such as parts of Atlantic Canada, Quebec, Ontario and British Columbia, events called *winter thaws* are common. Usually occurring in January and February, they consist of a few days of mild weather and typically come with significant rainfall. River flows may rise very rapidly and sufficiently to trigger breakup on many local rivers. This is the *winter breakup* which can be more severe than a spring event, not only because of its premature nature: dealing with the aftermath of flooding is hampered by the cold weather that resumes in a few days; while many jams do not release but freeze in place, posing an additional threat during subsequent runoff events.

Onset of Breakup

Defining the onset of the breakup event at any particular location along a river as the time when the winter ice cover is set in sustained motion (e.g. see Beltaos, 1995b), a number of onset criteria have been formulated in the past few decades. Most are completely empirical, relying on various combinations of water level, ice thickness, freeze-up conditions, and air temperature indices such as degree-days of thaw. A common empirical criterion is:

$$H_B - H_F = kh_{io} - F(S) \tag{1}$$

in which H_B = water surface elevation at which the ice cover starts to move; H_F = water surface elevation at which the ice cover formed during the preceding freeze-up event = *freeze-up level*; h_{io} = ice cover thickness prior to the start of melt; F = a site-specific function of S, the latter being an index of thermal effects on the ice cover, often taken as the cumulative heat flux to the ice or simply the accumulated degree-days of thaw; and k = site-specific coefficient, to date known to vary between 2 and 10. Note that this type of criterion does not apply to thermal breakup events, characterized by in situ disintegration of the ice cover and insignificant ice breaking or jamming.

Equation 1, and others like it, do not explicitly account for hydrodynamic or morphological effects; hence, they can only be applied to the particular river site at which they have been calibrated, i.e. they are *site-specific*. Application to another site on the same river, or to a different river, can only be made if adequate local data are available. This limitation can, in principle, be overcome with criteria that are based on a physical-process hypothesis. A number of these have been proposed in the literature and were recently reviewed and evaluated by the writer (1995b) using field data from five different river sites. The following equation, based on the simple requirement that ice plates formed by transverse cracking are set in motion when there is adequate water surface width, was found to adequately describe all five data sets (Beltaos, 1995b):

$$\frac{W_B - W_i}{h_{io}} = \frac{\beta(m-0.50)\sigma_{fo}}{8m^2\tau} f(S_5) \qquad (2)$$

in which W_B = water surface width at the stage at which the breakup is initiated; W_i = width of ice cover = river width at the freeze-up stage minus side strips caused by hinge cracking prior to breakup; h_{io}, σ_{fo} = ice cover thickness and strength just before thermal deterioration begins; m = radius of curvature divided by channel width; τ = downslope force per unit area applied on the ice cover due to its own weight and flow shear; S_5 = accumulated degree-days of thaw from a base of -5°C as recommended by Bilello (1980); ß = dimensionless coefficient between 0.3 and 1.5; and f = an empirically determined function accounting for loss of ice strength and thickness by penetrating solar radiation and top/bottom melt. While Eq. 2 appears to include the main factors and exhibit plausible trends, it is still in a preliminary stage of development and further verification is needed with more river sites. Moreover, we are not yet able to account for such complications as the effects of islands, open leads, or breaking fronts (to be discussed later). Nevertheless, the physical insight suggested by Eq. 2 can be utilized to describe the main characteristics of the breakup and jamming processes, as explained next.

Evolution of Breakup

Noting that channel width depends on water level and, thence, on discharge, we see that Equation 1 includes the effects of such factors as antecedent weather and hydrologic conditions (W_i, h_{io}, S_5), channel morphology and slope (m, W_i, W_B, τ), and hydrodynamic forces applied on the ice cover (τ). For simplicity, let us first consider a premature breakup, so that thermal effects are not a factor. The breakup initiating discharge, Q_{in}, corresponds to the stage at which the water surface width is equal to W_B. At a given river site, where m is fixed and the stage - discharge - τ relationship is defined by local bathymetry and slope, Q_{in} depends on ice thickness and water level during the preceding freeze-up, H_F. At the same time, the variable channel slope, bathymetry and planform cause Q_{in} to change irregularly along a river reach, as depicted in Fig. 2. The highest Q_{in} values are usually associated with sharp bends where the radius of curvature is relatively small.

When the prevailing river flow is between the least and largest values of Q_{in}, breakup will have been initiated in one or more sub-reaches as shown (discharge, $Q > Q_{in}$). Elsewhere, the ice cover will have remained in place and caused jam formation by impeding the flux of broken ice from upstream. As the flow continues to rise, more and more intact ice will break up, and a number of ice jam releases will take place, until the upper limit of Q_{in} is reached and all the ice is cleared from the reach. For any given site, there is an ice-clearing discharge, Q_{cl}, which is the O_{in} value for the farthest downstream location where an ice jam can cause significant backwater at the original site. Figure 3 summarizes these concepts and illustrates the degree of severity that can result from different combinations of freeze-up levels and flow hydrographs. When the freeze-up flow Q_F is low, the corresponding water level, H_F, will also be low. Moderate or high runoff events later on in the winter or spring, will tend to produce flow peaks that exceed both Q_{in} and Q_{cl}. This will produce a mechanical event of moderate severity because the worst that can happen is an ice jam persisting until the flow Q reaches the value Q_{cl}. On the other hand, high freeze-up flows and levels may produce thermal events if the runoff is low or moderate (peak less than Q_{in}) but, coupled with high runoff, they can be the most dangerous: ice jams will persist until a very high Q is attained, thus causing very high backwaters and stages (Fig. 1).

