Climatic Effects on the Changing Ice-Breakup Regime of the Saint John River

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As part of the Saint John River Ice and Sediment study, the ice regime of the upper Saint John River has been documented during the period 1992-1997. Three winter breakup events took place during this time, one in 1995 and two in 1996. This was unexpected, since that part of the river had not been known to experience winter breakups. During the same period (1992-1997), very high flows occurred during the spring breakup events of 1993 and 1994. Analysis of hydro-climatic records reveals that these occurrences are parts of long-term trends. A slight warming has been accompanied by a considerable increase in the occurrence of mild winter days, thus contributing to increasing rainfall amounts. This results in augmented flows during the winter, which are lately becoming capable to effect breakup of the river ice cover. An increase in April rainfall is also associated with increasing freshet and spring breakup flows. These trends entail ecological and economic risks that are likely to increase in the future if the warming trend is maintained or accelerated.

1. Introduction

The Saint John River Ice and Sediment study is conducted jointly by the National Water Research Institute, the New Brunswick Department of the Environment and the New Brunswick Power Commission (Beltaos et al, 1994). The study reach covers a large part of the Upper Saint John, starting at Dickey, Maine and ending at St Leonard, NB (Fig. 1). Frequent occurrence of major ice jams on the Saint John River during the spring breakup has resulted in serious flooding and damages, most recently during 1987, 1991, and 1993. One of the study objectives is to gain improved understanding of the processes conducive to ice jamming and develop strategies for possible mitigation, including flood forecasting and warning as well as more permanent structural measures.

The field component of the study, comprising annual documentation of the ice regime of the river from 1992 to 1997, has been completed. When the study began, the normal winter-spring sequence of ice cover phases was understood to be as follows: freeze-up between late November and early January; solid ice cover during January, February, and March; breakup in April or early May. However, during the period of observations, three

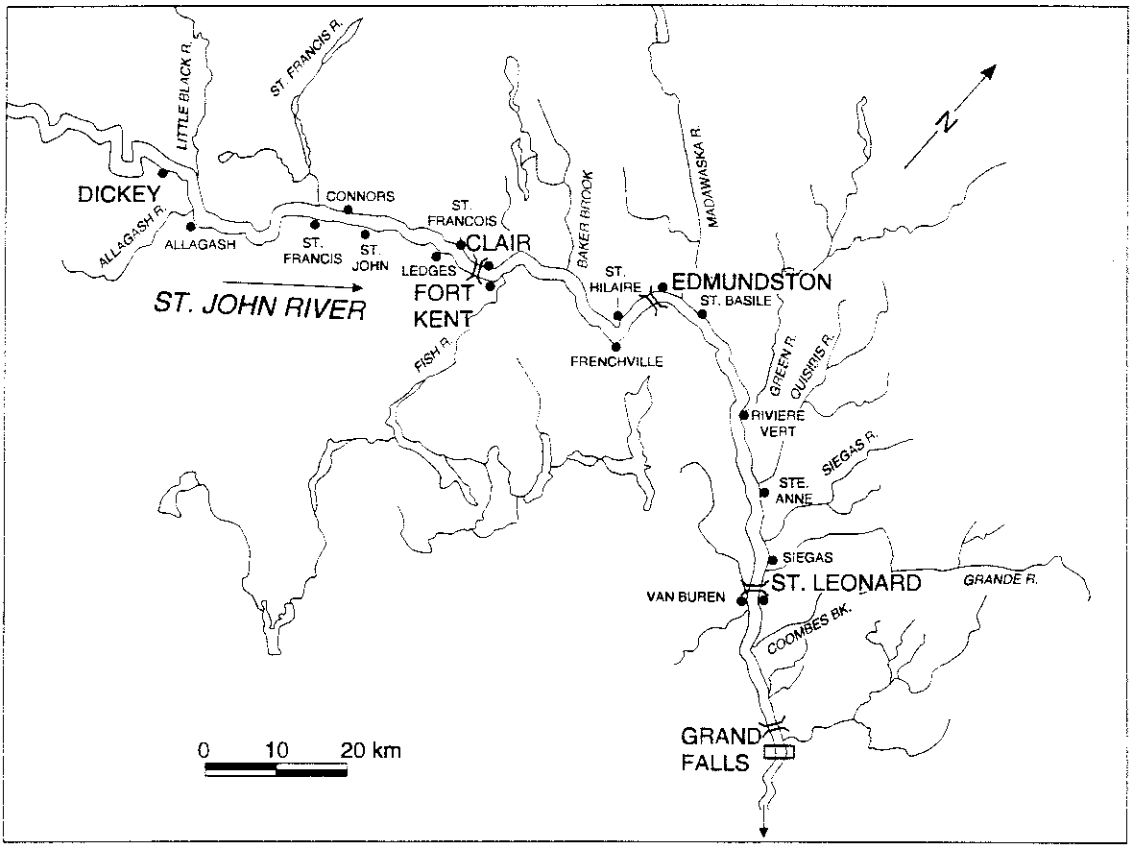

Fig. 1. Schematic diagram of the study reach: from Beltaos et al. 1996, with changes. For clarity, the river is drawn much wider than it is (actual width = 150–300 m).

winter breakup events took place, one in 1995 and two in 1996, all three resulting from brief thaws attended by significant rainfall. Apart from the immediate risk of ice-jam flooding, winter events may also enhance the severity of the coming spring breakup, via high freeze-up levels and large thickness due to ice jams that freeze in place when the cold weather resumes (Beltaos, 1997). Another unusual occurrence pertains to the very high spring freshet flows that were experienced in 1993 and 1994.

