BREAKUP PREDICTION ON A NON-REGULATED RIVER[1]

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ABSTRACT

Appropriate mitigation of flooding due to ice jams requires a knowledge of the time of occurrence and severity of ice jams. The severity is difficult to predict but if the onset of breakup can be forecasted, then the window of concern can be better defined.

Recent observations of breakup on the Athabasca River upstream of Fort McMurray have resulted in a better understanding of the breakup process, as it occurs over a relatively long reach. It is apparent that open water leads develop initially in the rapid areas and, largely independent of discharge, become more widespread as energy is absorbed by the system. As the fraction of open water increases, the effective average albedo decreases, resulting in a more efficient absorption of solar energy and a net acceleration of the melting processes. At some critical fraction of open water, an instability is produced, ice jams form, and the river clears itself of ice.

A numerical model, developed to predict the generation of open water, was tested against one year of observations and was found to function very well. Using measured values of daily air temperature, solar radiation and discharge and initializing the model by defining the maximum winter ice thickness, the day of the first consistent stage increase and the last day of accumulated snow on the ice cover, it was found that the observations of open water could be calculated using an exposure factor of 0.75; an albedo of ice and water of 0.3 and 0.05, respectively; and a convective heat transfer coefficient over ice and water of 10 W/m^2-°C and 15 W/m^2-°C, respectively.

Sensitivity analysis suggested that the variations of the albedos and the heat transfer coefficients within appropriate and accepted limits did not significantly alter the model performance. It was most important to have a good definition of the maximum winter ice thickness, the date of first thinning (the last day of a substantial snow cover) and the first day of appreciable rise in stage.

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INTRODUCTION

The City of Fort McMurray, Alberta, is located on the Athabasca River at the confluence of the Clearwater River. Ice jams, which have been documented as far in the past as 1875, often form downstream of the confluence and cause serious flooding within the lower portion of the city. These ice jams have been well characterized and ice jam rating curves have been developed (Andres and Doyle, 1984) to relate ice jam water levels to the discharge.

Unfortunately, very little is know about the breakup process itself. This deficiency arises from the very dynamics of the process, the extremely long length of the river reach which must be observed and the general inaccessibility of the area. Nevertheless, observations of the breakup process (Andres and Rickert, 1984, 1985) have contributed towards a qualitative but at least a rational view of how the snow pack levels and temperatures affect the progression of breakup from small tributaries down to the lower Athabasca River.

To mitigate potential ice jam related flood damages, an operational system is necessary to forecast the timing of the onset of breakup, herby shortening the window of concern during the March and April melt period. This requires a quantitative characterization of the breakup process. The systematic measurement of areas of open water on the Athabasca River, over a period of about three weeks in 1986, allowed for such an assessment and ultimately led to the development of a numerical model relating the breakup progression to atmospheric conditions.

This paper briefly describes the 1986 breakup observations on the Athabasca River upstream of Fort McMurray and addresses a simple model which may be applicable in forecasting the onset of breakup. The applicability of the model is assessed, a calibration carried out and a sensitivity analysis is done to identify the most relevant model parameters. Conclusions and recommendations are made with respect to the direction and extent of further work.

CURRENT BREAKUP PREDICTION TECHNIQUES

The accurate forecasting of the time of breakup on rivers is a significant problem in cold regions around the world. Much of the earliest technology was developed by the Soviets and has been extensively documented by Shulyakovskii (1963). He defines breakup as the first day of "ice drift" or, presumably, the first day of general instability when surges develop and running ice can be observed. In his view, breakup is caused by a combination of the reduction in the ice cover thickness and strength due to melting and an increase in the discharge and river stage which then leads to the physical breaking of the cover. This stage increase causes the ice cover to crack in a variety of locations and eventually to rise free of banks and push downstream. The amount of heat, ΣE necessary to produce breakup can be defined as

