BREAKUP FORECASTING ON THE MACKENZIE RIVER AT THE FORT PROVIDENCE FERRY CROSSING, NWT

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ABSTRACT

This paper presents the results of a four year investigation of breakup processes on the Mackenzie River at Ft. Providence, located in the southwestern portion of the Northwest Territories. Here, the Mackenzie River flows from the outlet of Great Slave Lake in a generally northwest direction interrupting the all-weather highway from Alberta to Yellowknife. As construction of a bridge is not yet economically feasible, the river crossing is achieved using a ferry in spring, summer and fall and an ice bridge during the winter. During the spring breakup period, after the ice bridge has been decommissioned for the season and when breakup processes threaten the ferry with moving ice, the crossing is closed and freight must be airlifted across the river by helicopter.

Because of the economic and political significance of Yellowknife, native communities and mining, and the large expense and inconvenience of air transport, there is considerable pressure to minimize the down time of ferry operation. This has involved the unusual step of continuing to operate the ferry through early winter while awaiting the ice bridge to be fully commissioned by maintaining a passage channel through the ice. It has been proposed that a similar operating scheme might be implemented in the spring, between decommissioning of the ice bridge and the initial ice movement at the ferry crossing, if major ice movements from upstream could be forecast with sufficient reliability and sufficiently in advance to allow the ferry to retreat.

INTRODUCTION

Figure 1 illustrates the study reach on the Mackenzie River which is located just downstream of Great Slave Lake, in the Northwest Territories (NWT). At the outlet of Great Slave Lake, Big Island divides the flow between the South Channel, which discharges the majority of the flow, and the shallow North Channel. The Mackenzie River widens significantly downstream of Big Island through the reach known as Beaver Lake, where the Kakisa River joins the Mackenzie River from the south. Just downstream of this confluence, the width of Mackenzie River gradually decreases through Burnt Point down to Providence Narrows (located at the upstream end of Meridian Island in the vicinity of the Big River site noted in Figure 1). At this point the river takes on an anastomosing characteristic with numerous large islands and distributaries splitting the flow. The town of Ft. Providence is located on the north bank of the main channel in the vicinity of the RCMP and Dock sites noted on the map. The main channel in this reach is known as Providence Rapids.

The area is remote, with access to the river by ground transportation limited to the area in the immediate vicinity of Ft. Providence. The Yellowknife Highway crosses the Mackenzie River approximately 12 km upstream of the town of Ft. Providence.

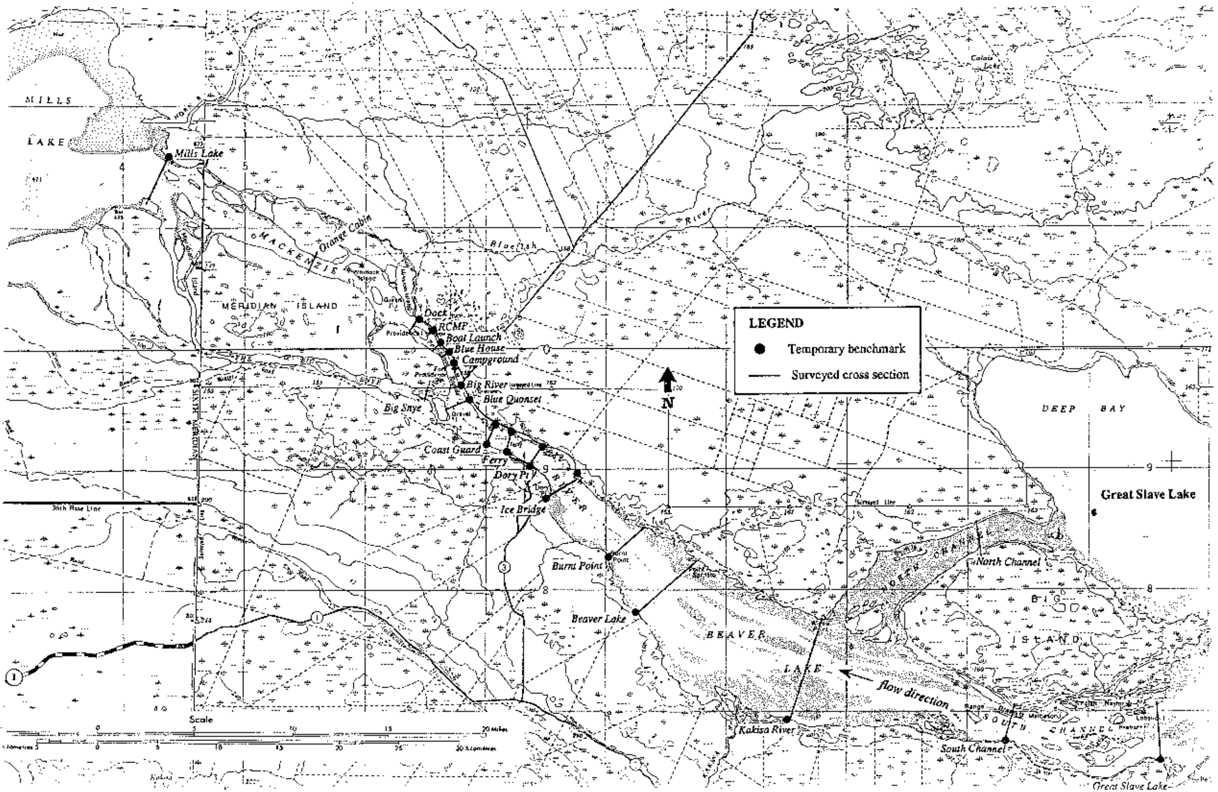
The purpose of this study was to develop the framework for a model of breakup for the Mackenzie River at the Ft. Providence ferry crossing, which would facilitate the safe operation of the ferry during this late winter period. Practically speaking, this means forecasting major ice movements with sufficient lead time to enable the ferry to retreat safely.