To determine whether such occurrences are random or arise from long-term trends, a hydro-climatic analysis was carried out, using flow and weather records for sites within the study area. The results of the analysis are reported in the following sections.

2. Data Sources

A general understanding of river ice processes within the study reach has been obtained from field observations and measurements during the 1992-93 to 1996-97 ice seasons. Of particular utility have been the findings with respect to the initiation (or 'onset') of breakup at the site of the international bridge between Clair, NB and Fort Kent, Maine (Fig. 1).

Historical daily flow data and river stages recorded at the Fort Kent gauge, operated by USGS (United States Geological Survey), have been kindly provided by USGS or downloaded from the corresponding internet site. The flow record begins in October, 1926. Weather records for Eastern Canada were purchased from Environment Canada's Atmospheric Environment Service. The closest site is Edmundston (Fig. 1), located some 35 km below Fort Kent. Ideally, a weather station should be selected so that it is located within the basin draining at the gauge, i.e. upstream of Fort Kent. However, there are no upstream stations, either in Canada or in the US, having as long and detailed records as at Edmundston. Over the years, four nearby climatic stations have been utilized, as summarized in Table 1.

Table 1. Climatic data stations at Edmundston

Station number	Latitude	Longitude	Elevation	Years of Record
8101300	47°22′ N	68°20′ W	174 m	1913-1957
8101301	47°22′ N	68°20′ W	152 m	1949-1979
810JL00	47°22′ N	68°17′ W	198 m	1979-1983
810AL00	47°20′ N	68°11′ W	152 m	1983-1996

The differences in elevations represent a range of 46 m, and could produce differences in recorded air temperatures and precipitation values. Overlapping records (first and second stations) indicate that there can be large differences in daily amounts of winter/spring rainfall, but these are reduced when total monthly values are calculated. There is a tendency for the station of the lower elevation to record a greater amount of rainfall. Daily mean temperatures compare more favourably, while the respective differences appear to be random, thus producing very similar monthly mean values.

3. Flows Required to Initiate Winter Breakup

Herein, the onset of breakup at a particular site is defined as the time when the winter ice cover is set in sustained motion, leading to rapid fracture into relatively small ice blocks that can accumulate against intact ice cover to form ice jams. Thus, this definition excludes: (a) thermal breakup events, characterized by in situ ice disintegration, rather than by movement and fracture; and (b) very brief or 'jostling' ice cover movements that result in mere repositioning of ice sheets within the channel boundaries.

Based on extensive field observations and data, Beltaos (1997) proposed the following equation to quantify the onset of breakup:

$$\Phi_B \equiv \frac{8m^2\tau}{m-0.50}\frac{W_B - W_i}{h_{io}} = \beta\sigma_o \frac{\sigma h_i}{\sigma_o h_{io}} \quad \left(= \beta\sigma_o F(S_5)\right) \qquad (1)$$

in which W_B = water surface width at the time breakup is initiated; W_i = ice cover width, usually equal to river width at the stage of the preceding freeze-up, minus shore strips formed by hinge cracks; h_i= ice cover thickness at the time of breakup; h_{io}= ice cover thickness before the start of thermal deterioration ($h_{io} \geq h_i$); m = local radius of curvature divided by the river width; τ = 'ice-driving' force per unit area = flow shear stress applied on the bottom of the ice cover plus downslope component of the cover's own weight; σ = flexural strength of the ice cover at the time of breakup; σ_o = undeteriorated ice strength; and β = dimensionless coefficient between 0.3 and 1.5. The fraction on the RHS of Eq. 1 reflects the reduction in the ability of the ice cover to resist flexure. Beltaos (1997) noted that this quantity cannot be determined theoretically without rarely available hydro-climatic data (Prowse et al. 1990), and used a surrogate thermal index represented by the empirical function $F(S_5)$. Here S_5 = accumulated degree-days above a base of -5° (Bilello, 1980). With this assumption, breakup onset data from several river sites in Canada were plotted in the form suggested by Eq. 1 and collapsed within a relatively narrow range. Data from the Clair bridge site are seen in Fig. 2 to fall within or near this range. The data points in Fig. 2 include both those obtained during the 1992-97 field program, and those deduced from an analysis of hydrometric records at the nearby Fort Kent gauge.