$$[1] \quad \Sigma E = f(t_i, t_s, \phi, v, Y_o, \Delta Y, \Sigma E_b)$$

where t_i and t_s are the ice thickness and snow depth, respectively, ϕ is a parameter describing the morphology of the stream, v is the flow velocity at breakup, Y_o is the stage prior to breakup, ΔY is the increase in stage at breakup and ΣE_b is the heat input at the bottom of the ice cover. The ice thickness, t_i the channel morphology, ϕ, and the pre-breakup stage, Y_o, do not change from year to year. The velocity and snow depth (hence, snow melt runoff volume) can both be approximated by the stage increase ΔY. The heat input to the bottom of the ice cover also is related to the runoff, hence, is also a function of ΔY. This equation thus can be rewritten as:

[2] $\Sigma E = f(\Delta Y)$

for any given reach of a river.

Shulyakovskii illustrates the applicability of this approach at a number of site specific locations. Unfortunately, regardless of the various attempts to improve the correlation between heat input and discharge and the date of breakups, none of the techniques are accurate enough to be operational.

Michel and Abdelnour (1975) defined breakup to occur when ice sheets would begin to detach from the upstream end of a solid ice sheet. Before detachment, the ice cover would submerge and oscillate due to the increasing discharge and flow velocity. Although this is an ideal situation, they reasoned that its occurrence would be a good index of the time when the cover would become unstable and breakup would occur. Dimensional analysis suggests that

[3] $f(v/\sqrt{\sigma/\rho},\ t_i/W,\ t_i/Y,\ \sigma/E) = 0$

where v is the flow velocity under the cover; σ and E are the flexural strength and elastic modules of ice, respectively; t_i, Y and W are the thickness of ice, depth of flow and width of the stream, respectively, and ρ is the density of water. Laboratory tests suggested that breakup should occur when

[4] $(V-V_o)/\sqrt{\sigma/\rho} = 0.055\ (t_i/W)^{3.8}$

where [4a] $V_o = \sqrt{2g(\rho-\rho_i)t_i/\rho}$

and is the velocity at which floes can be entrained at the head of an ice cover. Thus, with a given ice strength and elastic modules, both which decrease over time as the ice temperature increases due to atmospheric heating, and an increasing velocity due to an increasing discharge from snowmelt runoff, one could forecast the onset of breakup.

Beltaos and Lane (1982) based much of their work on that of Shulyakovskii and demonstrated that a relationship between the rise required to initiate breakup, Y_b-Y_f (where Y_b is the stage at breakup and Y_f is the maximum freeze-up stage) and the total heat input to the surface of the ice cover, ΣE could be used to predict the onset of breakup at a site specific location. For one particular case study, it was apparent that the stage increase required to initiate breakup was significantly higher for low inputs of atmospheric energy (premature breakup) whilst for high energy input, a relatively small increase in stage was required.

Beltaos (1984) also looked at breakup in the broader context of a whole river reach. He indicated that a necessary condition to breakup is that $Y > Y_f$ over a significant portion of the reach. As the stage increases, longitudinal cracks or fractures form parallel to the bank. After these cracks develop, transverse cracks also form, most probably from horizontal bending caused by differential stresses due to meandering platform of the river. Also as the stage increases, the width increases, and the sheets get more room to move, eventually accumulating against some naturally occurring impediment. Once the stage increase is sufficient to move all the ice sheets downstream, the critical ice clearing discharge has been exceeded, and breakup has been established.

In conceptual terms, the stage necessary to clear the channel of ice, Y_b, can be written as

$$[5] \quad Y_b/Y_f = f(t_i/W_f, \sigma/\tau)$$

where τ is the stress being applied to the cover by the flow. Once this is known, the discharge required to produce breakup then can be determined from

$$[6] \quad Q_b = (0.62/n_o)\ [Y_b-(\rho_i/\rho)t_i]^{5/3}S^{1/2}$$

where n_o is the composite roughness and S is the river slope.

