ICE BREAKUP OF THE NASHWAAK RIVER, NEW BRUNSWICK[5]

Prowse, T.D.[1], Beltaos, S.[2], Burrell, B.C.[3], Tang, P.[3], and Dublin, J.[4]

1. National Hydrology Research Institute, Environment Canada, Saskatoon, Saskatchewan
2. National Water Research Institute, Environment Canada, Burlington, Ontario
3. New Brunswick Department of the Environment, Fredericton, New Brunswick
4. Atmospheric Environment Service, Environment Canada, Fredericton, New Brunswick

ABSTRACT

The Nashwaak River, New Brunswick is shown to have a long history of ice jam flooding, with ice jams being a contributing factor in 42 major floods recorded over the last 180 years. The hydroclimatic characteristics of the basin are reviewed and shown to produce both mid-winter and spring breakups. A model for breakup prediction is reviewed and results from an ice jam analysis are presented.

La rivière Nashwaak au Nouveau-Brunswick a une longue histoire d'inondations causées par les embâcles, ce facteur ayant contribué à 42 inondations majeures au cours des 180 dernières années. Les caractéristiques hydroclimatiques du bassin sont examinées; il est démontré qu'elles produisent des débâcles au milieu de l'hiver et au printemps. Un modèle de prévisions des débâcles est étudié et les résultats d'analyse d'un embâcle sont présentes.

INTRODUCTION

Ice jams are a regular occurrence on ice-covered rivers and are frequently responsible for severe flooding accompanying the breakup process. Case studies of breakup-ice jam problems have been documented in all climatic regions of Canada and almost every province (Petryk, 1985). This paper reviews the situation on the Nashwaak River, a maritime river that has a lengthy record of ice jam flooding. All authors are members of the New Brunswick Subcommittee on River Ice, a group instituted to support the Canada-New Brunswick Flood Damage Reduction Program. Given the depth and breadth of work conducted on the Nashwaak, this brief paper can only summarize some of the more salient results.

BASIN DESCRIPTION

The Nashwaak River is a major tributary of the estuarine portion of the Saint John River. The river basin has a drainage area of 1760 km^2 (Figure 1) and is nearly completely forested, with wooded areas and farm fields interdispersed with ribbon residential development along the highways which generally parallel the lower 50 km of the river. There are two incorporated municipalities in the Nashwaak River valley: The City of Fredericton (pop. 44350) and the Village of Stanley (pop. 2115). Unincorporated communities include Nashwaak Bridge, Taymouth, Durham Bridge, Nashwaak Village, and Penniac (Figure 1). Approximately 2600 people live along the river (GEMTEC, 1989).

[5] NHRI Contribution No. 89037

The Nashwaak River flows from its headwaters in the Miramichi Highlands in an easterly direction to Nashwaak Bridge. In this upper portion of the catchment, the river and its narrow flood plain are confined by steep valley walls. From Nashwaak Bridge, the river flows in a southerly direction to its confluence with the Saint John River at Fredericton. This lower portion of the Nashwaak River basin lies within the New Brunswick Lowlands, characterized by gentle relief generally less than 100 m above mean sea level, and broad flood plains. The river noticeably widens with channel width varying from approximately 23 m at Nashwaak Bridge to 46 m near Fredericton. The flood plain is primarily used for pasture, although a large portion has been overgrown by shrub.

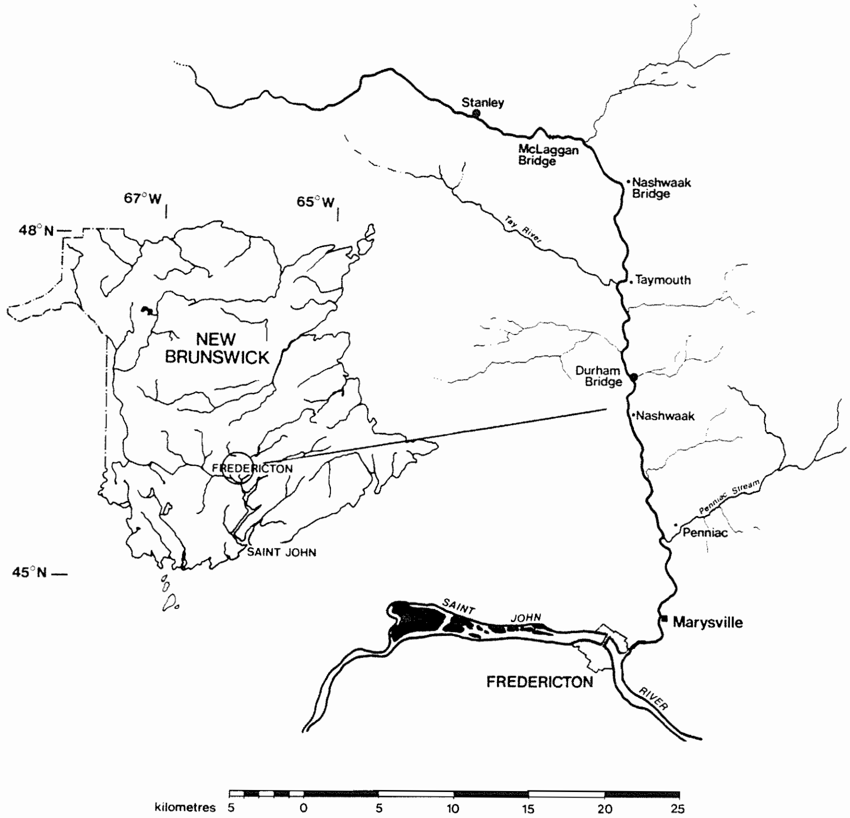

Figure 1. Nashwaak River New Brunswick

Despite close proximity to the Atlantic Ocean, the climate of the Nashwaak River Basin is predominately continental, with warm humid summers, long cold winters and no dry season. Mean annual temperatures decrease with elevation from 5.4°C at Fredericton Airport near the mouth of the Nashwaak River to approximately 3.0°C in the headwaters. During January, the coldest month of the year, monthly average temperatures range from -9.2°C at Fredericton to an estimated value of -12°C in the headwaters. It is not uncommon to have minimum temperatures during winter fall to -25°C or below. As an indication of the relative severity of the winter season, accumulated freezing degree days average 896.0 per annum at Fredericton compared with 956.7 for Montréal and 634.0 for Toronto. There are no distinct wet or dry seasons and precipitation can be said to be more or less evenly distributed with snow comprising 25 percent of the annual total precipitation. A slight precipitation gradient results in 300 - 350 mm of snowfall in the headwaters and 250 - 300 mm in the lower portions of the basin. Although winter snow cover usually melts and runs off in April, it can occur as early as mid-March and as late as mid-May.