Current Ferry Operating Plan

When freezeup begins in the fall, there is a risk of moving ice to the ferry. However, there is considerable pressure to minimize the down time of ferry operations while awaiting the ice bridge to be constructed. Therefore, the ferry was reconfigured in 1982 to operate throughout and beyond the freezeup period (into January in most cases). This required the installation of double engines at each end of the ferry and a strengthening of the hull.

As freezeup progresses, the surface concentration of moving ice increases. Ferry operations continue until surface concentrations approach 100%. At this time, the ferry retreats to the bank and waits for a solid ice cover to form. This interruption in

Figure 1. Location of cross sections and temporary benchmarks on the Mackenzie River near Ft. Providence.



service averages about 24 to 48 hours. When a solid ice cover develops at the ferry crossing a channel is excavated through the ice using backhoes operating from the deck of the ferry. Once constructed, the ferry operates through this passage channel maintaining the opening as necessary, until ice bridge construction is complete and the ice bridge is commissioned for all traffic.

Typically, the ice bridge becomes unusable in late April. Ferry operations resume on the Mackenzie River at Ft. Providence within about 24 to 72 hours of breakup and clearing of the ice within the ferry reach. Over the 30 year period between 1962 and 1991, this resumption date varied between 6–May and 31–May, with a mean date of 17–May. Therefore, the period of interruption can be as short as one week, or in excess of three weeks. Of primary concern at this time of year is the risk of moving ice to the ferry. Therefore, the decision on when to initiate ferry operations has depended, to a large extent, upon a qualitative assessment of the quantity and type of ice floes in Beaver Lake.

Proposed Ferry Operating Plan

To shorten this critical period just prior to breakup it has been proposed that the ferry is operated during this time by cutting a passage channel through the ice cover as is done in the early winter (Lanteigne and MacAlpine, 1993). Under this proposal, ferry operations would cease during the period in which the ice in the ferry reach breaks up and clears out. Operations would resume after this, with brief interruptions during the passage of Beaver Lake ice and (later on) Great Slave Lake ice, as is presently the case. During all major ice movements, the ferry would retreat to the bank.

A decision on the feasibility of this proposal required an assessment of the means and reliability of forecasting these major ice movements each year, using limited observations and readily available hydrometeorological data.

DATA COLLECTION PROGRAM

Research into the nature of breakup at the Ft. Providence ferry crossing began with a preliminary study conducted in the spring of 1991, by Dr. R. Gerard of the University of Alberta. Temporary benchmarks were established along the accessible portion of the river, and ice characteristics, water levels and open water development were monitored during the breakup.

In 1991-92, a three year observation program was initiated by the authors to quantify the nature of breakup. The field observation program was particularly comprehensive in that first year, including freezeup monitoring, mid-winter surveys of ice characteristics and snow cover, detailed breakup observations and summer surveys (to define channel geometry). At that time the WSC gauge (10FB001) was located upstream of the ferry crossing, at Dory Point, and was not operational during the winter. Therefore, a pressure transducer, linked to a datalogger, was installed at the ferry crossing during the late winter of 1992 to measure the water level. Instrumentation for measuring solar insolation and air temperature were installed and connected to the same datalogger. Additional dataloggers, equipped to measure water and air temperature, were installed upstream at the Kakisa River and Great Slave Lake sites noted in Figure 1. Water levels were monitored in the remote areas upstream and downstream of the ferry reach by installing staff gauges in and beside the ice cover, and by rod and level in the reach accessible by road. Discharge measurements were also conducted in the ferry reach.

Based on the extensive data collected during the 1991-92 season, an hydraulic model was developed for the early breakup period. The observational program was refined, limiting data collection to those key factors identified as crucial to the development of the ice breakup forecasting model. The WSC gauge was moved to the south berm of the ferry crossing in the fall of 1992, and became operational year round. WSC staff reactivated the program of discharge measurements, including mid-and late-winter measurements. This provided key data for the refinement of the hydraulic model. During the 1992-93 mid-winter site visit, the research team established a more comprehensive meteorological station at the airport in Ft. Providence. The observation program continued in the 1993-94 season with minor refinements. Government of the Northwest Territories (GNWT) Transportation staff continued the monitoring program in 1994-95. Because of the significant value of the additional year of data to the model development, the 1994-95 data were included in the development of the forecasting models. Details of all of the data collected over this four year period, and of the methods used, are provided in the report by Hicks *et al.* (1995).