All of the above models are similar in that each defines a critical stage or discharge necessary to produce breakup for a given amount of heat input. However, two of the three methods use data from a site specific location to establish the relationship without a regard for the reach scale processes which ultimately produce breakup at any given location. Furthermore, the heat input term is responsible for a number of factors. It leads to the thinning and delerioration of the ice cover and also to the generation of runoff from snow melt. Each of these components contribute to breakup but their specific effects are not separated.

MODEL DEVELOPMENT

Observations on the Athabasca River (Figure 1) suggest that breakup on a reach scale occurs by a combination of mechanical and thermal processes. Prior to the generation of snowmelt runoff, the ice cover is relatively intact. The natural variability of the freeze-up process results in a very heterogeneous ice cover. The relatively low discharge at which the cover forms and the subsequent low winter flows result in an ice cover situated at extremely low stage in the portion of the channel where the width is most sensitive to changes in stage. Once snowmelt begins, the flow increases and the ice cover is lifted free of the banks against which it is floating or the shallow areas on which it is resting. With the stage increase, the top width increases, but with the constant ice width the net effect is to produce open water. The amount of open water is a function of the stage prior to the generation of runoff, the channel characteristics, and stage increase.The lower albedo of the water, compared to that of ice, results in the creation of local heat sinks which produce larger local areas of open water. This then accelerates the ice melting process and leads to ever increasing proportions of open water. Concurrently, after the snow cover has been removed from the ice surface, the ice cover begins to absorb energy and thin. This thinning of the ice cover also accelerates the process by which open water is generated because there is a decreasing amount of ice for the water to melt.

These processes lead to the overall weakening of the reach averaged ice condition. The combination of a thinner ice cover and a greater fraction of open water, due to both the melting of the ice cover and the increased width as the stage increases, leads to an unstable situation. This facilitates the mechanical destruction of the ice cover, the formation of ice jams, and subsequently, the production of surges which ultimately destroy section of competent ice and produce open water conditions. The model discussed herein is meant to describe the process by which an ice cover goes from being totally intact to the point of incipient instability when ice jams form, surges develop and a generalized ice run occurs.

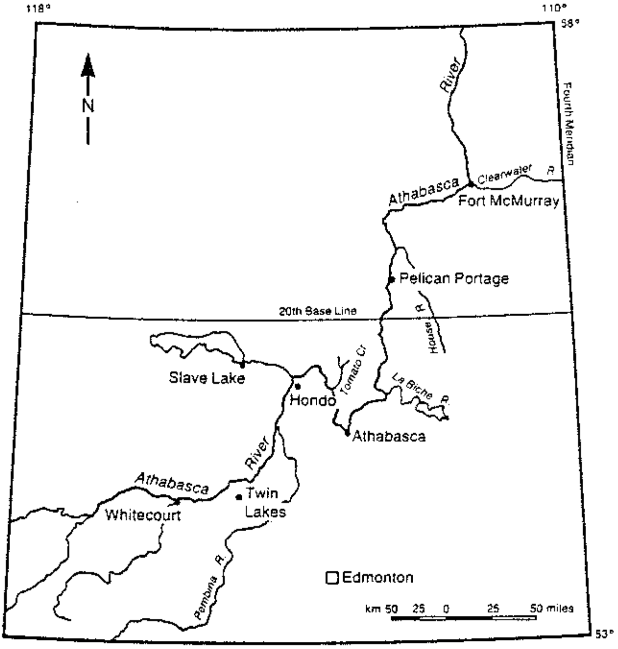

Figure 1. Study area

Open water initially is generated when the ice cover is lifted free of its pre-melt position by the increase in discharge. Assume that the width, W can be written as a function of stage, Y

$$[7] \quad W = mY^{n}$$

and the stage is a function of the discharge, Q

$$[8] \quad Y = pQ^{q}$$

then $$[9] \quad W = mp^{n}\, Q^{nq}$$

where m, p, n and q are constants derived from the channel characteristics and the roughness of the ice cover. Thus, if W_f is the width of the river stage just prior to breakup, then the effective open water, as a faction of the initial width, can be designated as