Most of the precipitation and many snowmelt events in the Nashwaak Basin are associated with the passage of extra-tropical storms spawned along the eastern seaboard of the United States. These can occur any time of the year, but are most frequent and severe during the winter season when the contrast between cold continental air and air masses over adjacent waters is the greatest. Strong flows of cold air forming behind developing storms contribute greatly to the intensification of these storms. Storm tracks have a southwest to northeast orientation, and their isohyetal patterns tend to be elongated in the direction of their movement. Thus, although precipitation may be general over much of the province for a storm, the extreme precipitation is usually concentrated in a relatively narrow belt, and the intensity and amounts fall off rapidly in the southeast and northwest direction from the track of the storm.

FLOOD HISTORY

Inundation of low lying, largely agricultural land along the Nashwaak River is an annual occurrence, but 42 major events have produced significant flood damage of more developed sections over the last 180 years (see Kindervater, 1986; LeBrun-Salonen, 1985). Ice jams were a contributing factor in 2/3 of these events, usually in combination with rainfall and snowmelt. The seasonal distribution of these events is shown in Figure 2. Five major jam events are described briefly below.

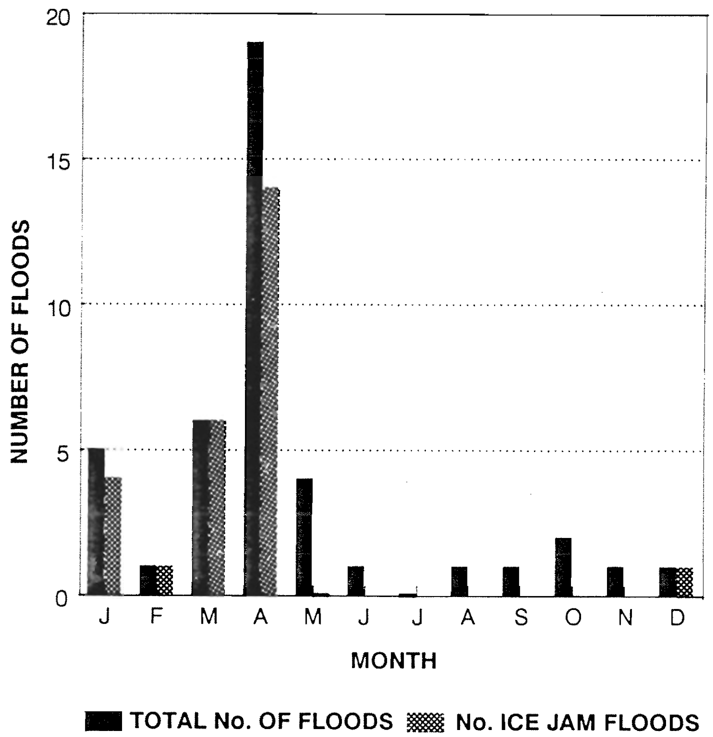

Figure 2. Flood events by month.

Case Studies

March 19 to March 24, 1902: Several ice jams occurred along the Nashwaak River resulting in extensive damages and one fatality. Heavy rainfall, and snowmelt due to high temperatures contributed to high streamflow and a premature breakup. The worst jam, comprised of logs and ice, formed at Stanley and lasted for several days. When this jam broke, large areas downstream were flooded by the surge of water causing the destruction of a 53-m steel bridge, several smaller bridges, and a mill dam.

March 26 to April 3, 1953: More than 50 mm of rain fell during a two-day period resulting in a sudden breakup and the formation of several ice jams. A large jam which had formed upstream of Stanley, released on March 30 and caused extensive damage in the Stanley area. Six families had to be evacuated from their homes. A well-packed jam formed between Taymouth and Durham Bridge resulting in the submergence of 3 km of the Canadian National Railway. Two attempts were made to remove the jam using explosives; the second attempt on March 31 was successful. Rail service was disrupted for over a week.

February 2 to February 4, 1970: Very low temperatures and an abnormally low snowfall caused a thick ice cover to form during the early winter. During the first week of February, heavy rainfall and unseasonably high temperatures initiated breakup. The heavy ice run destroyed bridges at Durham Bridge and Marysville. Several houses and summer cottages were damaged or destroyed, necessitating the evacuation of some residents along the river by helicopter.

March 26 to March 29, 1979: Mild temperatures and heavy rainfall contributed to premature breakup leading to the formation of several ice jams. The Village of Stanley sustained the greatest flood damages as the largest jam formed just downstream of the Stanley bridge. Twelve families had to be evacuated and there was extensive property damage. Ice jams at McLaggan Bridge and Nashwaak Village caused major traffic disruptions.

April 1987: Rapid snowmelt led to increased flows causing premature breakup resulting in ice jamming at Stanley, and near McLaggan Bridge. At least nine homes in Stanley were evacuated and roads were closed for several days. Specific hydrometeorological details concerning this event are described later.

Flood Damages

Estimation of total ice-related damages is difficult because comprehensive, quantitative data is not generally available. Some of the most well documented and significant direct flood damages are associated with hydraulic structures. During the March 1902 ice jam flood, five dams and two bridges within the Nashwaak River Basin were destroyed. During the February 1970 event, bridges with an estimated value of $990,000 (1983 dollars) were destroyed at Nashwaak Bridge and Stanley. Ice runs and ice jam floods have resulted in 11 other incidents of damage to bridges. Direct flood damages have also occurred to businesses, residences, summer cottages and agricultural facilities.