The role of thermal effects, initially ignored for simplicity, will be to progressively reduce the Q_{in} and Q_{cl} values as heat is transferred to the ice cover. This process involves reductions in both ice thickness, due to bottom melt, and in strength, due to penetrating solar radiation and preferential melting at crystal boundaries (Ashton, 1985; Prowse et al, 1990). It is difficult to predict such effects, however, owing to complexities introduced by the snow cover and its changing reflective/absorptive properties as melt progresses. Even when the over-ice snow has completely melted, there can be difficulties in assessing the same properties for the top ice layer which now controls a part of the heat flux. Consequently, thermal effects on the ice cover are accounted for via simple thermal indices, such as the degree-days of thaw.

Ice Jams

A major cause of ice jam formation has already been identified as the longitudinal variability of the breakup onset flow, Q_{in} (see also Fig. 2). The most obvious ice-jamming sites are associated with an abrupt rise in Q_{in}, such as sharp bends, slope or flow velocity reductions such as river mouths or reservoirs, and channel constrictions. Reaches with islands, and man-made obstructions to the flux of broken ice are also candidates. The maximum water depth that can be caused by an ice jam at any given location is the so-called *equilibrium depth*, a parameter that can be calculated theoretically with reasonable confidence (see also Fig. 1). It primarily depends on channel width and slope (both being aspects of channel morphology) and flow, a hydrological parameter that is determined by weather conditions as well as runoff characteristics of a watershed. The actual water depth caused by an ice jam can be equal to, or less than, the equilibrium value, depending on the volume of broken ice that is available to form the jam. This volume is limited by upstream river conditions and by the pre-breakup thickness of the ice cover, thus being a function of stream morphology and climate. This aspect is not addressed in the simple equilibrium theory, but can be investigated using a numerical ice-jam model (e.g. see Beltaos, 1997). While an ice jam is in place, it can cause widespread flooding, usually aggravated by great quantities of ice floes spilling onto the floodplain where deposition of sediment can be detrimental to property but beneficial to habitat replenishment.

It is not fully known how ice jams release. One mechanism is ice clearing, as mentioned previously. This is simply a matter of dislodging the intact sheet ice cover at sites where Q_{in} is relatively large (e.g. a sharp bend) by gradual increase of the river flow. A second mechanism is the formation and gradual expansion of an open lead in the ice sheet downstream of the jam until the rubble is able to move. A third, which can also be viewed as a sub-case of ice clearing, may be due to the arrival of a surge from upstream which not only raises the water level but also greatly magnifies the hydrodynamic forces acting on the ice cover, as discussed next.

The release of an ice jam is followed by a surge, that is, a sharp rise (drop) in water levels downstream (upstream) of the jam. The *celerity*, or the speed of propagation of the surge front, can be 10 m/s or more; the actual velocity of the flow is always less than the celerity but comparable to, or more than, what is experienced under the rarest of open-water floods. Values of 5 m/s are not uncommon, imparting enormous kinetic energy to ice floes, with obvious repercussions to river structures. Because hydrodynamic forces are proportional to the square of velocity, they can easily be augmented by an order of magnitude. Surges are thus capable of major bank erosion and bed scour, being a threat to many aquatic organisms or to the stability of bridges by undermining in-stream piers. They can also dislodge downstream ice jams via increased tangential forces, τ, and channel widths, W_B (see Eq. 2). Very high concentrations of suspended sediment appear to accompany ice-jam surges (Beltaos et al, 1994; Milburn and Prowse, 1996), posing an immediate threat to certain fish species and interfering with spawning habitat when the sediment eventually deposits. In cases of over-bank flooding, the swift drop in water levels upstream of the jam can cause extensive fish mortality because it allows little time to return to the main river (e.g. Thames River below Chatham, February 1984).

The *ice run*, that is, the rubble from the released jam trails the front of the surge whose rate of propagation defines the celerity. When an ice run encounters competent ice cover that has not been dislodged by the surge, a *breaking front* usually forms. This is a sharp transition between rubble and intact ice, that moves downstream as the intact ice edge is broken up and incorporated into the rubble. Breaking fronts may move for very long distances or they may be arrested at some point, thus causing a new jam. Exactly what causes the arrest is not known; shallow river depth, or strong and thick ice cover are two possibilities.

GOVERNING FACTORS AND CLIMATIC INFLUENCES

The preceding brief description of ice breakup and jamming phenomena suggests that the main governing factors are related to stream morphology, flow hydrograph, and ice. Two obvious climatic parameters for ice thickness growth and decay are air temperature and precipitation. Such factors as solar radiation, cloudiness, humidity, and wind speed are also relevant. However, they are either fixed by local geography or difficult to predict as part of a climate change scenario. Consequently, they will not be discussed explicitly in what follows, though we should keep in mind that they might be responsible for impacts that cannot be entirely attributed to changes in temperature and precipitation.

The flow hydrograph is influenced by all of the mentioned climatic factors. The type of precipitation, liquid or solid, plays a prominent role, often dictating whether a breakup event will occur at all. Runoff characteristics of a watershed constitute an important non-climatic determinant of the hydrograph.

Summarizing this discussion, we can list the following factors:

1. Channel morphology: width, depth, slope, presence of islands, curvature, etc.

2. Watershed characteristics related to runoff such as surface retention, infiltration, elevation, slope, aspect, forest cover, groundwater conditions, and degree of urbanization.