$$[10] \quad \Theta = (W/W_f) - 1$$

Now, consider an elemental area of an ice cover (Figure 2) having an area $\Delta x \Delta z$ of which Θ is the fraction of open water. For an air temperature T_a and solar radiation H, the net heat transfer to the water surface can be given by

$$[11] \quad \Theta\, \Delta x \Delta z\, [\Gamma(1-\alpha_w)H + h_w T_a]$$

where the first term is the radiation component and the last term is the convective component and where α_w is the albedo of water; Γ is the exposure factor which reduces the effective solar radiation; H is the average daily radiation flux; h_w is the convective heat transfer coefficient above water; and T_a is the average daily air temperature.

To formulate the model, one must describe the process by which open water is created. It is assumed that open water is initially initiated by the rise in stage due to the increased runoff due to snowmelt and is given by equation [10]. Furthermore, all the energy that is absorbed by the open water leads to the creation of the equivalent amount of additional open water the next day. Thus

$$[12] \quad d\Theta/dt = (1/\rho_i L t_i)\, [\Gamma(1-\alpha_w)H + h_w T_a]\Theta$$

Finally, ice thinning begins on the day when all the snow on the ice cover has melted and occurs at a rate at which energy is absorbed into the ice cover;

$$[13] \quad \Gamma(1-\alpha_i)H + h_i T_a$$

where α_i is the albedo of the ice cover, h_i is the convective heat transfer coefficient above the ice surface and the other terms have been defined previously. Additional energy is added to elemental ice cover by friction caused by the flow under the ice cover. This component is relatively small and has not been included in the analysis and the change in the ice thickness can be written as

$$[14] \quad dt_i/dt = -[\Gamma(1-\alpha_i)H + h_i T_a]/\rho_i L$$

Equations [10], [12] and [14] can be combined and solved analytically. However, the radiation, air temperature and discharge are all given in discrete daily units and therefore, it is more practical to write the equations in a discrete form, such that

$$[15] \quad \Theta_{j+1} = \Theta_j(W_j/W_f)\{1+[\Gamma(1-\alpha_w)H + h_wT_a]/\rho_i L t_{j+1}\}$$

where

$$[16] \quad t_{j+1} = t_j - \{[\Gamma(1-\alpha_i)H + h_iT_a]/\rho_i L\}$$

and

$$[17] \quad W_j/W_f = mp^n \, Q_j^{nq}/W_f$$

By defining, from the records, the maximum thickness of the ice cover, the day on which the stage begins to systematically increase and the day when the last of the snow has melted. The increase in the fraction of open water can be computed on the basis of the daily values of discharge, solar radiation and air temperature.