Indirect costs due to disruption of railway and highway traffic have also been high. For example, Route 8, a major transportation artery between Fredericton and Newcastle, has been inundated on several occasions. There have also been several washouts of highways and railways.

The stress caused during evacuation of residences are among the intangible human costs of flooding along the Nashwaak River. Homes were evacuated during at least seven ice jam flood events. One life has also been lost. During the flood of March 1902, a woman was swept off her feet by a sudden surge of water resulting from the release of an upstream ice jam (LeBrun-Salonen, 1985).

Peak Water Levels

To identify the overall magnitude of floods along the Nashwaak River and the lower reaches of two tributaries: the Tay River and Penniac Stream, a contract study was conducted by GEMTEC (1989). It was based on historical data and field surveys of past water levels and tree scars. Since 1896, 28 of the 39 recorded flood events were associated with ice jams. Figure 3 shows the maximum flood elevations produced over this period by ice and open water events. The highest recorded levels were due to: the 1987 ice jam flood from Stanley to Nashwaak Bridge, the 1970 ice run from Nashwaak Bridge to Taymouth, and the 1961 open water flood along the lower part of the Nashwaak Valley from Nashwaak Village to Upper Marysville (GEMTEC, 1989).

NATURE OF ICE BREAKUP

To develop an understanding of the breakup sequence and dominant processes, a field program was initiated in 1983 using dedicated ice observers. Figure 4 is a schematic compilation of these observations, showing conditions on only those days characterized by significant change in the ice regime. As evidenced by Figure 4, breakup ice clearance often occurs on some of the lower tributaries, such as the Tay and Penniac Rivers, before the colder, upper reaches breakup (e.g. note March 25, 1985) or flush clear of ice jams (e.g. April 1 and 2, 1987). This in contrast to the case of northward flowing rivers

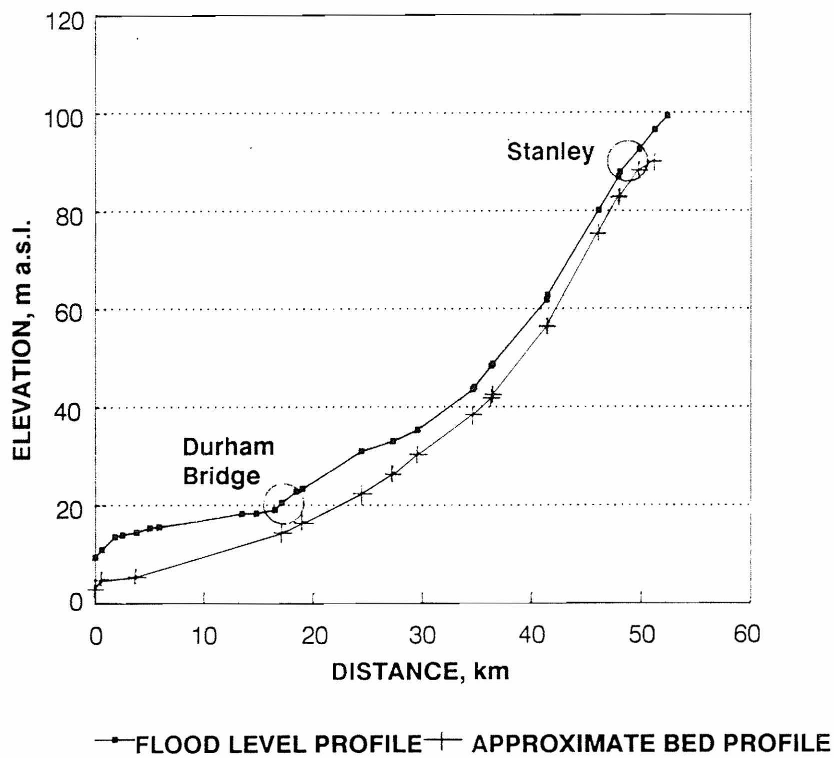

Figure 3. Flood and bed profiles (after GEMTEC, 1989).

where the breakup front originates in warm headwaters and progresses downstream into colder reaches occupied by intact, competent ice. Duration of breakup on the Nashwaak (i.e. from the first significant breakup of the tributaries to the final ice clearance on the main stem) usually requires several weeks, such as in 1983, 1985 and 1988, although it can also be very rapid lasting little more than a week as in 1987.

Extremes in breakup conditions that occur on the Nashwaak can be best illustrated by comparing the 1986 and 1987 events (Figure 5). Prior to this, some background regarding potential breakup conditions are required. In general, breakup is driven by downstream forces created by increased flow and resisted by the intact ice sheet. The magnitude and rate of increase in discharge can be highly variable depending on the amount of snow, and the rate at which it melts, runs off and is augmented by rainfall. Similarly, the resistance of the ice sheet to the advancing breakup front, as determined by ice thickness and strength, can also be highly variable. Typical peak ice thicknesses on the Nashwaak for the months of January, February and March are approximately 0.39, 0.46 and 0.51 m, respectively (after LeBrun-Salonen, 1985), although inter-annual variability also exists depending on the severity of the winter. Severity refers not only to how cold conditions were for ice growth but also to how warm conditions were for ice thinning, particularly in the period immediately preceding breakup. Similar to the temperature-index method for predicting ice growth, Bilello (1980) proposed that reductions in ice thickness can be estimated by:

[1] $\Delta h_i = \beta \, T_D$

where β is an empirical coefficient (m/°C/d) and T_D is accumulated thawing degree days (°C/d) with a base of -5°C.