SYSTEMATIC PATTERNS OF BREAKUP OBSERVED IN THE STUDY REACH

Over the three years of this study, extensive observations of the sequence of ice deterioration and breakup were monitored by flying over the river and video-taping the reach on a daily basis. Together with the hydrometeorological data collected, this information permitted the development of a description of the nature of breakup in two key sub-reaches: the ferry reach and in the Beaver Lake area.

Breakup in Beaver Lake

Breakup in this reach is of importance in this study for two reasons. First, breakup in this area is predominantly thermal, with the development of open water progressing from small open water areas initiated at the upstream end of the outlet channels of Great Slave Lake as a result of the release of warm water in late winter. Thus, calibration of a thermal model in this reach would provide the thermal parameters for input into a model of breakup for the ferry reach, which would be comprised of both thermal and dynamic components. Second, each year the ice moving downstream from this reach typically interrupts spring ferry operations for 24 to 48 hours, and it is important to be able to forecast this event.

Warm water flowing under the ice cover tends to thin the ice, resulting in the downstream propagation of a melting front (thermal breakup). Early ice melting is primarily influenced by the issuance of warm water from Great Slave Lake which, because of its large storage capacity, can maintain water temperatures slightly above $0^{\circ}C$ through the winter season. As open water areas increase in the north and south channels at the lake outlet, heat from solar radiation and the overlying air mass begins to be absorbed by the water directly and this energy melts the ice. As the open water areas increase more heat can be absorbed and the development of open water at the lake outlet accelerates through the breakup season.

It has consistently been observed that the breakup in the upper reach is predominantly thermal until both the North and South Channels are completely open. At this point the open water area is approximately 280 km^2. Subsequent open water development in the Beaver Lake area occurs as a result of cracking and breaking of ice in addition to thermal deterioration. It has been observed that the rate of open water development tends to become nearly linear at this time. With the exception of the 1994 breakup, in which dynamic effects occurred sooner than average, the rates of open water development after this point were also quite consistent: 37.4 km^2/day in 1992; 42.4 km^2/day in 1993; and 39.1 km^2/day in 1995.

Breakup in the Ferry Reach

The ferry reach extends upstream from the dock in Ft. Providence to the Ice Bridge section. It is comprised of two subreaches: the narrow, steep section through the Providence Rapids and the wider, flatter reach upstream of the rapids that contain the ferry crossing.

In response to increasing outflows from Great Slave Lake in mid- to late April, water levels throughout the reach begin to rise gradually. Ice frozen to the ground near the banks becomes inundated with water. Open water leads, due to the melting of the underside of the ice cover, begin to develop in the Providence Rapids. As discharge increases, overflow of water onto the ice cover at the downstream end of these leads occurs. Typically, the ice in the rapids section loses its integrity without affecting the competence of the ice at the ferry crossing.

Breakup of the ice cover at the ferry reach is initiated by the movement of ice in Providence Narrows. The flow in this section of the reach is accelerating and both gravity and drag effects on the ice cover are higher in this area than in the section upstream. The ice cover in the upstream portion of the Providence Rapids collapses, followed by the ice sheet breaking away from the upstream ice cover near the Blue Quonset. This ice sheet then moves through Providence Narrows to the upstream portion of the Providence Rapids. This fractures the ice cover in the rapids and consolidates the ice floes, forming a thickened accumulation. The resulting accumulation may consist of ice floes ranging in size from small pieces (of the order of 10 m or less in diameter) tightly packed together (typically located in the downstream portions of the jam), to large juxtaposed sheets ($^{1}/4$, or more, river widths in diameter) typically located near the head of the accumulation. The jammed ice floes decrease the hydraulic efficiency of the channel and often result in a rapid increase in water levels. This increase propagates upstream, increasing water levels at the ferry crossing and into Beaver Lake, where its effect is diminished by the large width of the river there. It is likely that this wave precipitates the initial movement of ice at the ferry crossing, both by lifting the ice cover above a key (constraining) level and by fracturing the ice sheet as it passes. Breakup of the ice cover between the ferry crossing and Providence Narrows follows as ice is fed into the Providence Rapids causing fluctuating water levels upstream.

It is important to note that the upstream propagation of a wave resulting from a shove in the Providence Rapids is not a necessary condition for breakup to occur in the ferry reach. In years where the breakup would be described as primarily thermal, dramatic fluctuations in water levels at the ferry crossing would not necessarily occur prior to breakup in the ferry reach. Consequently, although the initial movement of ice at the ferry crossing has on some occasions been preceded by a rapid or significant increase in water level at the ferry crossing and/or water levels at the ferry crossing rising in excess of the freezeup water level, the data to date proves neither is a necessary precedent for ice movement at the ferry crossing. Therefore, though either occurrence should be taken as warning of imminent ice movement at the ferry crossing, neither should be considered a necessary condition for such an occurrence.