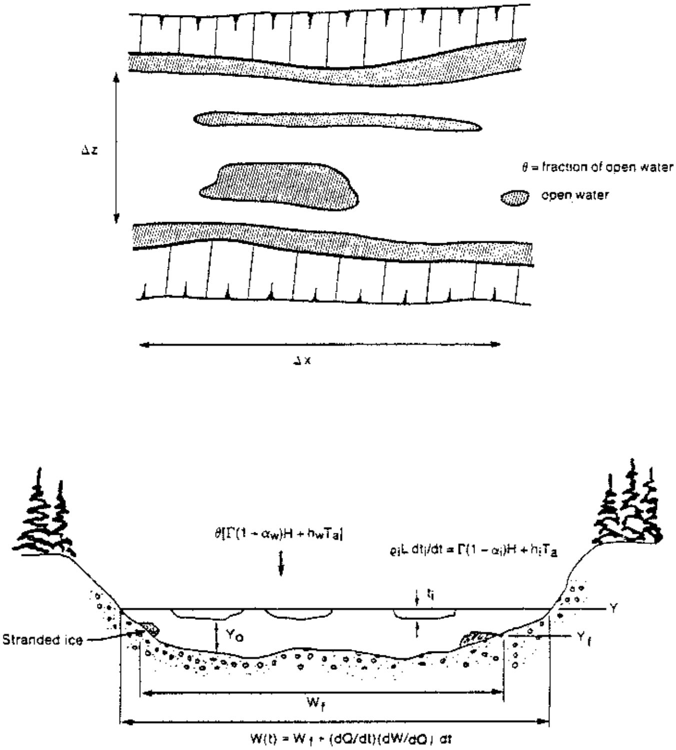

Figure 2. Schematic representation of the processes which produce open water

BREAKUP CHARACTERISTICS

The model was verified on the bases of the documented breakup progression between the mouth of the Pembina River and Fort McMurray on the Athabasca River between April 3, 1986 and April 18, 1986. Five aerial reconnaissances were made with the frequency of the observations increasing as the breakup process accelerated. The main purpose of the observations was to document the percentages of open water and/or overflow in the reach of interest. The intent here was to somehow quantify the processes rather than simply describing the breakup in a qualitative manner.

The winter of 1985-86 was below average in terms of snow accumulation. During the third week of March, just prior to the onset of melting, the accumulated water equivalent of the snow pack was about 45 mm or 62% of normal. The complete melting of the snowpack occurred rapidly over a period of ten days, beginning on March 25, after about 40°C-days of accumulated melt. The Twin Lakes snow pillow, which probably typifies the plains snow condition, illustrates the melt rate (Figure 3).

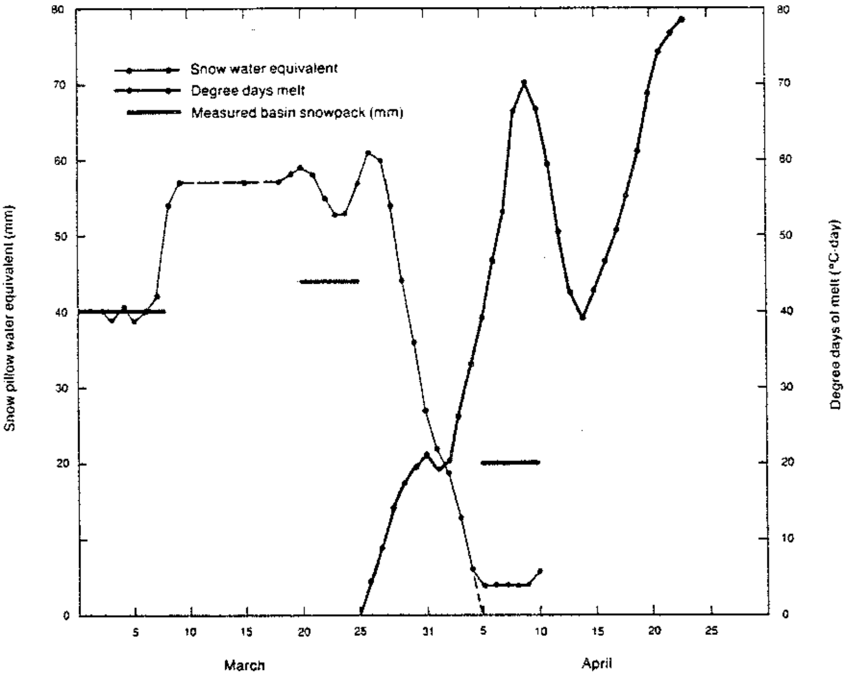

Figure 3. Degree days of melt and snow pack reduction at the Twin Lakes snow pillow, 1986

Water Survey of Canada (WSC) records indicate that the end of winter ice thickness varies between 0.75 m and 1.2 m. Although this is a temporal variation from year to year it is also probably indicative of the areal variations for any one year. Measurements at Fort McMurray (Malcovish and Andres, 1988) in March, 1986 revealed a mean ice thickness of 1.1 m, whilst similar measurements at Hondo (Van Der Vinne, 1988) showed a mean ice thickness of 0.90 m. Therefore, the end of winter ice thickness adopted for this year was 1.0 m. This value seems to be relatively typical from year to year and also probably from location to location. However, there is no doubt that much thicker ice is evident in areas where significant frazil accumulations occur. This thick ice is probably offset by thinner ice along thalwegs, but is undoubtedly the last remaining ice to be removed by the surges.