Resistance of an ice sheet to breakup, as controlled by ice strength, depends on its temperature and the absorption of solar radiation. For cold ice sheets (i.e. <0°C), strength of the ice cover generally decreases as it begins to warm. Significant reductions in strength can also occur after the ice sheet reaches 0°C, primarily due to

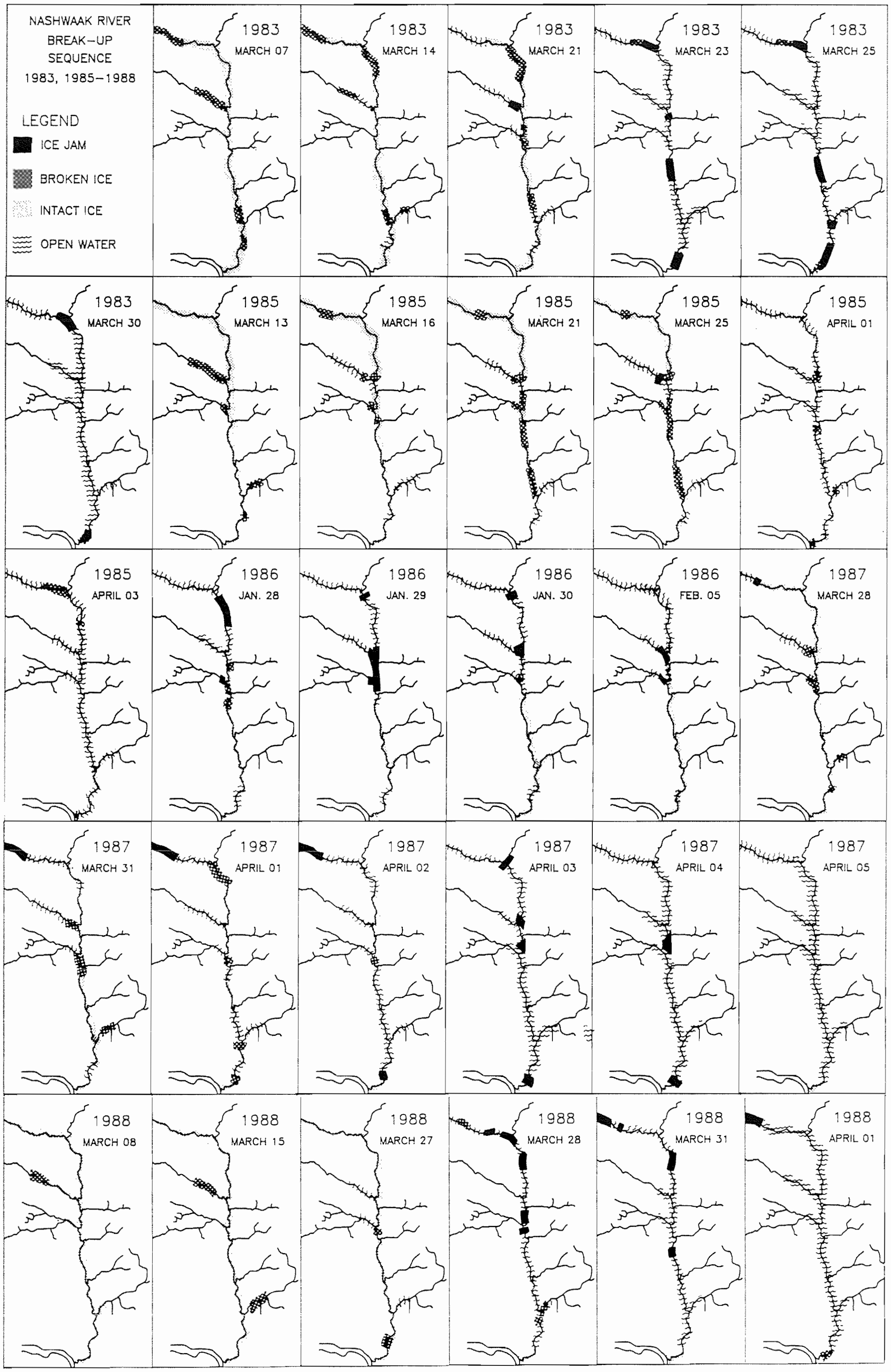

Figure 4. Summary of breakup observations.