3. Climatic factors, such as air temperature, amount and type of precipitation, cloudiness, humidity, wind speed, etc.

Direct Climatic influences

Let us now focus on the climatic effects and consider how each parameter influences ice breakup and jamming.

By-and-large, air temperature determines the timing of freeze-up and breakup. A general rise in temperature at any given region, will tend to delay freeze-up and trigger the breakup sooner. Temperature alone, however, is not a sufficient indication as to possible changes in freeze-up and breakup flows which control the severity of the event. Either quantity may increase or decrease, depending on a number of other climatic and watershed-related factors.

Coming to ice thickness, one would expect that warmer winters would produce thinner ice covers, and thus reduce the persistence and potential severity of ice jams. Here, however, one has to be discerning: the rate of ice thickness growth decreases with time, owing to the increasing insulation provided by the thickening ice sheet itself and by the snow cover. In many parts of Canada, there is a period during the winter that ice thickness hardly changes. A general rise in air temperatures would then produce a relatively small reduction in the pre-breakup ice thickness, the value that influences the breakup process. The opposite holds for areas of more moderate climate: the winter ice is relatively thin (under 0.3 m or so), and changes in temperature may have considerable impact on a percentage basis. In fact, there could well be instances where the thickness is reduced to nil, implying increased incidence of seasons without ice cover formation.

Precipitation is probably the most important factor influencing the flow hydrograph. Rainfall has an immediate influence, snowfall a delayed one. Changes to climate can produce changes to both the freeze-up and the breakup flows via quantitative changes in precipitation. More importantly, however, there could be *qualitative* changes because normal winter snowfall events may become rainfall events due to elevated air temperatures. This may lead to winter breakups in areas that have not known them in the past.

Indirect Climatic Influences

Climate, to a degree, shapes the terrain and vegetation of a particular region. Therefore, a change in climate could alter channel morphology or river basin characteristics and even groundwater supplies, and thence influence the ice regime in an indirect manner. For example, a change in forest cover, known to be one of the likely impacts of climatic change, can influence the runoff process, and thence, the flow hydrograph. Prairie grasslands are expected to expand northward and eastward, in step with reductions in available soil moisture (Hengeveld, 1995). This could lead to higher spring flows due to faster snowmelt. However, such effects are too complex to predict without carrying out detailed site-specific studies.

One indirect effect that may be attended by conspicuous impacts is the change in the levels of large water bodies. As a result of global warming, the sea level is predicted to rise by as much as 40 to 110 cm over the next century (Hengeveld, 1995). Because river slope is very small near the river mouth, the river-sea interaction region will shift many kilometres inland. This could produce a great variety of physical, chemical, and ecological changes. From the ice-jam perspective, it would most likely create new problems by moving the site where there is an abrupt change in slope, a known ice-jam instigator. The flatter the river exit is, the further upstream are such effects likely to migrate. Riverside communities and nearby infrastructure such as bridges, roads or railway lines, may be particularly vulnerable.

In Central Canada, on the other hand, many rivers empty into the Great Lakes or the Saint Lawrence, whose levels are expected to drop by as much as a metre or more under the doubled-Carbon Dioxide ($2xCO_2$) scenario (Mortsch and Quinn, 1996). This would greatly augment the local slope, resulting in major morphological changes to the river planform. It is not immediately evident what this would do to the ice regime because a number of additional factors have to be considered, and it is best to deal with such questions on a case-by-case basis. There are many other lakes that receive the waters of major Canadian rivers, such as Lakes Winnipeg, Athabasca, Great Slave, and others. Long-term changes in their levels need to be examined from the viewpoint of river ice impacts.

Basic Trends and Scenarios

It is worthwhile to pause here in order to illustrate what type of trends can be produced by changes in some of the climate-controlled factors. Consider first changes in the flow hydrograph. Using Fig. 3 as a guide, we may note that an increase in freeze-up flow would raise the freeze-up level, hence raising both the Q_{in} and Q_{cl} values. All other things being equal, this would result in more frequent thermal events but also in an increased potential severity of mechanical breakups, via the increased Q_{cl}. In other words, major ice jamming would be expected to happen less frequently, but to be more damaging when it does occur. {This trend appears to have been the cause of habitat degradation at the Peace-Athabasca Delta following the construction of the W.A.C. Bennett dam on the Peace. Flow regulation has resulted in dramatic increases of freeze-up flows while there has been no significant change in breakup flows near the Delta area (Prowse et al, 1996). Ice-jam occurrence and flooding has been drastically reduced after the construction of the dam, resulting in long-term drying of the perched ponds and lakes of the

Delta system}. On the other hand, an increase in breakup flows, alone, would not change the damage potential of extreme events, limited by the unchanged ice-clearing flow, Q_{cl}, but would increase their frequency of occurrence.

Figure 3 can also provide some guidance as to the impacts of a reduced ice thickness. Other things being equal, a lower value of the pre-breakup ice cover thickness will tend to reduce both the Q_{in} and Q_{cl} values, thus producing more frequent mechanical breakups whose damage potential is, however, reduced. This effect is qualitatively similar to that of a reduced freeze-up flow.