The temperature regime of the Athabasca River basin was characterized from AES records at Whitecourt, Edmonton, Slave Lake and Fort McMurray, and the mean basin air temperature was computed using the Thiesson polygon technique. During the month of March, the maximum daily temperature seldom rose above 10°C. A brief warm spell occurred during the first week of April when the maximum temperature reached 24°C, but this was followed by a significant cooling trend for about six days when the maximum temperature never rose above 0°C. The first positive degree days (melting) occurred on March 25 and by April 9, about 70°C-days of melt had been accumulated (Figure 3). However, very cold conditions after April 9 drove down the accumulated heat index to almost half its peak value, before additional gains were evident on April 14. The maximum of 70°C-days was not re-established before the breakup was completed on April 20.

The average basin solar radiation was computed on the basis of measured solar radiation at Edmonton and measured hours of bright sunshine at Edmonton, Slave Lake and Fort McMurray. As for the air temperatures, the computed basin solar radiation was determined by applying the Thiesson polygon technique. The daily solar radiation fluctuated significantly, from day to day, with variation averaging about 50% of the mean over a number of days. As expected, there was a significant increase in the solar radiation as the days got longer. Prior to March 21, the upper limit of the daily total solar radiation remained relatively constant at about 12 GJ/m^2. However, after that day, there was a significant increasing trend, so that by the middle of April, the upper limit of total daily solar radiation was about 22 GJ/m^2.

Mean daily discharges on the Athabasca River in the study area were estimated by WSC. Recognizing that under-ice estimates of flow are difficult to predict, especially during a transitional period such as breakup, there is some error associate with this exercise. Prior to March 25, the Athabasca River exhibited a steady discharge of about 150 m^3/s. On March 25, there began a gradual increase until the discharge reached 260 m^3/s on April 10. On that date, the bulk of the runoff began with mean daily discharges rising above 300 m^3/s and reaching 360 m^3/s on April 17.

During the observation flights, the fraction of open water and/or overflow was estimated from both direct observation and by analyzing oblique 35 mm aerial photographs. For any given length of open water, the fraction of the channel width which was deemed to be composed of open water was estimated to the nearest 1/5 of the channel width. For any given reach of interest, the fraction of open water was accumulated and defined as a fraction of the reach length. It is apparent that the fraction of open water increases in time, as would be expected. The results are shown in Figure 4 and summarized in Table 1. On April 3, the overall slope of the line defining the accumulated fraction of open water was very small and essentially constant. This indicates that there was very little open water, and that conditions were very similar throughout the entire reach of the Athabasca River. On April 8, the slope increases significantly in the reach between the mouth of the Pembina River and Tomato Creek. This indicates that open water was being generated at a faster rate in this reach than along the rest of the river. By April 16, although there was little change in the upper reach, the reach of river between the 20th base line and Pelican Portage became the most active. This activity was maintained to April 18, at which time incipient breakup conditions had been reached with a very dynamic breakup occurring the next day.