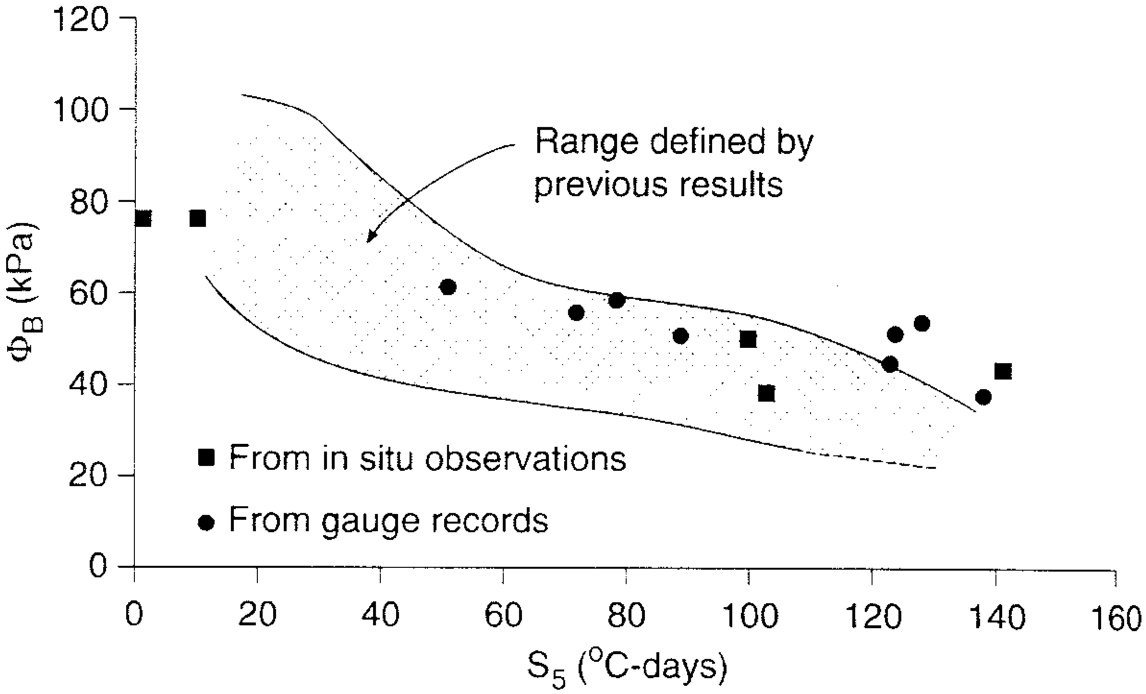

Fig. 2. Breakup initiation data for the Saint John River at Clair International bridge and range of previous findings in other rivers.

To calculate breakup initiation flows applicable to winter events, the value of S_5 is set at 0°C-days, since such events result from brief thaws and rapid runoff, which allow little time for thermal deterioration of the ice cover. The value of the LHS of Eq. 1 is thus taken as 80 kPa by extrapolating back to the vertical axis of the graph in Fig. 2. Using the end of January as a typical time of a winter breakup event, the applicable ice thickness can be estimated from past data to be at least 0.28 m, and 0.44 m on the average. For typical freeze-up conditions (W_i = 187 m), it can be shown that these thickness values correspond to breakup initiation flows of Q_B = 510 and 640 m^3/s, calculated from detailed bathymetric and water surface slope data in the vicinity of the Clair bridge site.

4. Analysis of Flow Records

To determine whether the winter breakup events of 1995 and 1996 were random occurrences or parts of long-term trends, the USGS hydrometric records at Fort Kent, Maine, located at about the mid-point of the study reach, were examined first. It was found that the peak daily flows for the 'winter' period, herein defined as the time between January 1 and March 15, exhibit a very slight decline until the 1950s followed by an increasing trend, as illustrated in Fig. 3. It is only in recent years, however, that peak winter flows have been large enough to effect ice breakup. The peak flow has exceeded the 510 m^3/s threshold five times: twice in 1996; and once in each of 1995, 1981 and 1979. From stage records, it is known that the 1979 occurrence did not initiate a breakup event, owing to: (a) the 'threshold excess' (= peak flow during event minus 510 m^3/s) being small; and (b) the event occurring in March, when the ice cover thickness would be well in excess of 0.28 m, the value used to compute the lower breakup initiation flow of 510 m^3/s. The remaining four instances are known to have caused breakup events.