EVIDENCE OF CHANGES TO THE ICE REGIME OF RIVERS

Since ice processes are sensitive to climatic inputs, the small but perceptible modification of Canadian and global climate that has occurred during the last one hundred years (Environment Canada, 1995) should be manifested in equally (or even more) perceptible changes in the ice regime. Apart from anecdotal accounts by long-term local residents (e.g. upper Saint John River) who appear to remember longer and colder winters in the past, there is limited documented evidence of changing river ice processes, as the following literature review indicates.

Zachrisson (1989) reported that earlier and more severe breakups are occurring in the river Tornealven which constitutes the boundary between Finland and Sweden. There is a strong correlation with rising April temperatures. A 3°C rise during 1870-1950 corresponds to 15 days of breakup advance. The author suggests that clear-cutting of forested areas and removal of numerous log-driving dams may have also played a role. Ginzburg et al (1992) examined time series of ice formation in rivers of Russia, Belorussia, and Ukraine, for the period 1881-1990. In general, ice appears later in these rivers by as much as 21 days in 100 years; a few streams exhibited the opposite trend, but the maximum change in this case was only 5 days in 100 years. Corresponding advances of up to 11 days in 100 years were reported for breakup dates by Soldatova (1993. More recently, Ginzburg and Soldatova (1996) re-examined freeze-up and breakup dates in six different zones of the former Soviet Union using spectral and statistical methods of analysis. This confirmed their earlier conclusions as to regional climate-dependencies.

In Canada, Williams (1970) reported that the breakup on the Saint John River (the locality is not mentioned but it is probably Fredericton, N.B.) occurred 15 days earlier in the 1950s than in the 1870s. Spring air temperature at Toronto was also examined as a crude index for the same period, and found to have increased by 3°C. Rannie (1983) indicates that the ice season in the Red River near Winnipeg has been shortened by about three weeks since the last century, due to almost equal changes in freeze-up and breakup dates. Fall and spring temperatures have both risen by about 2.5°C. Burn (1994) examined records of 84 hydrometric gauging stations in west-central Canada, and found that the snowmelt peak flow tends to arrive earlier than it did in the past. The average rate of advance was 0.25 days/year, though a few stations showed the opposite trend.

Brimley (1996) considered the duration of the ice season in Atlantic Canada, as revealed by hydrometric gauge records in the past 45 years or so. The results highlight the spatial variability of Maritime climate, and are consistent with local winter temperature trends though not entirely explainable by temperature. The largest rates of change were found in Cape Breton and Newfoundland (up to +3 days/year!), in response to colder winter temperatures. The magnitude of change is strikingly greater than that of previously quoted data. A possible explanation may be in the brief, and often intermittent ice cover formation in Atlantic Canada streams, due to the occurrence of one or more mid-winter thaws. Such events may not happen as often under colder winter temperatures. For south-central British Columbia, Doyle (1997, pers. comm.) examined the ice-in, ice-out dates at seven Water Survey of Canada hydrometric stations, where the ice normally starts to form in December and clears by the end of February. The local winter weather is variable so the ice cover may be intermittent in some years. Doyle found no trend over the period of record, ranging from 35 to 70 years. The corresponding change in average winter (December to February) temperature for that part of Canada during the period 1895-1992 is given as +0.8 °C (Environment Canada, 1995), though this value is not statistically significant, due to the greater variability of winter temperatures. It is also possible that temperature effects may be neutralized by compensating changes in flow discharge.

The above examples provide mere glimpses of the overall picture. It is difficult to draw any general conclusions from the limited evidence at hand as to what is happening to the river ice cover, and use them to predict what may occur in the future due to greenhouse-gas impacts. Conspicuously lacking is information on the frequency and severity of ice jam events, perhaps because it is not as readily obtainable as "ice-in" and "ice-out" dates. A study of past and present breakup and ice-jam conditions is required, perhaps through a comprehensive analysis of hydrometric station data, taking into account both hydrologic and morphologic aspects. This task would involve historical data that are archived in Water Survey of Canada offices but not normally published.

FORESEEABLE CHANGES TO THE ICE-JAM REGIME OF CANADIAN RIVERS

Considerable warming and change in precipitation patterns are predicted by General Circulation Models (GCMs) under the $2xCO_2$ scenario. There are limitations to the fidelity with which GCMs simulate natural processes, hence there is no full agreement between various models on the degree of warming. The consensus is that, in Canada, it will amount to a few or several degrees Celsius, being more pronounced in the winter months and in the more northern latitudes. Less predictable is the regional distribution of precipitation, but the models agree (Hengeveld, 1995) on an increased winter precipitation across Canada, though the snow season will be shorter. The uncertainties in precipitation modelling make it impossible to predict how the runoff will be specifically affected in different regions of the country. The only clue is that water resources in northern Canada are likely to become more abundant, though the annual spring runoff will likely be smaller and occur earlier.

We have seen that the river ice regime at a specific site is essentially a function of the flow hydrograph and the weather conditions during the ice season. Modified weather conditions can be obtained directly from the output of a GCM. Flow hydrographs can, in principle, be predicted on a case-by-case basis using the GCM output as input to a hydrologic model (e.g. see Morin and Slivitzky, 1992). This approach is subject to uncertainties deriving from gaps in atmospheric science and from scale incompatibility, that is, the enormity of the GCM grid size (about 90,000 km^2, Hengeveld, 1995) relative to that of most river basins. Additional limitations stem from gaps in hydrologic modelling and from the relative "youth" of river ice science. The latter relies heavily on empiricism to compensate for lack of basic knowledge on many aspects of the ice breakup and jamming process. Consequently, reliable predictions as to how the anticipated climatic modifications will influence the ice regime of specific Canadian rivers are difficult to make at present. Only general trends can be identified, as outlined next.