In all four years of observations to date, the initial movement of ice was consistently the failure of the ice cover in the upstream portion of Providence Rapids. In those same four years, the initial movement of ice at the ferry crossing occurred 1 to 6 days later. Although the timing is not precisely documented, the field observations made during 1991 confirm that the failure of the ice cover in the vicinity of the Big River section preceded the initial movement of ice at the ferry crossing. Clearly then, the initial movement of ice at Big River is a key indicator of imminent ice movement at the ferry crossing, and it was therefore a primary objective of this study to develop the a model to forecast this occurrence. It is not yet known what impact the construction of a ferry passage channel through the late winter ice cover would have on the nature and timing of the initial movement of ice at the ferry crossing.

FORMULATION AND APPLICATION OF THE BREAKUP MODELS

Based on the observations of breakup in the study reach to date, two key reaches have been identified. As discussed above, the mode of breakup in these two reaches is distinctly different. In the upstream reach breakup is predominantly thermal with the thermal development of open water progressing downstream from the outlet of Great Slave Lake. In the ferry reach itself, the breakup is primarily mechanical, with the initial movement occurring as a result of reduced strength due to thermal deterioration and increased forces on the ice cover due to increasing river discharge.

Modelling the Development of Open Water at Great Slave Lake

It is possible to develop a thermal breakup model for the development of the open water area just downstream of Great Slave Lake by considering the energy fluxes at the ice surface (Ashton,1986; and Gray and Prowse, 1993).

If all of the heat components providing heat to the ice cover are considered positive, and those extracting heat from the ice cover are considered negative, the sum of the heat components is the heat available to melt the ice cover, Q_m:

$$Q_m = Q_{si} + Q_{li} + Q_{ei} + Q_{hi} + Q_{ai} + Q_{fi} + Q_w \qquad (1)$$

where:

Q_{si} is the net solar radiation absorbed by the ice (or snow);

Q_{li} is the net longwave radiation heat exchange between the ice (or snow) surface and the atmosphere;

Q_{ei} is the heat gain or loss due to condensation or evaporation from the ice (or snow) surface;

Q_{hi} is the sensible heat exchange between the ice (or snow) surface and the atmosphere due to convection;

Q_{ai} is the heat directly advected to the ice (or snow) surface by snow or rain;

Q_{fi} is the heat energy contributed to the ice cover as a result of fiction between the ice cover and the river flow; and

Q_w is the heat directly advected to the ice cover by warm water flowing under the ice.

All terms are expressed in joules/second or watts (where J/s = W). Ice melt begins once the net heat input to the ice cover is positive. With the exception of the heat advected to the underside of the ice cover by the river flow, all of the terms on the right hand side of equation (1) would be expected to melt the ice either by increasing its porosity, or by thinning it from the top. Heat from the river flow would thin the ice from the bottom, with the greatest effect expected at the upstream edge of the melting front (the downstream edge of the open water area).

Heat is advected to the underside of the ice cover by the river flow when the water temperature is in excess of 0°C. As discussed above, water enters the river from Great Slave Lake at a temperature, T_{lake}, slightly above 0°C. After passing the upstream edge of the open water area, its temperature begins to rise as it is heated by incoming solar radiation and the warm air which are in direct contact with the water in the open water area. The heat available from warm water flowing under the ice cover is then:

$$Q_w = Q_{lake} + Q_{sw} + Q_{lw} + Q_{ew} + Q_{hw} + Q_{aw} + Q_{fw} \qquad (2)$$

where:

Q_{lake} is the heat energy contained in the warm water issuing from the lake;

Q_{sw} is the net solar radiation heat incident to the open water surface;

Q_{lw} is the net longwave radiation exchange between the water surface and the atmosphere;

Q_{ew} is the heat of gain or loss due to condensation or evaporation from the water surface;

Q_{hw} is the sensible heat exchange between the water surface and the atmosphere due to convection;

Q_{aw} the heat advected to the water surface by snow or rain;

Q_{fw} the heat energy contributed to the water as a result of friction between the river flow and its physical boundaries; and

Q_g the heat energy conducted from the river bed to the river flow.

Again, all terms are expressed in joules/second or watts (where J/s = W).

Practically speaking, some of the terms in equations (1) and (2) are negligible when compared to the larger terms, such as the incoming solar radiation (which ranges from about 100 to 300 W/m^2). Specifically: the heat component from the river bed, which is estimated to be in the order of 1 to 4 W/m^2 (Ashton, 1986); the heat created by friction due to the flow shear on the physical boundaries, which is estimated to be in the order of 0.2 W/m^2 (Hicks *et al.*, 1995); and, the heat advection by snow and rain which is estimated to be in the order of ±0.3 W/m^2 (Hicks *et al.*, 1995). As a result, equations (1) and (2) simplify to:

$$Q_m = Q_{si} + Q_{li} + Q_{ei} + Q_{hi} + Q_w \tag{3}$$

$$Q_w = Q_{sw} + Q_{lw} + Q_{ew} + Q_{hw} + Q_{lake} \tag{4}$$

Two approaches were considered in quantifying the terms in the thermal modelling of breakup for this reach. First, a complete energy budget was considered. This approach required quantification of each of the terms on the right hand sides of equations (3) and (4). The second approach was simpler and conceptually based, which is more empirical but has the advantage of being less data intensive. The solar radiation term is included explicitly but all the remaining temperature dependent terms (convection, evaporation, and longwave radiation) are linearized by using a calibrated heat transfer coefficient applied to the difference between the air temperature and the temperature of the ice or water surface (Andres, 1984). The latter approach therefore requires only the solar radiation, air temperature, discharge and lake water temperature as input data.