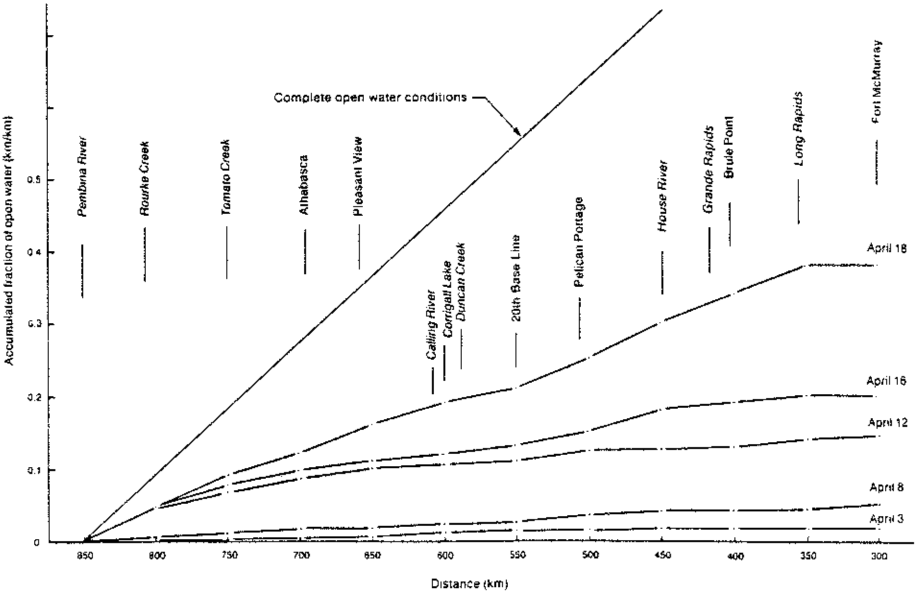

Figure 4. Accumulated fraction of open water on the Athabasca River between the Pembina River and Fort McMurray

The most interesting thing, when looking at Figure 4, is the relative consistency of the open water fraction along the entire river. There were no reachs at the river where massive amounts of open water were produced in isolation from the other reaches. What is more apparent is a uniform and consistent increase in open water with time, rather than in space.

Table 1. Summary of the ice cover and meteorologic data characterizing the breakup on the Athabasca River, 1986

Date	Snow on[1] Ground (mm)	Open Water (%)	Degree Days Melt (°C-days)
March 26	60(44)[2]	<1	0
April 3	13(20)[2]	2	20
April 8	4	5	66
April 12	0	19	50 (70)[3]
April 16	0	21	46 (80)[3]
April 18	0	39	55 (92)[3]
April 19	0	>50	61 (100)[3]

(1) water equivalent at the Twin Lakes snow pillow
(2) brackets indicate basin average
(3) brackets indicate melt discounting sub-zero temperatures April 10 - April 14
(4) measured at Athabasca

MODEL CALIBRATION

Calibration and/or application of the model requires the evaluation or definition of seven variables, aside from those variables associated with the channel characteristics. In general, the albedos and the heat transfer coefficients should be universal and not a function of location or time. Hence, they can be assigned with a reasonable degree of confidence from other studies. The initial ice thickness and the start dates on which the model computations begin are assigned from observations of river stages and snowpack characteristics and are specific to the year being analyzed. The only variable requiring calibration is the exposure factor, Γ, which is a function of the channel planform, valley wall characteristics and the sun angle. Table 2 summarizes the model parameters used in the calibration.

The exposure factor, Γ, was evaluated by applying the model to the data summarized in Table 1 with daily values of air temperature, solar radiation and discharges as inputs. Figure 5 compares the calculated values of the fraction of open water to those measured. It appears that the most appropriate value of Γ for this reach of river is 0.75. The goodness of fit is quite remarkable, except for the April 12 point. It may be possible that the April 12 value was overestimated, given the inherent inaccuracies of estimating the fraction of open water or there was considerable overflow on that day. However, the rate of change is quite well represented over the entire breakup period and given the simplicity of the model, its results appear to be sufficiently accurate.