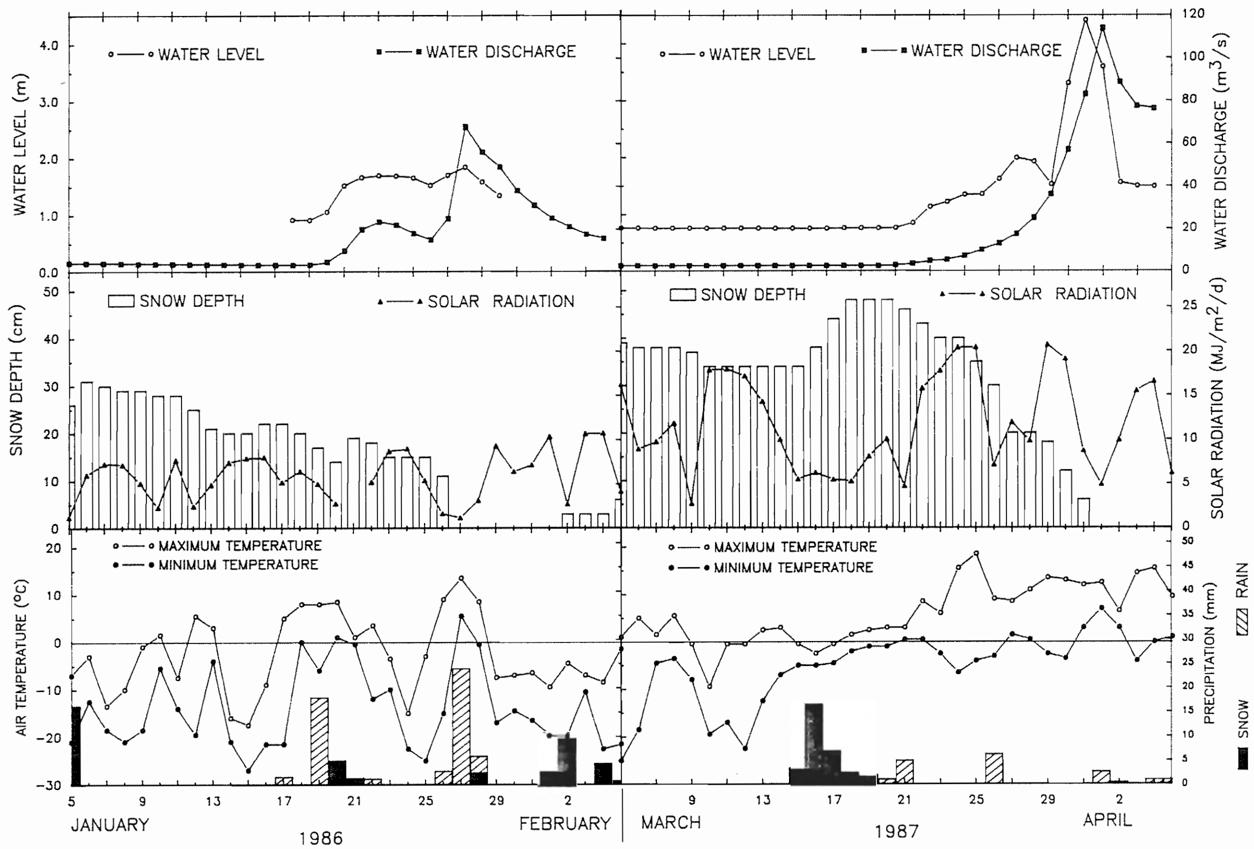

Figure 5. Hydrometeorological conditions during 1986 and 1987 breakups.

structural decay resulting from the absorption of solar radiation. In general, the greatest changes in strength result from long protracted melt/breakup events in which solar radiation is the dominant heat flux. In contrast, only minimal reductions in strength should result from rapid rain-on-snow melt/breakup events, where exposure to radiation is at a minimum. The 1986 and 1987 events represent these two extreme sets of conditions.

1986 Mid-Winter Breakup

The late fall of 1985 was characterized by below normal temperatures and snowfall, but by the first week in January 1986, total snow depth had reached 0.32 m - the maximum for 1986 and approximately 0.12 m above normal (Figure 5). Throughout January, periodic warming trends reduced the snow depth to only 0.15 m by January 25 at which time most of the province began to be affected by a low pressure system tracking northward along the eastern seaboard. Over the next three days, maximum air temperatures rose to 13.5°C, a total of 31.4 mm of rain fell and the snowpack was reduced to a trace. The associated runoff rapidly increased discharge to a peak of approximately 70 m³/s on January 28. Some jamming occurred but not of sufficient severity to cause backwater flooding. Immediately following breakup, cold weather conditions arrested melt, decreased flow and refroze the cover. Periodic melt events through the winter kept the snowpack at low levels such that a very mild, second breakup occurred in the spring of 1986.

Resistance of the ice cover to the mid-winter 1986 flood wave is best described to be at an intermediate condition because the ice cover was thin yet relatively strong. At 0.34 m on January 17, cover thickness was only 0.05 m less than the mean January thickness but thin compared to the >0.5 m peak winter thickness. The cover was believed to be relatively strong for two reasons. Firstly, significant radiation decay unlikely occurred before breakup because the ice sheet temperature would have been below the melting point due to the cold air temperatures that immediately preceded the melt event. (Mean air temperatures averaged -9.4°C from January 22-26). Second, radiation receipts were low because of the time of year and the thick cloud associated with such a rain-on-snow event. Global radiation decreased from 9 $MJ/m^2/d$ under clear skies on the 25th to less than 2 $MJ/m^2/d$ during the main melt period. The only day in which significant radiation decay could have occurred was on the 28th after the insulating snow cover was depleted, however, this was also the day of major breakup.

1987 Spring Breakup

Similar to 1986, the main 1987 breakup resulted from the melt of an above normal snowcover, although it occurred in spring and runoff was largely unassisted by rainfall. (Figure 5). Notably, there was no significant mid-winter thaw and below normal temperatures prevailed until mid-March. Mean daily air temperatures rose above freezing on March 19 and remained at above normal levels for the remainder of the event, accompanied by a steady depletion of the snowpack. Radiation inputs were also high with solar input averaging 13.4 $MJ/m^2/d$ between March 19 and March 28, the day of major breakup initiation. Rapid depletion of the snowpack due to the above normal temperatures and high radiation resulted in a noticeable rise in water levels and discharge by March 21 with flow continuing to rise to a peak on April 2. The more erratic record of water levels is related to the ice conditions as discussed under the following sections on breakup prediction and ice jam analysis. Notably, the peak flow of 114 m^3/s on April 2 was the peak flow for the spring of 1987. In other years over the period 1983 - 1987, peak discharge occurred well after the breakup event and much lower discharge characterized the actual breakup event.

At the beginning of the melt period, mean ice thickness was 0.22 m (based on a 20 point Water Survey of Canada measurement conducted on March 20 at Stanley). Notably, this is less than half the long-term mean ice thickness for March and half the 0.43-m value reported at the same site for February 25, 1987. It suggests that the ice cover thinned at a rate of approximately 9 mm/d. This thinning could only have occurred from subsurface melt since, as indicated by the snow depth record, no significant surface melt occurred between the February and March ice measurement dates.

Although an approximate 50% reduction in ice thickness is high, the rate of thinning is not exceptional when compared to data from other rivers. For example, Billello (1980) found the β coeffient in Eq. [1] to range from approximately 0.004 to 0.01 m/°C/d for northern Canadian and Alaskan rivers. In the 1987 Nashwaak case with T_D = 50 and Δh_i = 0.21 between February 25 and March 20, Eq. [1] results in $\beta \simeq 0.004$, a value at the lower end of the range for northern rivers. More years of record are required to verify this value.