From our understanding of river ice processes, we may expect the most noticeable changes to occur in the temperate regions of the country, such as SW Ontario and parts of British Columbia and Atlantic Canada: the already brief and capricious river ice cover season may disappear completely or become more intermittent. This should be good news on the socio-economic front. It could, however, be disastrous to aquatic species that depend on the ice cover for survival during the winter, and lead to a ripple effect throughout the ecosystem.

A large part of Canada, comprising the central tier of latitudes, experiences long river ice seasons, lasting several months and being devoid of mid-winter breakups. This is certainly the case with west-central Canada. Parts of Ontario and Quebec do experience the occasional winter breakup, seemingly more often in recent years, due to increased incidence of winter thaws and rainfall. An example is the upper Saint John River, New Brunswick, where records (USGS, Fort Kent gauge) for the last 25 years and in situ observations indicate that 3 of 6 winter breakups occurred during 1995 and 1996, the fourth being also recent (December 1990) and leading to one of the most disastrous spring events on record (Beltaos et al, 1996). Published daily flows going back to 1926-27, indicate that no winter breakup events occurred prior to 1971. These findings are consistent with temperature and flow trends for the winter months (Fig. 4; see also Hare, 1997).

The typical change we are likely to see in the central tier of Canadian latitudes is the appearance of winter breakup events, either as an entirely new occurrence in some areas, or simply a more frequent one in other areas. Ice thickness will be reduced though not sufficiently to alleviate the risk of ice jamming. Warmer temperatures may also cause faster and more snowmelt runoff, thus exacerbating the hazards associated with the final (spring) event. As a result, there is potential for increased socio-economic impacts but the effects on ecology are more difficult to anticipate.

In northern Canada, the winter is so cold that significant occurrence of winter thaws is not expected, even though the local warming is predicted to be the largest. A reduction in ice thickness is likely but much will depend on concomitant changes in the snow cover. In percentile terms, the reduction is not expected to be large because the rate of ice growth is small, once a thickness of a metre or so is attained. Depending on the changed spring runoff hydrograph, the spring breakup may be more or less benign, though the scarcity of the population would limit any socio-economic impacts.

Less frequent jamming would have certain adverse ecological impacts because floodplain habitat replenishment would be diminished, as indicated earlier with regard to the large northern river deltas. At the same time, the lengthened open-water season would allow exposure of riverine species to UV-B radiation that would otherwise have been absorbed by the ice cover. Whether and where this might be a serious concern will depend mainly on the relative increase in the duration of the open water season. Because the latter is short in northern areas, such increases may be substantial.

RESEARCH NEEDS

The preceding discussion has outlined a preliminary attempt to identify the kind of general changes in the ice-jam regime of Canadian rivers that may be foreseen under the global warming scenario. It is emphasized that many other changes may be experienced, depending on specific, but presently unpredictable, modifications to local climatic patterns. However, Atmospheric Science has made considerable advances in recent years, and the sophistication of GCMs is increasing. Computing capacity is also growing at a fast pace, so there is hope that many of the weaknesses of the current generation of GCMs will be rectified within the next decade.

To take advantage of such progress, river ice science must also advance to the point that it can furnish quantitative prediction capabilities as a function of climatic input and channel morphology. This cannot be accomplished satisfactorily at present because there is still considerable reliance on empirical formulae and methods. For instance, it is often assumed that several climatic variables - except air temperature - do not change much from year to year, thus enabling correlations with simple thermal indices such as degree-days of frost or thaw. Such methods may not be reliable in the climate-change context and there is a strong need to develop physics-based models, by improving basic understanding of river ice processes. The same applies to empirical methods that assume unchanging basin geography and channel morphology, by fixing the site of application (e.g. see Eq. 1). As we have already seen, climate change may alter such features, thus undermining site-specific empiricism. A more serious handicap is the need for prior calibration using historical data. If, as is usually the case, such information is not available, application of a site-specific empirical method to predict future trends is not possible.

A parallel effort needs to be made toward improving our capability to predict what may happen to riverine ecosystems throughout the country. The ecological dimension of river ice has only recently been examined in some detail (e.g. see Prowse and Gridley, 1993). Inter-disciplinary studies, combining biological and physical expertise would have the best chance of success.

At the same time, it is important to continue monitoring and assessing the current status of the ice regime of Canadian rivers and how it may be changing. A comprehensive study of hydrometric station data to investigate trends in hydrologic and ice processes would be a starting point. Such a study can be readily implemented using existing data and methodology (e.g. see Beltaos et al, 1990). The main objectives would be to quantify the effects of climatic changes that have already occurred on the ice-jam regime of Canadian rivers, and to identify river sites that may be of concern with respect to economic and ecological developments.

SUMMARY

River ice jams have major social, economic and ecological impacts throughout Canada. River ice processes in general, and ice breakup and jamming in particular, are determined by three climate-dependent factors: (a) the flow hydrograph; (b) the thickness of the winter ice cover; and (c) the stream morphology. By examining the changes that can be triggered by alterations to any one of these factors, it is shown that climate has a dominant influence on breakup and jamming processes. The limited evidence that is available to date indicates that the duration of the ice season is changing, in step with small but perceptible temperature increases. However, very little work on changes to the breakup regime and the severity of ice jams has been done.