In the complete energy budget model, the values for the water and ice surface albedos were taken from the literature. Because of the long period over which the thermal breakup in Beaver Lake occurs and based on qualitative observations of ice surface albedo, the use of two values of ice albedo was considered appropriate: 0.9 for the early melt period, and 0.7 after the ice surface darkened noticeably. The albedo of the water surface was taken as 0.08.

Application of the complete energy budget without calibration resulted in an underestimation of the rate of open water development. Sensitivity analyses of the effects of parameter variation determined that the ice surface albedo had a significantly higher effect on model results than any of the other parameters involved in the simulation. Therefore, to improve the fit to the data, the ice surface albedo was adjusted. Wind speed and relative humidity were not measured at the site in 1992. Therefore, only the data from 1993, 1994 and 1995 could be used in the calibration of the complete energy budget model. The optimum values of the ice surface albedo were found to be 0.45 during the early melt period and 0.35 later on. This is clearly too low, and results from the poor definition of the parameters in the other terms in the energy budget. Figure 2 presents the results, where it is seen that a reasonable fit to the measured data was obtained using the complete energy budget approach with the calibrated ice surface albedo.

The parameters to be calibrated for the simpler model were the heat transfer coefficient between the air and the ice cover and the heat transfer coefficient between the air and the water surface. For the reasons discussed above, the value of the ice cover albedo was taken as 0.9 for the early melt period, and 0.7 after the ice surface darkened noticeably. The water surface albedo was increased to 0.10 to account for the effects of evaporation and longwave radiation. The 1992 data could be included in this analysis, because wind speed and humidity data were not required.

The optimum values of the heat transfer coefficient between the air and the ice cover, h_i , and the heat transfer coefficient between the air and the water surface, h_w, which generally range from of 10 to 20 W/m^2°C (Andres, 1984) were found to be: $h_i = 8$ W/m^2°C and $h_w = 20$ W/m^2°C. These are similar to what Van Der Vinne

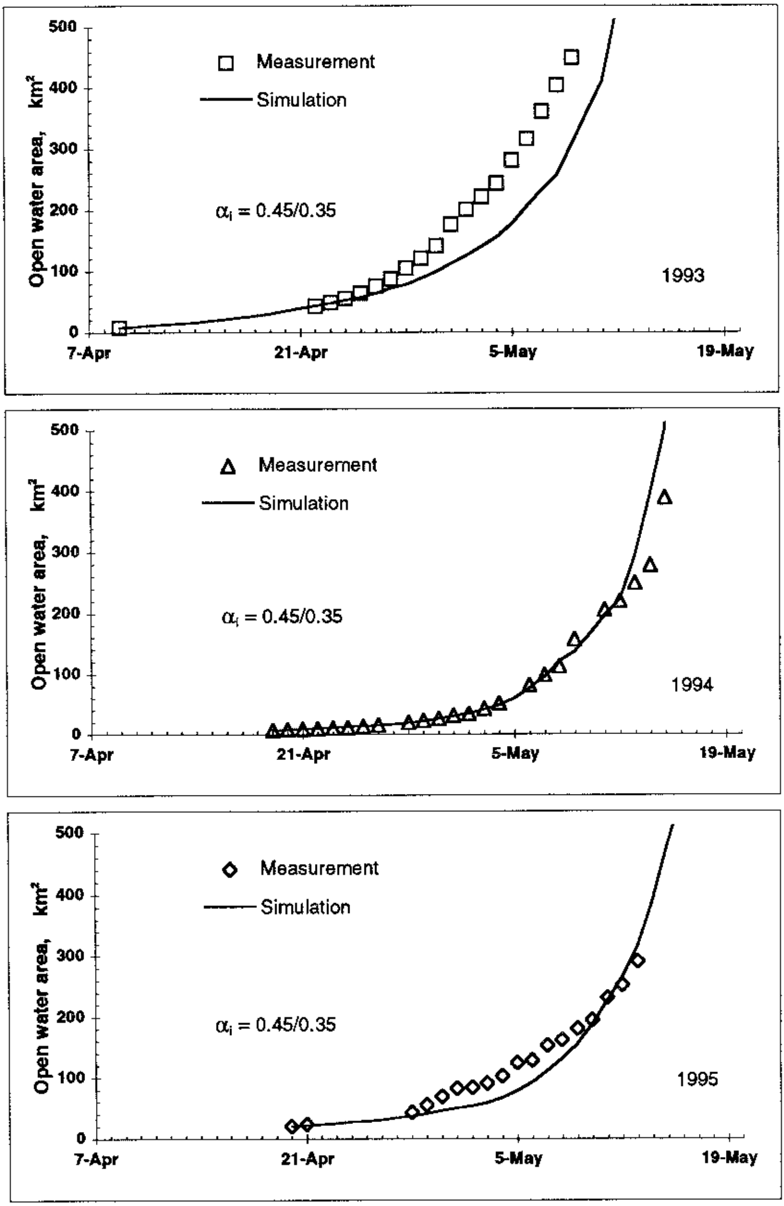


Figure 2 Surface albedo calibration for the energy budget approach, all years.