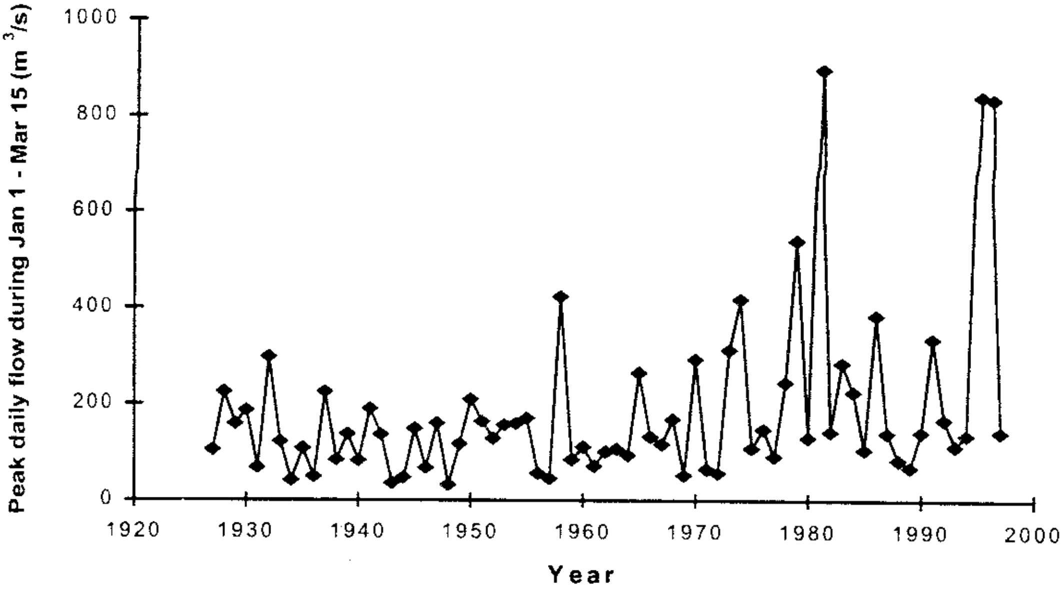

Fig. 3. Variation of peak 'winter' flow in past seventy years (Fort Kent).

Consideration of individual months for the entire winter-spring period (December-May) has indicated similar trends (Fig. 4), except for May, which has experienced a decline after 1960 or so. For each month, the average trend over the entire record was determined by linear regression, and the results are summarized in Table 2.

In this table, the parameter P_F is the significance level of the F-statistic, i.e. the probability that the regression-derived slope could occur by chance, if in reality there were no trend in the data (null hypothesis). Trends associated with P_F values over 0.05 are not considered 'statistically significant' (Draper and Smith, 1981), though the 0.05 level may be too stringent in many practical situations. Moreover, conventional parametric

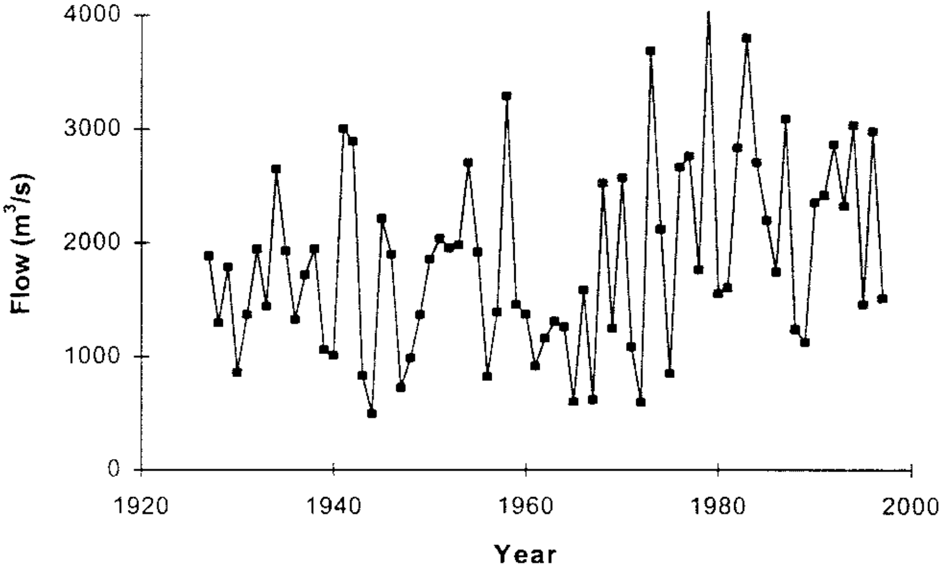

Fig. 4. Variation of peak April flow in past seventy years (Fort Kent).

Table 2. Statistics of monthly peak-flow trends[1] in the period December to May (Ft Kent)

Month	December	January	February	March	April	May	Mean annual flow
Slope (m^3s^{-1}/yr)	+0.9	+1.9	+2.4	+2.2	+12.3	-4.7	+0.2
R^2	0.005	0.09	0.12	0.014	0.09	0.014	0.004
P_F	0.57	0.01	0.004	0.33	0.01	0.32	0.59
P_{MK}	0.17	0.06	0.006	<0.002	0.03	0.27	0.44
Percent 100-year change[2]	+27	+119	+205	+84	+66	-24	+7

[1] Straight regression lines fitted to all data points.