Because of limitations in general circulation modelling and in river ice science, it is not possible to reliably predict how the breakup event of any given river reach will be modified by the anticipated warming due the greenhouse effect. Only general trends and related socio-economic and ecological concerns can be identified at present. They are mostly of quantitative nature, that is, spring breakup and jamming may become more or less severe or occur sooner. A qualitative change that may appear in a large part of Canada, is the incidence of winter breakups, triggered by rainfall events that would, under an unchanging climate scenario, be mere snowstorms.

To improve our capability for anticipating climatic impacts related to ice processes, it is important to bridge the many gaps in basic river ice science, that are presently circumvented by resort to empiricism. A parallel effort should be made to analyze archived hydrometric station data in order to find out what changes may be occurring in the ice-jam regime of Canadian rivers. Inter-disciplinary work on the links between river ice and stream ecology would assist us in identifying ecological concerns that may arise from potential modifications to the ice regime.

REFERENCES

Ashton, G.D. 1985. Deterioration of floating ice covers. J.of Energy Resources Tech., 107, 177-182.

Beltaos, S.(ed). 1995a. River ice jams. Water Resources Publications, Highlands Ranch, Co., USA

Beltaos, S. 1995b. Breakup of river ice. National Water Research Institute Contribution No. 95-125. Prepared for IAHR book *River Ice Processes and Hydraulics*, Chapter 5.

Beltaos, S. 1997. User's manual for the RIVJAM model. National Water Research Institute Contribution No. 97-18, Burlington, Canada, 43 p.

Beltaos, S. and Burrell, B.C. 1992. Ice breakup and jamming in the Restigouche River, New Brunswick. Proc., IAHR Ice Symposium, Banff, Canada, 437-449.

Beltaos, S., Burrell, B.C. And Ismail, S. 1994. Ice and sedimentation processes in the Saint John River, Canada. Proc. IAHR International Ice Symposium, Trondheim, Norway, August, Vol. 1, 11-21.

Beltaos, S., Burrell, B.C., and Ismail, S. 1996. 1991 Ice jamming along the Saint John River: A case study. Can. J. of Civ. Eng., 23(2), 381-394.

Beltaos, S., Gerard, R., Petryk, S., and Prowse, T.D. 1990. (Working group on river ice jams): Field studies and research needs. NHRI Science Report #2, Saskatoon, Canada.

Bilello, M.A. 1980. Maximum thickness and subsequent decay of lake, river and fast sea ice in Canada and Alaska. U.S. Army, Cold Reg. Res. and Eng. Lab., Rpt 80-6, Hanover, N.H., USA, 160 p.

Brimley, W.A. 1996. Hydrologic monitoring to detect climate change. Proc., Symposium on Climate Change and Variability in Atlantic Canada. Halifax, NS., in press.

Burn, D.H. 1994. Hydrologic effects of climatic change in west-central Canada. Journal of Hydrology, 160(1994), 53-70.

Carlson, R.F., Zarling, J.P., and Link, L.E. 1989. Cold Regions Engineering Research - Strategic Plan. Journal of Cold Regions Engineering, ASCE, Vol. 3, No. 4, pp. 172-190.

Environment Canada. 1985. Flooding in New Brunswick: an overview 1696-1984. Water Planning and Management Branch, Inland Waters Directorate, Atlantic Region, Dartmouth, NS, 13 p.

Environment Canada. 1995. The state of Canada's climate: monitoring variability and change. SOE Report No. 95-1. Ottawa, Ont., 52 p.

Gerard, R. and Davar, K.S. 1995. Chapter 1: Introduction. In *River Ice Jams* (edited by S. Beltaos), Water Resources Publications, Highlands Ranch, Colorado, USA.

Ginzburg, B.M. and Soldatova, I.I. 1992. Long-term oscillations of river freezing and breakup dates in different geographic zones. Meteorology and Hydrology, No. 6, 101-108.

Ginzburg, B.M., Polyakova, K.N., and Soldatova, I.I. 1992. Secular changes in dates of ice formation on rivers and their relationship with climate change. Soviet Meteorology and Hydrology, 12, 57-64.

Hare, F.K. 1997. Climatic change and the hydrologic cycles: A perspective. Paper presented at The 1997 H.G. Acres Seminar, Niagara Falls, Ontario, Canada.

Hengeveld, H. 1995. Understanding atmospheric change. State of the Environment Report No. 95-2, Environment Canada, Ottawa, Canada.

Humes, T.M. and Dublin, J. 1988. A comparison of the 1976 and the 1987 St. John River ice jam flooding with emphasis on antecedent conditions. Proc. Workshop on Hydraulics of River Ice/Ice Jams, Winnipeg, Canada, 43-62.

Marsh, P. and Hey, M. 1989. The flooding hydrology of Mackenzie delta lakes near Inuvik, N.W.T. Canada. Arctic, Vol. 42, No. 1, 41-49.

Morin, G. and Slivitzky, M. 1992. Impacts de changements climatiques sur le regime hydrologique: le cas de la riviere Moisie. Revue des Sciences de l'Eau, 5(1992), 179-195.

Mortsch, L.D. and Quinn, F.H. 1996. Climate change scenarios for Great Lakes basin ecosystem studies. Limnol. Oceanogr., Vol. 4 (5), 903-911.

Milburn, D. and Prowse, T.D. 1996. Open-water versus under-ice rating curves for suspended sediment: an example from a large northern river. Proceedings, 13th International Symposium on Ice, IAHR, Beijing, China, Vol. III, 873-880.