(1995) reported for a small lake in Alberta. Figure 3 shows the calibration results for the four years of record using these values. The simpler model provided a better fit for a single set of calibrated parameters, than the complete energy budget model.

Although the complete energy budget method is not difficult to apply, it is data intensive. Also, the daily averages of some of the data, such as wind speed and humidity, might not be representative of the average value over the whole area under investigation or over a day. Furthermore, relative humidity and wind speed are not straightforward to forecast. Therefore, the energy budget method is limited in its applicability as a forecasting model. Based on this and the slightly more consistent results obtained, the conceptual modelling approach is recommended.

Modelling the First Movement of Ice at Providence Rapids

As discussed earlier, breakup in the ferry reach is not entirely thermal. Although heat is the agent of deterioration and strength reduction, the ice clears through a process of cracking, breaking and moving downstream. Therefore, in addition to the thermal aspects of breakup considered in the Beaver Lake model, the effects of the flow on the ice cover must be considered, as well. This includes the consideration of the effect of drag on the underside of the ice cover which is a function of the discharge in the channel, the energy gradient and the interactive effects of the ice on flow hydraulics. Also important is the strength or competence of the ice cover to resist the forces tending to fracture it. Finally, the mechanism of failure may vary; the ice cover may fail in bending, compression, shear or a combination of the three. Attempting to forecast a dynamic breakup deterministically involves consideration of the loads imposed on the ice cover and the resistance of the ice cover to failure or breaking, both of which vary in time. The rate of change of each depends upon initial conditions (ice thickness, snow depth on the ice cover and late winter discharge) and on varying conditions through the pre-breakup period (discharge and water level fluctuations, and heat input to the ice). For the latter, it is the rate of change of these variables which dictates the rate at which breakup will progress.

Quantifying Ice Deterioration

A key component of any dynamic breakup model which considers the loads on the ice cover, and the ice resistance to those loads, is ice deterioration. The strength reduction which eventually causes the ice cover to succumb to imposed loads must be quantified. It has been observed that ice strength varies with ice temperature and ice