[2] Calculated as: slope times 10000, divided by average peak flow over period of record.

tests, such as the F-test, may not be meaningful in the present case because the regression residuals themselves exhibit temporal trends and are not normally distributed. Consequently, the Mann-Kendall test (Hirsch et al, 1982; Burn, 1994), which is based on the signs of differences between temporally shifted pairs of a variable, was also applied. In Table 2, the quantity P_{MK} represents the probability that the observed data series could occur by chance under the null hypothesis (i.e. 'there is no trend in the data'). According to the Mann-Kendall test, the observed trends for December, May, and the annual flow are not statistically significant. The following interpretation of the results presented in Table 2 is thus subject to this limitation.

First, we may note that the mean annual flow does not seem to have changed appreciably, a result that is corroborated by the findings of Hare et al (1997a and b) who examined annual Saint John River flows further downstream (Grand Falls, Mactaquac). In percentage terms, the largest flow increases are associated with the main winter months, January and February, which again points to an increased potential for winter breakup occurrence. The increase in April peak flows is the most pronounced in absolute terms, suggesting a 100-year augmentation of 1230 m^3/s, a considerable amount for the upper Saint John River. A similar increase in freshet peaks was reported by Hare et al (1997a and b) for downstream reaches of the river. Note that the freshet most frequently occurs in April.

The year-to-year variability of monthly peak flows was also investigated by considering the variable $V = |Q(N+1) - Q(N)|$, in which Q(N) is the peak daily flow for any given month in year N. Except for the month of May, this quantity also increases with time, and a strong relationship was found between trends in Q and V for all of the examined months.

5. Analysis of Climatic Records

The above noted trends in river flows are consistent with the observed changes in the ice regime of the river. Since the flow hydrograph is governed by climatic inputs, it is of interest to consider whether corresponding trends can be detected in weather records. The main climatic parameters considered in the analysis are the mean monthly air temperature and the accumulated monthly rainfall, as obtained from the records of the four Edmundston stations described in Table 1.

Typical temperature results are shown in Fig. 5 for the month of February. A slight warming trend is discernible, as evinced by the regression line plotted through the data points. Similar trends were found for other winter/spring months (Table 3). The rates of warming are of the order of 1°C per century, while the P_F values suggest that the null hypothesis ('no upward trend') cannot be statistically rejected for most of the months considered. Nevertheless, the observed trends are consistent with previous findings for the Saint John River basin and for the country as a whole, though they differ from findings in other parts of Atlantic Canada (Hare et al, 1997a and b).

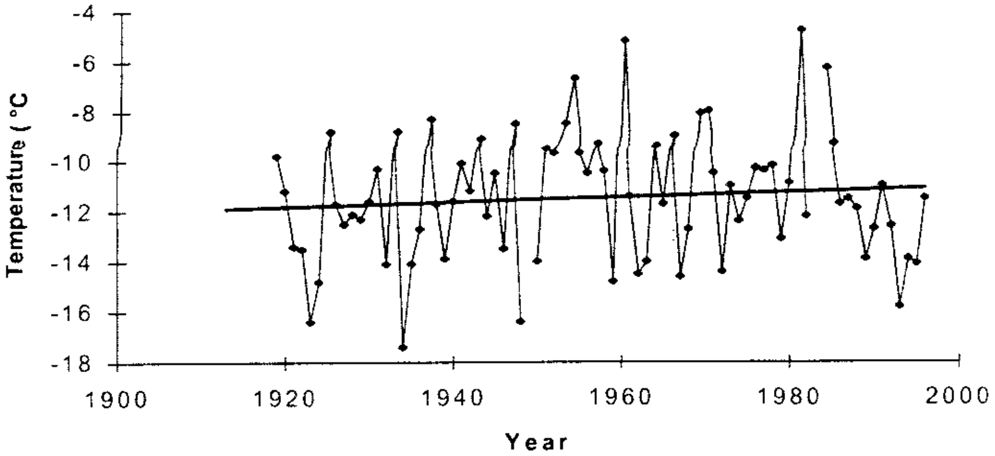

Fig. 5. Variation of mean February air temperature in past eighty years (Edmundston).

Table 3. Statistics of monthly temperature trends[1] for the period December to May

Month	December	January	February	March	April	May
Slope (°C/yr)	+0.0042	+0.011	+0.0093	+0.021	+0.016	+0.013
R^2	0.0011	0.0094	0.0071	0.038	0.051	0.032
P_F	0.78	0.40	0.47	0.09	0.05	0.13

[1] Straight regression lines fitted to all data points.

The question now arises as to whether a slight rise in air temperature could result in the kind of changes already detected with respect to the flow hydrograph. An important indicator here could be the number of mild days that may occur during a given month or ice season. Mild weather enhances the probability of a rainfall event occurring, which in turn may lead to increased runoff. Defining 'mild' as a day with mean air temperature above 0°C, the percentage of mild days occurring in January and February is depicted in Fig. 6. The strong increasing trend is likely caused by the typical behaviour of probability distributions in ranges of rare events. This concept is illustrated in Fig. 7. The shaded area under the curve, to the right of the value 0°C, represents the small probability of a mild day occurring during a winter month. Note that the total area under the curve is equal to one. Even a slight shift of the curve towards the right (i.e. an increase in the mean of the distribution) can greatly augment this probability and thence the number of mild days per winter.