Peace-Athabasca Delta Project, 1973. Technical Report, The Peace-Athabasca Delta Project Group, Information Canada, Ottawa, Canada, 176 p.

Prowse, T.D., Demuth, M.N., and Chew, H.A.M. 1990. The deterioration of freshwater ice due to radiation decay. Journal of Hydraulic Research, IAHR, 28(6), 685-697.

Prowse, T.D. and Gridley, N.C. (editors). 1993. Environmental aspects of river ice. NHRI Science Report No. 5., National Hydrology Research Institute, Saskatoon, Canada.

Prowse, T.D., Conly, M. and Lalonde, V. 1996. Hydrometeorological conditions controlling ice-jam floods, Peace River near the Peace-Athabasca Delta. Northern River Basins Study Project Report No. 103, NRBS. Edmonton, Canada, 66 p plus appendices.

Raban, R. 1995. An ice engineering overview. Proc., 8th River Ice Workshop, Kamloops, BC, in press.

Rannie, W.F. 1983. Breakup and freeze-up of the Red River at Winnipeg, Manitoba, Canada, in the 19th century and some climatic implications. Climatic Change, 5, 283-296.

Soldatova, I.I. 1993. Secular variations in river breakup dates and their relationship with climate variations. Soviet Meteorology and Hydrology, 9, 89-96 (in Russian).

Williams, G.P. 1970. A note on the breakup of lakes and rivers as indicators of climate change. Atmosphere, 8, 23-24.

Zachrisson, G. 1989. Climate variation and ice conditions in the river Torneälven. Proc., WMO Conf. on Climate and Water, Publications of the Academy of Finland, Vol. I, 353-364.

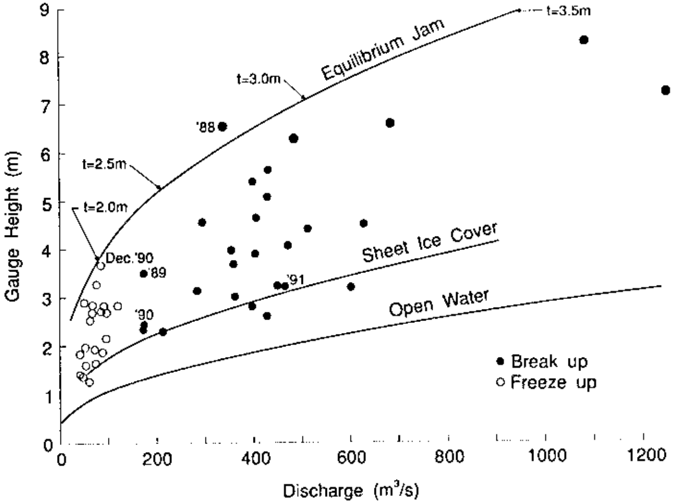

Fig. 1. Peak ice-influenced water levels recorded at the Water Survey of Canada hydrometric station on the Restigouche River near Rafting Ground Brook, N.B. (t=computed thickness of ice jam at the indicated discharge). Data provided by R. Lane, WSC, Fredericton, NB, Canada.

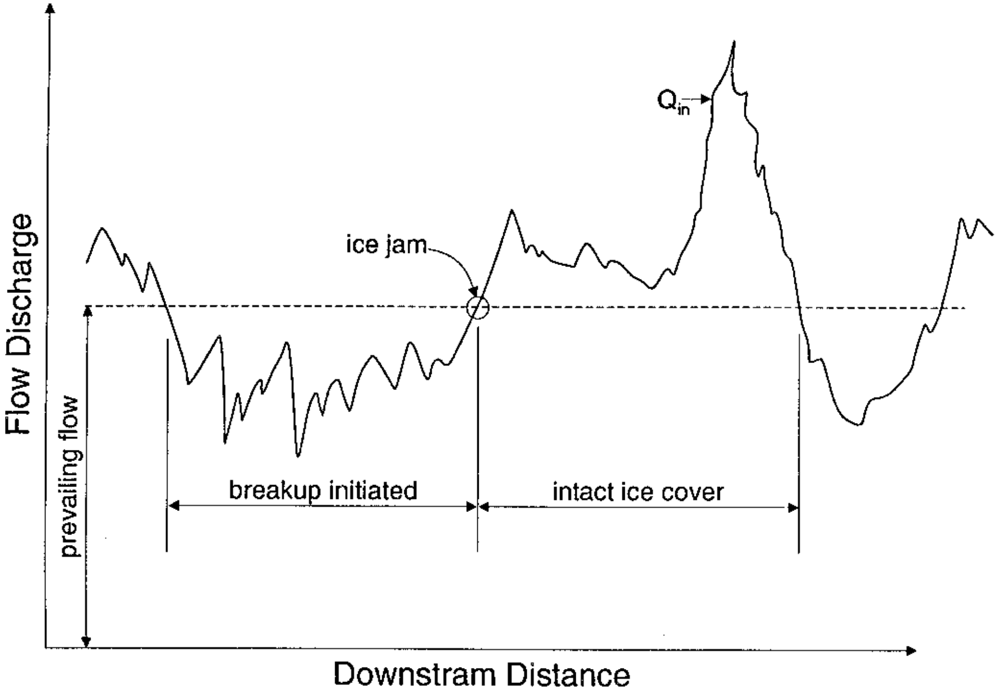

Fig. 2. Schematic illustration of the conditions for breakup initiation, ice-jam formation, and ice clearance, using the concept of a variable Q_{in}, as indicated by Equation 2.