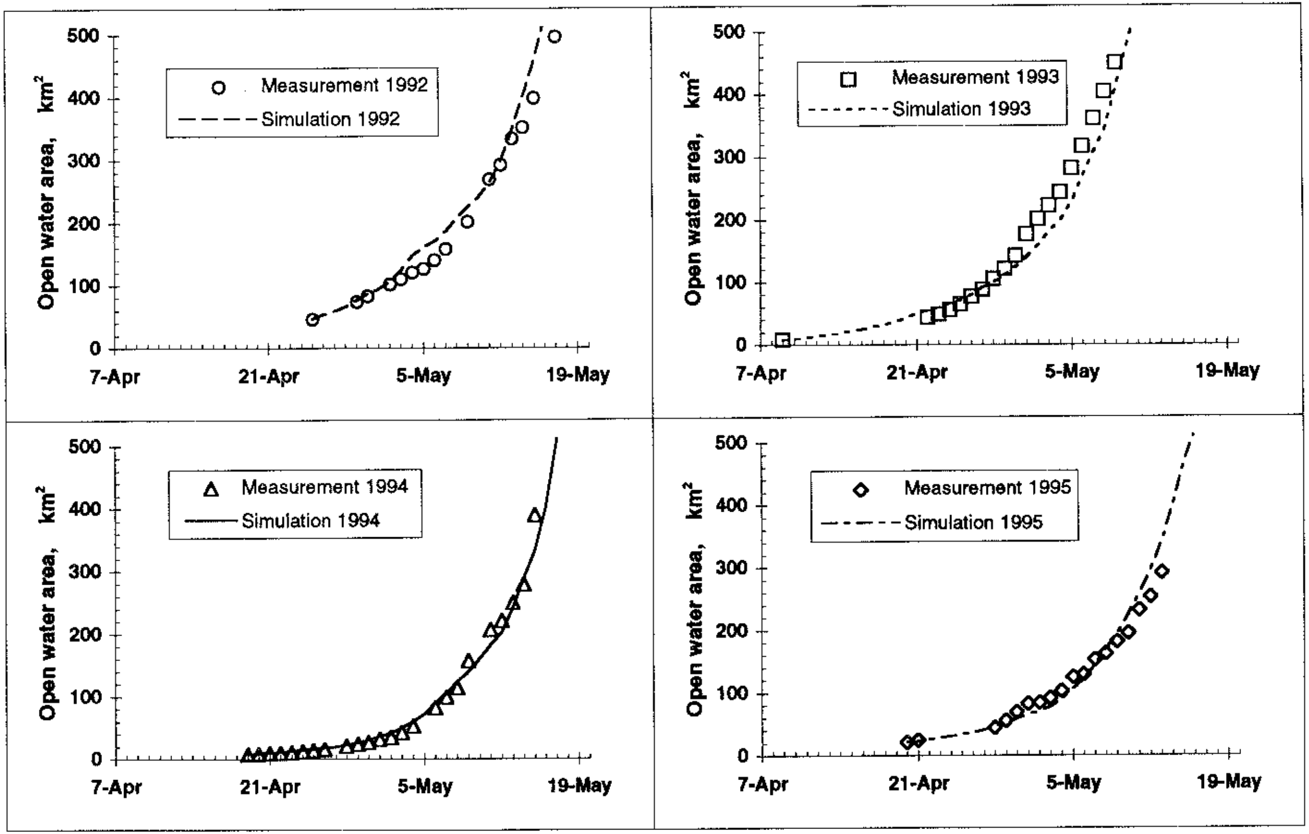


Figure 3 Simulation of open water area development with the conceptual model, $h_i = 8$ W/m^2°C, $h_w = 20$ W/m^2°C.

porosity and once heat input from the sun begins to increase the porosity of the ice through intergranular melting, the ice strength reduces rapidly.

Based on a cubic model of intergranular melt, Bulatov (1970) presented the following theoretical equation to evaluate the relationship between the strength reduction and the porosity of an ice cover:

$$\Phi = 0.645 \left(1 - \sqrt{\sigma/\sigma_o}\right)^2 \tag{5}$$

where: F is the porosity of the ice cover;
s is the reduced ice strength, in Pa; and
s_o is the initial ice strength (at the time the ice starts to melt), in Pa.

This model assumes that the rate of melt at the cube corners, where three faces meet, would be 1.5 times great than the rate of melt at the edges, where two sides meet.

Ashton (1985) presented the following equation based on uniform melting in Bulatov's cubic-grained model of intergranular melting:

$$\Phi = 0.645 \left(1 - \sqrt{\sigma/\sigma_o}\right)^2 - 0.1674 \left(1 - \sqrt{\sigma/\sigma_o}\right)^3 \tag{6}$$

The last term in equation (6) approaches zero under the assumption that the cube corners melt at 1.5 times the rate of the cube edges (Ashton, 1985) and equation (6) reduces to equation (5).

Ashton (1985) also presented an equation to calculate the strength reduction (strength ratio) in terms of porosity based upon a hexagonal-grained model of internal melting:

$$\sigma/\sigma_o = 1 - 2.813 \sqrt{\Phi} \tag{7}$$

which may be rearranged to obtain:

$$\Phi = 0.1264 \left(1 - \sigma/\sigma_o\right)^2 \tag{8}$$

In graphical comparisons between equations (6), (8), and data for a variety of ice types measured by Shishokin, Korenkov and Butyagin (data reported by Bulatov, 1970), Ashton (1985) made an error in the presentation of equation (6). This error has been reproduced in a number of subsequent papers by other authors. In Figure 4 it is seen that the corrected curve for Ashton's adaptation of the cubic-grain internal melt model (equation (6)) is not significantly different from Bulatov's original cubic-grain internal melt model (equation (5)). More significantly, Ashton's hexagonal-grain melt model (equation (8)) is not consistent with either of the cubic-grain melt models. Ashton's model predicts a rapid decrease in strength as porosity increases, with the ice strength going to zero at a porosity of only 13%. For Bulatov's cubic-grain internal melt models (equations (5) and (6)), the porosity reaches 45 to 64.5%, respectively, before the strength goes to zero. In this study, Bulatov's original model, equation (5), was used to calculate the progressive deterioration of the ice cover strength through the breakup period, as a function of the cumulative heat input.

Failure Criteria

Four mechanisms of ice cover failure were considered in this study: failure due to crushing of the ice cover; failure in shear along hinge cracks parallel to the banks (as proposed by Ferrick and Mulherin, 1989); shear failure of an intact ice cover (no hinge cracks) along planes parallel to the bank; and buckling failure. The ratios of the resistance of the ice cover (based on calculations of its reduced strength due to thermal deterioration) to the to the stresses resulting form the drag and gravity forces acting on the ice cover were evaluated for each mechanism, at the time of the initial movement of ice. The ratio, which should decrease over time and approach one at the time of incipient failure varied as follows:

Type of Failure	**Reduced Strength/Imposed Stresses at the Time of the Initial Movement of Ice**
Compression	0.8 to 7.8
Crack shear	0.21 to 0.48
Internal shear	1.3 to 13.0
Buckling	11.4 to 56.6

The values obtained in the analysis of crack shear were less than one from the commencement of melt, indicating that shear resistance along hinge cracks plays little or no role in preventing the initial movement of ice at this site. The values for the ratio obtained based on a failure in compression, internal shear and buckling failure