Given the lengthy period of warm temperatures and high radiation preceding breakup, some radiation decay is also likely to have occurred. An estimate of the decrease in strength resulting from this decay can be made according to the approach outlined in Prowse et al. (1988). The technique first involves calculation of ice porosity from the amount of radiation absorbed by the ice sheet. This required ice thickness and global radiation data (Figure 5), and an estimate of the optical properties of the snow and ice layers. The beginning of radiation decay was assumed to be the day that the mean daily air temperature rose above 0°C (March 19). Ice thickness was obtained assuming a continued decrease of the measured 9 mm/d thinning. Snow depth on the river was derived from the land snow record (Figure 5) multiplied by a coefficient of 0.86 that accounted for observed differences in land and river snow depth (coefficient is an average obtained from comparison of land and river snow surveys at three intervals during the winter months). The snow albedo was set to 0.9 after new snowfalls and decreased according to a relationship with accumulated daily maximum temperatures (U.S. Army, 1956). A value of 0.5 was assigned after periods of rain. Attenuation coefficients for snow and ice were obtained from Prowse et al. (1988). Since a relatively deep snow cover prevailed until breakup, much of the incoming radiation was either reflected or absorbed by the snow. A porosity of 0.01 was reached on March 28, indicating that the strength of the ice at breakup was approximately 75% that of March 19, the beginning of appreciable melt.

1986 - 1987 Comparison

Owing to the thermal thinning and decreases in strength, the overall resistance of the spring ice cover during the 1987 event must have been much lower than the thicker and stronger cover associated with the mid-winter 1986 event. In the comparison then, the condition of a mid-winter, rather than a spring, ice sheet presented a potentially higher resistance to upstream flow and, hence posed a greater flood hazard. In the end, however, more severe flooding occurred in 1987 than 1986 because of the overriding importance of higher discharge (see Figure 5) and, in the case of Stanley, the closer proximity of ice jams.

BREAKUP PREDICTION

To assist in the forecasting of the onset and severity of flooding, a river ice breakup model has been used for the site near Durham Bridge. The model is semi-empirical and based on a method developed by Beltaos (1984) who used some of the parameters proposed by Shulyakovskii (1963). It requires input concerning standard meteorological and hydrometric conditions. Required hydrometric data includes: maximum stable freeze-up stage (H_F), and pre-breakup flow, stage and ice thickness. Meteorological data including sunshine hours, mean daily air temperature, and windspeed are used to derive a measure of the heat input to the ice cover. The heat input is summed over the pre-breakup period and is used to reflect expected changes in ice resistance due to ice thinning and strength reductions induced by radiation decay.

The time of breakup is determined from a relationship between the total heat input and the rise in river stage above H_F. The maximum stage at breakup is forecast from the prevailing discharge and a relationship between the total heat input and H_F. Once a warm weather trend is predicted, the model is initiated with initial values for H_F and ice thickness, and updated on a daily basis using observed hydrometeorological data including periodic measurements of ice thickness. A flow chart describing the operational procedure is shown in Figure 6. If breakup occurs but the ice cover subsequently refreezes (as in mid-winter), the procedure is repeated with a revised H_F value derived from the refreezing event.

Early tests of the model by Beltaos and Lane (1982) and more recent operational evaluations are promising as evidenced by the results for the years 1986, 1987 and 1988 in Table 1. In 1988, the breakup date was correctly predicted as March 27, whereas in the other two years, it was over-predicted by a few days. One possible reason for the 1987 over prediction is that H_F was reset to a mid-winter value following a breakup and refreezing event. In reviewing the data, it was discovered that only a partial breakup had occurred and that H_F should have been set to the value for the original fall freeze-up.

This model is only for breakup prediction and does not consider effects resulting from subsequent breakup activity. The highest stage and most flooding occurs not at the time of initial ice breakup but during the subsequent ice removal phase when ice jams tend to develop. The following section deals with some of the efforts devoted to understanding this phenomenon at Stanley, a site of recurrent and often damaging ice jams.

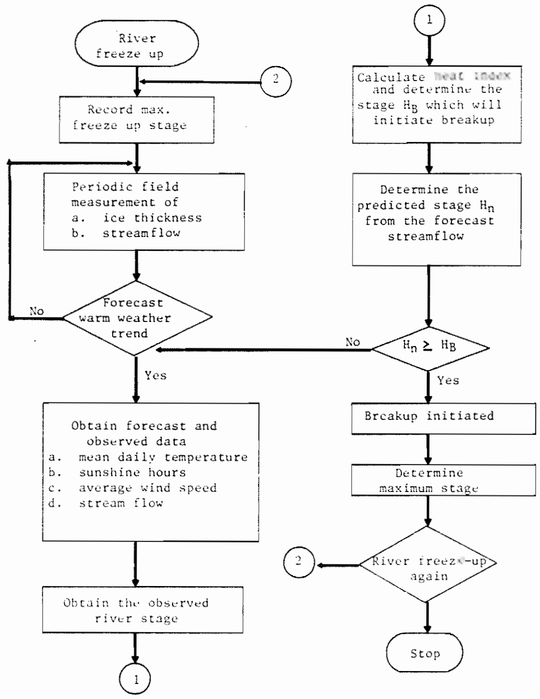

Figure 6. Flow chart for breakup prediction model.

Table 1. Model Results

Year	Breakup Stage (m) Predicted	Observed	Breakup Date Predicted	Observed	Max. Stage (m) Predicted	Observed
1987-1988	19.56	19.42	27 March	27 March	20.94	20.28
1986-1987	18.36	19.00	24 March	29 March	20.12	20.41
(with revised H_F)	18.77		28 March		20.12	
1985-1986	19.09	19.90	28 March	31 March	21.13	21.28

ANALYSIS OF BREAKUP JAMS AT STANLEY

In this section, the breakup water levels measured at Stanley since 1982 are compared with predictions based on existing ice jam theory. A similar analysis has been performed for the Durham Bridge gauge (Beltaos, 1984). For the most part, the Nashwaak River is a single channel of mild sinuosity and fair width (~50 m). Based on data from King et al. (1985) and surveys of representative cross-sections in the jam reach that normally influences the Stanley gauge, reach-averaged, open-water hydraulic and channel resistance characteristics were defined as summarized in Table 2. Channel slope is approximately 4 m/km, a value that characterizes the stream as very steep.