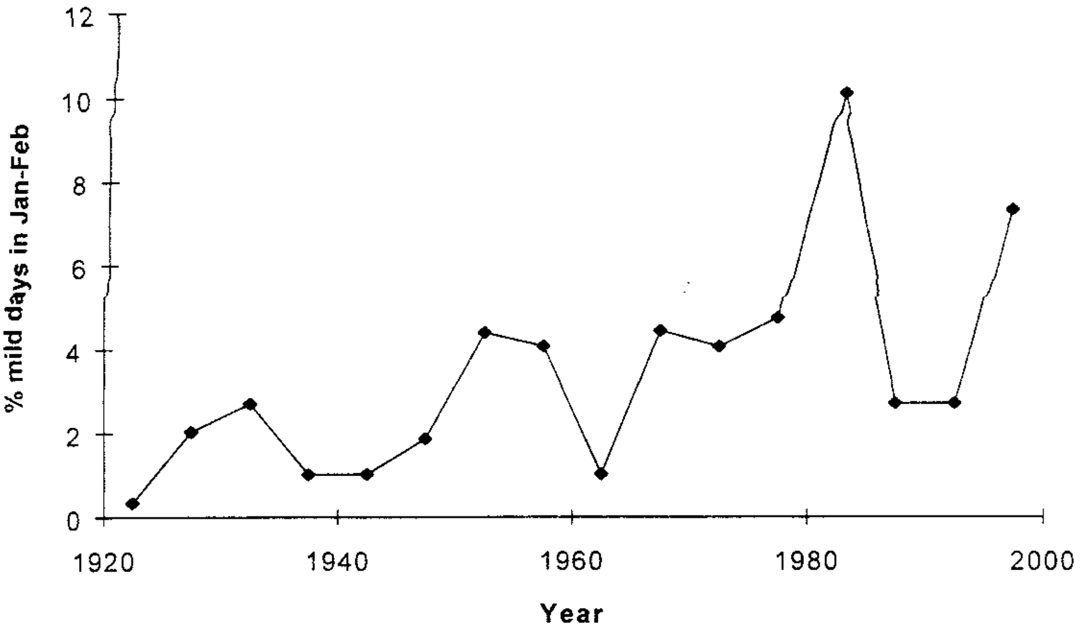

Fig. 6. Occurrence of mild (>0°C) days during the main winter months (Edmundston). Each data point represents a five-year average and is plotted at the middle of the respective time interval (except for the latest, applicable to the years 1996-1998).

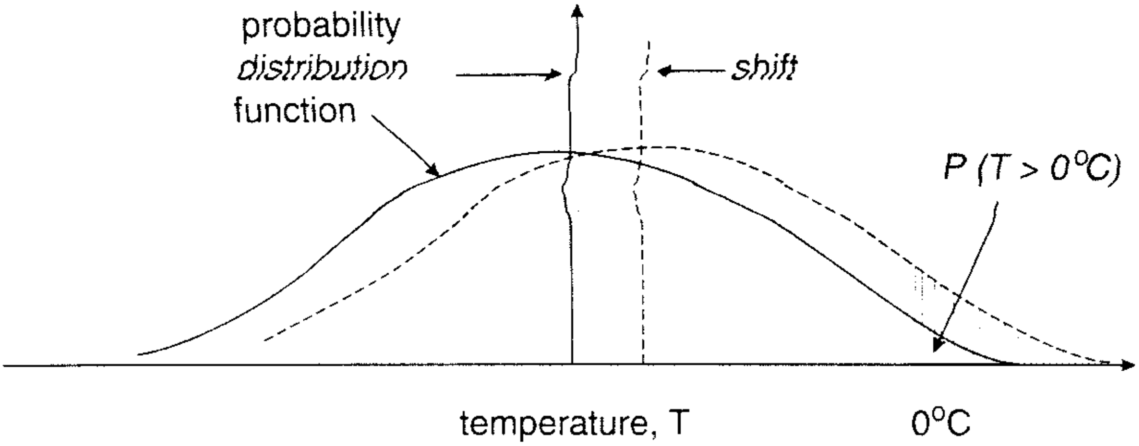

Fig. 7. Schematic illustration of the sensitivity of rare-event probabilities to a shift in the mean value of a random variable.

The increased incidence of mild days suggests the possibility of enhanced rainfall, since more precipitation events may now produce rainfall instead of snow. This expectation is confirmed by rainfall data, as illustrated in Fig. 8, and summarized in Table 4. In the latter, the significance parameter P_F is subject to the same limitations as those described earlier with reference to Table 2; hence, the non-parametric statistic P_{KM} is also listed.