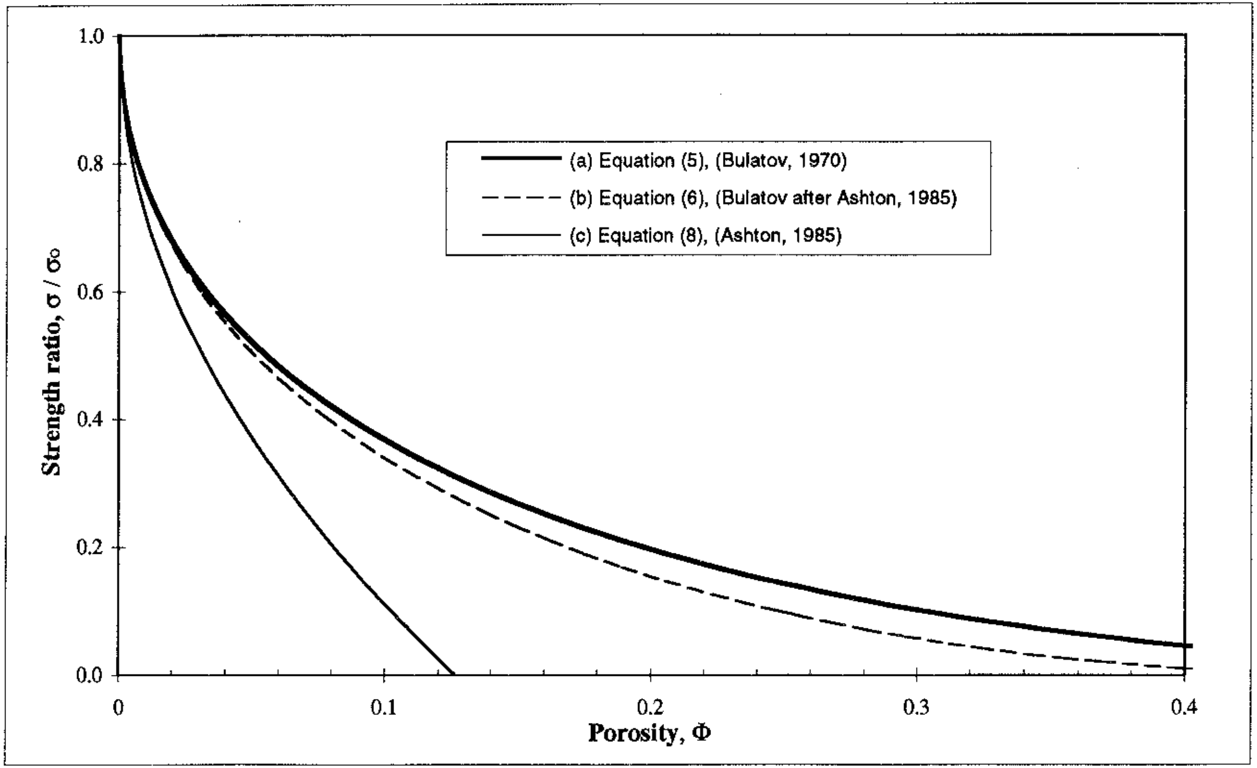


Figure 4 Strength reduction with increase in porosity.

are consistent in that they vary from each other by a consistent factor, which is to be expected, given that the same approach is used to calculate the deteriorated strength of the ice as a result of thermal influences.

Comparing the four criteria, none can be considered a reasonable mechanism for the initial fracture of ice. None are better that the simple cumulative heat input approach, which accounts only for total heat input. This is not unexpected, as loads on the ice cover would only be expected to increase through the breakup period in response to increasing discharge (which increases both the fluid drag on the underside of the ice cover and the slope of the water surface) and it has been determined that discharge increases only gradually here because of the storage effects of Great Slave Lake. The lack of consistency from year to year can be attributed to a number of factors including non-uniformity in the ice thickness, open leads in the ice cover through Providence Rapids, and varying snowmelt conditions. These factors are of importance both in terms of the difficulties associated with obtaining representative data and in terms of the limitations of the one-dimensional modelling approach used here. Consequently, only more detailed data collection is not sufficient. New models are required which take into account such two-dimensional effects.

CONCLUSIONS

Breakup at Ft. Providence results from a combination of thermal and dynamic effects. In the Beaver Lake reach the breakup is mostly thermal, with open water developing in a downstream direction from Great Slave Lake. The rate at which the open water developed was modelled using both the theoretical energy budget equations and a simpler empirical approach. Calibrated heat transfer coefficients from other studies, when used in the empirical heat transfer model, provided better fit to the observed data than the complete energy budget model.

Breakup in the ferry reach is dominated by dynamic effects and is initiated by the collapse of the ice cover in the vicinity of Providence Narrows. Four dynamic models of ice failure were examined in an effort to develop a model for the initial movement of ice at Providence Narrows, but none were found to be superior to the forecast based on cumulative heat input. A substantial amount of work is still required to develop appropriate techniques to forecast breakup for all but the simplest situations.

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