Using the above data it is possible to calculate maximum breakup levels by assuming the presence of an equilibrium, "wide"-channel jam that fully affects the gauge site (Beltaos, 1983). An equilibrium jam is one that is long enough to contain an "equilibrium" reach, in which the jam thickness and flow depth are approximately uniform

Table 2. Reach-averaged hydraulic characteristics and channel resistance, Nashwaak River at Stanley.

Gauge Height (m)	Discharge (m^3/s)	Area (m^2)	Water Surface Width (m)	Average Flow Depth (m)	Average Velocity (m/s)	Bed Friction Factor	Bed Manning Coeff.	Bed Roughness* (m)
0.80	5.1	16	42	0.39	0.3	1.220	0.150	0.52
1.20	36	30	51	0.59	1.2	0.130	0.037	0.09
1.60	96	54	58	0.95	1.8	0.094	0.034	0.08
2.00	214	78	64	1.23	2.8	0.050	0.026	0.03
2.50	359	111	73	1.52	3.2	0.045	0.026	0.03
3.00	498	151	85	1.77	3.3	0.051	0.028	0.04

*Calculated as the 84-percentile value of absolute roughness, $d_{b,84}$.

and the total water depth is at a maximum. The "wide" type of jam is by far the more common at breakup and its thickness is governed by the applied forces and its own internal strength, so that (Pariset et al., 1966):

[2] $\mu s_i \,(1-s_i)\, \rho g t^2 = B\,(\tau_i + w_i)$

in which ρ = water density; g = gravitational acceleration; s_i = specific gravity of ice = 0.92; t = equilibrium thickness of jam; B = channel width at the level of the lower boundary of the jam; τ_i = shear stress applied by the flow on the lower boundary of the jam; w_i = downslope component of the jam weight per unit area = $s_i \rho g t S$; S = water surface slope = open water slope in equilibrium reach; and μ = dimensionless coefficient that depends on the internal friction of the jam. Cohesion may also be present but is neglected for breakup jams.

Beltaos (1983) developed a method to couple Eq. 2 with hydraulic resistance equations and thence explicitly calculate the jam thickness, t, and the flow depth, h, given channel geometry, slope, and discharge. The total water depth, H, is then calculated as

[3] $H = h + s_i t$

which can be used to derive a jam stage-discharge relationship. It is emphasized that such a relationship can only provide an upper envelope to actual breakup levels because the latter may or may not be caused by nearby equilibrium jams of the wide kind.

An almost universal assumption in previous literature is to neglect that portion of the flow which occurs as seepage through the voids of the jam. Recent work (Beltaos and Wong, 1986) indicated that this is justified in most instances because t and h are usually comparable or t is less than h. If t is much larger than h, however, the seepage component of the flow could be significant. It can be shown by re-arranging Eq. 2 that the ratio t/h increases with the factor SB/h which for the Nashwaak River at Stanley is uncommonly large (~0.3; compared with ~0.03 for the same river at Durham bridge or with ~0.05 for the Athabasca River at Fort McMurray).

Laboratory experiments with small rocks and plastic blocks indicate that the flow discharge, Qp, through the voids of the jam is (Beltaos and Wong, 1986):

[4] $Q_p = \lambda A_J \sqrt{S}$

in which A_J = wetted cross-sectional area of the jam; and λ = a "conductivity" coefficient having dimensions of velocity and dependent on ice jam porosity, ε, and configuration of the individual blocks in the jam. It can be shown that $\lambda = \varepsilon u_s/\sqrt{S}$, with u_s = average water speed through the voids portion of A_J.

Using the detailed method outlined by Beltaos (1983) and taking seepage into account, water level-discharge relationships were derived for different values of λ. These are plotted in Figure 7, along with data points describing the maximum breakup levels that occurred in the years of record (1982-88). Note that the no-seepage curve ($\lambda = 0$) does not provide a satisfactory upper envelope of the data points, contrary to what has been found in other rivers, including the Nashwaak River at a different location (Beltaos, 1984).

The best upper envelope for the data points shown in Figure 7, is obtained for λ = 4 m/s (μ_s = 0.6 m/s). However, this value is much greater than 1.3 m/s, an estimate made by extrapolating the small-scale, laboratory findings of Beltaos and Wong (1986).