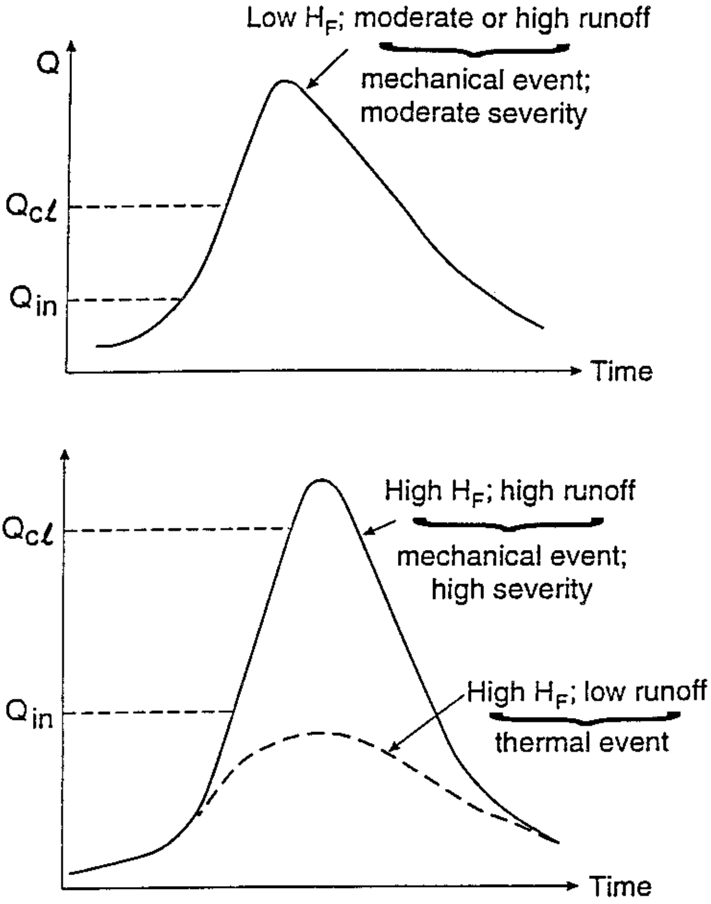

Fig. 3. Types of breakup events produced by different combinations of freeze-up levels and spring hydrographs.

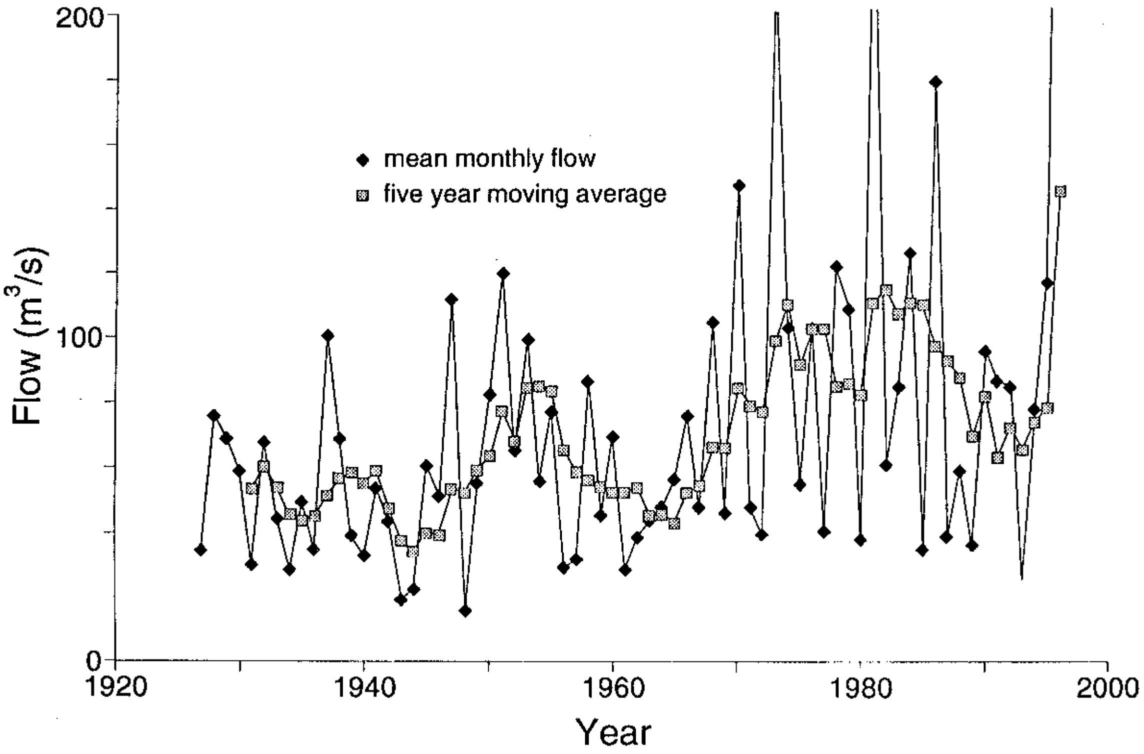

Fig. 4. Mean February flow of Saint John River at Fort Kent hydrometric station. Note increasing trends with time, for flow magnitude as well as flow variability. Data provided by J. Nielsen, United States Geological Survey, Augusta, Maine, USA.