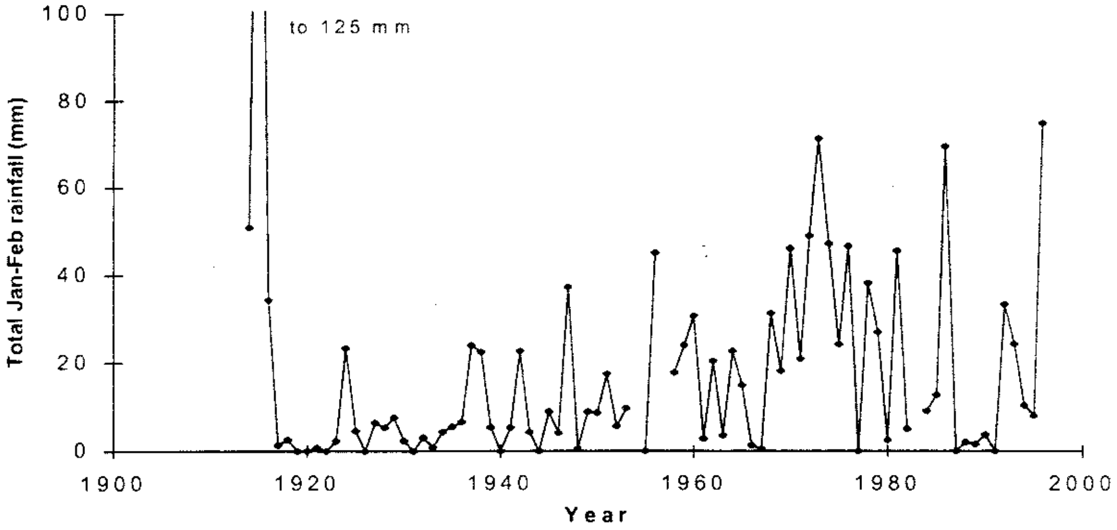

Fig. 8. Combined rainfall during January and February (Edmundston).

Table 4. Statistics of rainfall trends[1] for the period December to May (Edmundston)

Month	December	January	February	March	April	May
Slope (mm/yr)	+0.18	+0.054	+0.03	+0.18	+0.30	+0.095
R^2	0.03	0.0064	0.0014	0.068	0.054	0.003
P_F	0.12	0.48	0.74	0.02	0.04	0.62
P_{KM}	0.33	0.08	0.18	0.002	<0.002	0.33

[1] Straight regression lines fitted to all data points.

Examination of concurrent data on total precipitation indicated negligible trends, suggesting that rainfall increases have largely taken place at the expense of snowfall. A noteworthy feature in Fig. 8 is the extremely high rainfall recorded for January and February of the year 1915. This resulted from intense runoff events that occurred in both months, each having a strong moderating influence on the corresponding slope values listed in Table 4.

6. Time of Arrival of the Spring Breakup

Increased air temperatures and higher flows are also manifested in earlier arrival of the spring breakup. Using a similar analysis as was done in Section 3, it was calculated that a typical breakup initiation flow for the spring breakup event (i.e., after allowing for full ice thickness growth and typical degree of thermal deterioration) is $Q_{Bspring}$= 570 m^3/s. The date when this flow is first exceeded in the spring can be defined as the 'probable time of spring breakup initiation' and used to examine possible changes over the period covered by the flow record.

This is illustrated in Fig. 9. The data points exhibit no trend during the first half of the century but a perceptible decreasing trend appears to begin in the late 1950s. Application of linear regression to the entire data set suggests an average rate of breakup advance of 11 days per century (d/c). This rate is approximately doubled if the no-trend period (up to the 1950s) is ignored. As a secondary index, the date of the first spring flow peak was also examined and similarly found to be occurring earlier, at an average rate of 15 d/c.