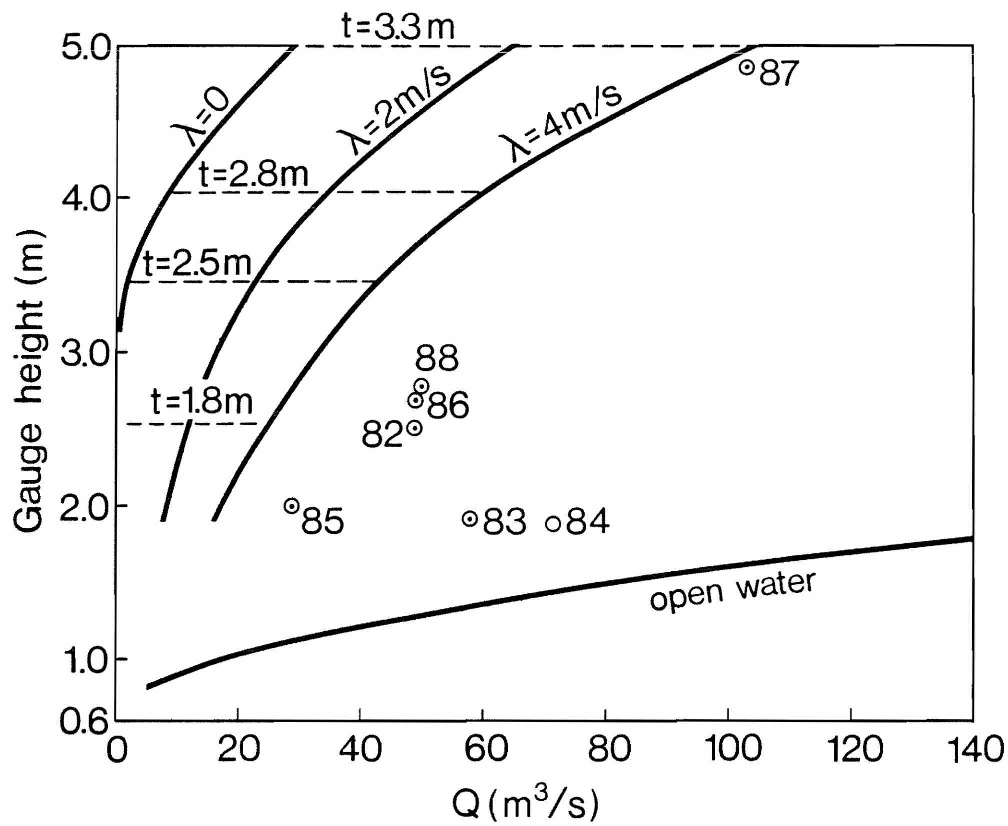

Figure 7. Maximum breakup levels at Stanley versus prevailing discharge for the years of record (1982-88). Also shown are theoretical, equilibrium jam curves for different values of seepage parameter, λ. Calculated ice jam thickness, t, is also indicated on the theoretical curves.

With the limited evidence at hand, it is not possible to determine whether seepage genuinely explains the present findings or if some other but unknown process is involved. To the writers' knowledge, this is the first instance where the no-seepage assumption has failed to provide a satisfactory envelope for the breakup levels. Clearly, more data are needed from rivers similar to the Nashwaak at Stanley, that is, very steep but fairly wide streams.

CONCLUSION

The hydroclimate of the Nashwaak River has resulted in frequent and often costly ice jam flooding. Breakup can occur anytime during the ice-covered season and last from little more than one week to several weeks. Breakup is usually initiated by downstream tributaries, although ice jams can develop in the upstream reaches even after the lower reaches have become ice clear. The severest breakups and ice jam flooding are most likely to occur in spring periods characterized by above normal snowpacks and rapid runoff produced by rain-on-snow events. The hydrometeorological conditions associated with such events tend to preclude significant thinning or mechanical decay of the ice sheet and, hence, the progression of the spring flood wave is resisted by a strong, competent ice sheet.

Considerable success has been achieved in predicting the onset and severity of breakup using a semi-empirical model that only requires as input: flow, stage and standard climate data. Application of accepted ice-jam analysis techniques has not been as successful and raises some questions concerning the possible seepage of flow through ice jams.

ACKNOWLEDGMENTS

Technical assistance provided by staff of the National Hydrology Research Institute, in particular I. Elliott and B. McCarthy, is gratefully acknowledged. Thanks are also due to Mr. Roy Lane of the Water Survey of Canada, Fredericton, for providing the recorder charts and other unpublished data for the Stanley gauge.

REFERENCES

Beltaos, S. 1983. River Ice Jams: Theory, Case Studies and Applications, JHE, ASCE, 109(10), pp. 1338-59.

Beltaos, S. 1984. Study of River Ice Breakup Using Hydrometric Station Records. Proc. Workshop on Hydraulics of River Ice, Fredericton, pp. 41-59.

Beltaos, S. 1987. River Ice Jams: Theory, Case Studies and Applications - Closure, JHE, ASCE, 113(2), pp. 246-255.

Beltaos, S. and Lane, R. 1982. Ice breakup characteristics of the Nashwaak River at Durham Birdge, N.B. National Water Research Institute, Environment Canada, unpublished report.

Beltaos, S. and Wong, J. 1986. Preliminary Studies of Grounded Ice Jams. Proc. IAHR Ice Symposium, Iowa City, Vol. II, pp. 3-14.

Bilello, M.A. 1980. Maximum thickness and subsequent decay of lake, river and fast sea ice in Canada and Alaska. U.S. Army, CRREL Report 80-6.

GEMTEC, 1989. An assessment of flood damage potential, Nashwaak River valley. Ground Engineering and Materials Technology Ltd. report for Canada-New Brunswick Flood Damage Reduction Program.

Kindervater, A.D. 1986. Flooding events in New Brunswick, an historical perspective. Water Planning and Management Branch, Environment Canada report IWD-AR-WPMB-84-65.

King, P., Watson, E. and Baird, P. 1985. Cross Sections of Nashwaak River from Giants Glen to Downstream Limits of Stanley. Canada Works Program Report, Contract No. 1829-DEG, Fredericton.

LeBrun-Salonen, M. 1985. A report on ice runs and ice jams on the Nashwaak River Canada Works '85 report (E.B. Curran Program Manager) for Environment Canada and New Brunswick Department of Environment.

Limerinos, J.T. 1970. Determination of the Manning Coefficient from Measured Bed Roughness in Natural Channels. USGS Water Supply Paper 1898-B, Washington D.C.

Pariset, E., Hausser, R., and Gagnon, A. 1966. Formation of Ice Covers and Ice Jams in Rivers, JHD, ASCE, 92(HY6), pp. 1-24.

Petryk, S. 1985. Casebook on Ice Jams. Working Group on River Ice Jams, Subcommittee on Hydraulics of Ice Covered Rivers, Associate Committee on Hydrology, National Research Council of Canada.

Prowse, T.D., Demuth, M.N., and Onclin, C.R. 1988. Pre-breakup changes in river ice strength. Proceedings of the 5th Workshop on Hydraulics of River Ice/Ice Jams, Winnipeg, Manitoba, pp. 283-303.

Shulyakovskii, L.G. 1963. Manual of forecasting ice-formation for rivers and inland lakes. Translated from Russian, Israel Program for Scientific Translations, 1966.

Tang, P.W. and Daver, U.S. 1984. Forecasting the Initiation of Ice Breakup on the Nashwaak River N.B. Proc. Workshop on Hydraulics of River Ice, Fredericton. pp. 65 - 91.

U.S. Army 1956. Snow Hydrology. Summary report the snow investigations. North Pacific Division, Corps of Engineers, Portland, Oregon.