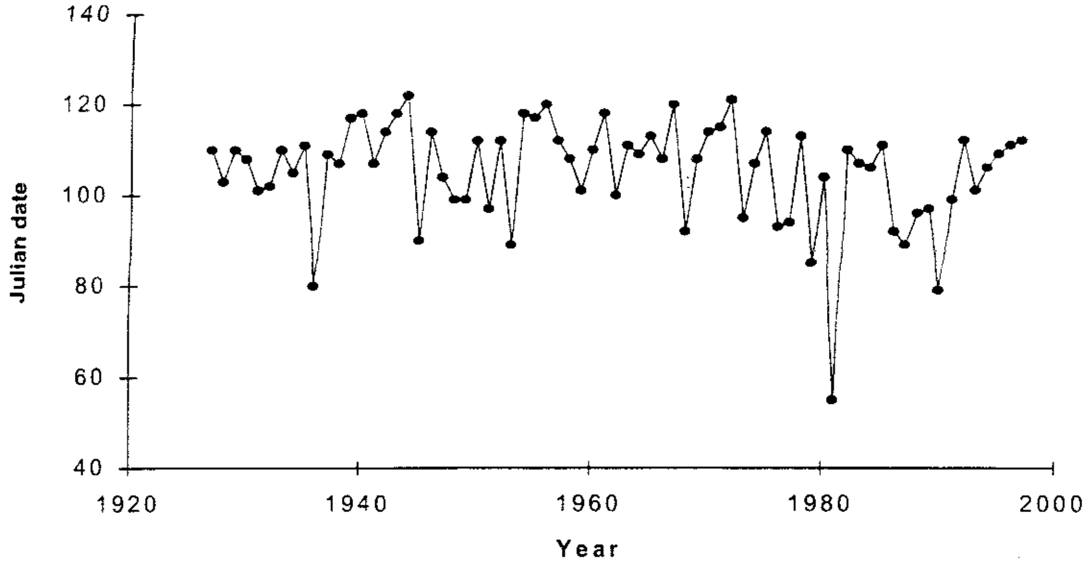

Fig. 9. Probable time of breakup initiation, defined as first day when Q>570 m^3/s. Linear regression: slope = - 0.11 days/year; $R^2 = 0.04$; $P_F = 0.08$.

These rates of advance of the spring breakup are comparable with what has been found elsewhere, both in Canada and abroad (Zachrisson, 1989: about 19 d/c in Sweden; Soldatova, 1993: up to 11 d/c in parts of the former Soviet Union; Rannie, 1983: about 11 d/c on the Red River near Winnipeg). Williams (1970) reported that the breakup on the Saint John River occurred 15 days earlier in the 1950s than in the 1870s (the locality was not mentioned but is probably Fredericton, NB). The rate of advance may be more pronounced in west-central Canada. According to Burn (1994), who examined records of 84 hydrometric stations, the snowmelt peak flow tends to arrive earlier, at an average rate of 25 d/c.

At the same time, the present results differ from findings in other parts of Atlantic Canada. Brimley and Freeman (1997) reported that the number of days with ice in the river has increased since 1952 (when the data became a part of the record) at stations located in Newfoundland and Nova Scotia. This is consistent with, though not entirely explained by, a concurrent reduction in temperature (see also earlier comments on temperature trends in Atlantic Canada, per Hare et al, 1997a and b).

7. Discussion

The preceding findings point toward the following sequence of causes and effects: Slightly warmer air temperatures enhance the incidence of mild winter and early spring days, which in turn causes increased amounts of rainfall. Increased rainfall produces higher runoff, and thence higher flow peaks during the winter and spring.

In addition to an increase in magnitude, the flow and rainfall trends also exhibit increases in variability (see Figs. 3, 4, and 8). The present climatic findings are thus consistent with the predictions of General Circulation Models, which take into account the effects of increased greenhouse gas concentrations. However, it is not possible at present to state whether the documented climatic changes over the past eighty years are a part of a naturally occurring cycle or triggered by global climate change. Be that as it may, the present data illustrate the high degree of sensitivity of river ice processes to climatic inputs and elucidate some of the changes to the ice breakup regime of Canadian rivers that may result from natural or anthropogenic warming.

The observed changes are two-fold. The first is the advent of winter breakup events in the upper part of the river, unknown until the 1980s. So far, the flows associated with winter runoff events can be sufficient to initiate breakup, but they have not attained magnitudes that may cause major ice-jam flooding. The main risk posed by such events, at present, is indirect: any ice jams that form during a winter event produce higher freeze-up levels when the cold weather resumes, as well as thicker ice covers. These factors enhance the potential severity of the spring breakup. The same outcome is likely to be reinforced by the second type of observed change to the breakup regime, i.e. the increase in the freshet flows. These effects are probably manifested in the relatively high frequency of spring flood events experienced in recent years (e.g. 1976, 1987, 1991, and 1993).

The impacts of the changing ice breakup regime are likely to be detrimental from both the ecological and the economic points of view. Economic impacts of ice jams are well known (Beltaos, 1995), and involve property and infrastructure damage, interference with navigation and constraints to hydropower generation. Equally important is the strong relationship between river ice and aquatic ecosystems, in terms of both habitat and life cycle (Prowse and Gridley, 1993; Prowse, 1994; Scrimgeour et al, 1994). River ice jams and the surges caused upon their release, can have many detrimental impacts on aquatic life, such as habitat degradation or even complete destruction, stress and mortality effects on aquatic species, or deposition of fines and deterioration of spawning grounds.

How pronounced the above noted impacts are likely to become in the future will depend on the degree to which the current warming trend is maintained or even accelerated over the coming decades. A reduction in the rate of warming would be a desirable outcome.

8. Summary and Conclusions

A small rise in winter air temperatures over the past 80 years has been accompanied by a large increase in the number of rare occurrences, such as mild winter days. In turn, this appears to have enhanced the amounts of winter and early spring rainfall, with corresponding increases in the peak flows occurring during the winter and early spring months. In the last two decades, the augmented winter flows have been sufficiently large to cause breakup of the river ice cover. The resulting ice jams freeze in place when cold weather resumes, and may pose increased risks of major flooding during the following spring breakup event. Increased freshet flow peaks, which almost always occur in April, pose additional risks of major ice-jam and flood events. If the current trends continue, economic and ecological impacts of ice jams are likely to increase.

Acknowledgements

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