Table 2. Summary of model parameters

Parameter	Range of Values	Reference	Adopted Value
α_i	0.20 - 0.45	Bolsenga (1977)	0.4
α_w	0.05 - 0.12	Anderson (1954)	0.05
h_w (W/m2-°C)	15.0 - 20.0	Andres (1984)	15.0
h_i (W/m2-°C)	10.0 - 20.0	Ashton (1983)	10.0
t_o (m)	0.90 - 1.10	-	1.0
Initial slage increase	-	-	March 17
Last snow	-	-	March 28

The shape of the curve defining the fraction on open water is a function of two processes. Initially, prior to about April 8, the open water is primarily a function of the discharge and because the ice is still relatively thick and there is less than 5% open water, variations in the thermal processes do not contribute substantially to changes. However, after April 8, the stage is relatively constant and with a substantial fraction of open water now apparent, the shape of the curve is primarily a function of the heat transfer processes. The increase in the fraction of open water reflects the warmer temperatures, the greater solar radiation and the thinner ice cover.

Figure 5 also indicates the effect that variations in the shading factor have on the computed ice thickness. Unfortunately, no measurements of thickness in the pre-breakup period are available, however, observations at Hondo (Van Der Vinne, 1988) suggest that ice thicknesses at breakup are generally 0.5 m and greater. This suggests that the ice thickness computations are not unrealistic and exposure factors between 0.5 and 0.80 are appropriate. It is apparent from this figure that the increased ice thickness caused by a reduction in the exposure factor may contribute to the delaying of breakup.

A sensitivity analysis was carried out to evaluate the impact that errors in some of the more subjectively prescribed values of the model parameters would have on the model output for the hydrologic and meteorologic conditions evident in 1986. Each of the six parameters, including the initial ice thickness, the albedos of ice and water, the convective heat transfer coefficient for ice and water and the exposure factor were altered within a prescribed range and compared against the field data and the output from the adopted calibration run. Variations in the albedo of water between 0.3 and 0.5 and the albedo of ice between 0.025 and 0.10 did not seem to make a significant difference in the output, and the development of open water was satisfactorily represented within ±1 day for the entire range of values chosen for each parameter. Similarly, variations in the convective heat transfer coefficients for water from 10 W/m^2-°C to 25 W/m^2-°C and for ice from 5 W/m^2-°C to 20 W/m^2-°C did not produce any striking differences in the calibration.

The effects of changes in the date of the initial stage increases prior to the appearance of open water on the rate of open water generated are shown in Figure 6. In this situation, a stage increase prior to March 21 does not have an impact on the rate of progression towards breakup. Because the gauge height and discharge were constant before March 21, no stage increase was evident until March 21 and so there was no deviation from the calibration curve. However, when the first stage rise was set at a time one day later, the reference width was subsequently increased and the measured stage increases after March 22 produced less initial open water causing a reduced fraction of open water and available for solar radiation absorption and therefore, delayed the onset of breakup significantly. Delaying the first day of stage increase by one day and by eight days caused breakup to be delayed by two days and six days, respectively.

The effects of varying snowpack depths are summarized in Figure 7. A relatively thick snowpack will take longer to melt, hence delaying the beginning of ice thinning. On the other hand, if there is little snow, the snow cover will be depleted much sooner. The latter situation ultimately results in a thinner ice cover during the period of open water generation and hence produces breakup at an earlier date. For example, if the snowpack is totally removed (ice begins to thin) nine days earlier, breakup is advanced by two days. Even if the ice cover starts to thin three days earlier, there is an acceleration of breakup by about one day. Delaying the onset of ice cover thinning by ten days, delays breakup by only one to two days. Variations in this scenario significantly effect the ice thickness over the duration of the breakup period with the mid-April ice thickness varying between 0.3 and 0.8 m, depending on the day of initial thinning. Although the ice cover varies tremendously, the change in the date of breakup is not all that substantial.

The final variable tested was initial ice thickness. It was apparent (Figure 8) that variations in the adopted initial ice thickness created significant changes to the model output. If the minimum ice thickness (0.75 m) was assumed, the onset of breakup was accelerated by three days. If the thickest ice cover (1.2 m) was assumed, breakup would be delayed by slightly more than one day. It appears that the natural variation in the ice thickness can affect significantly the time of breakup.

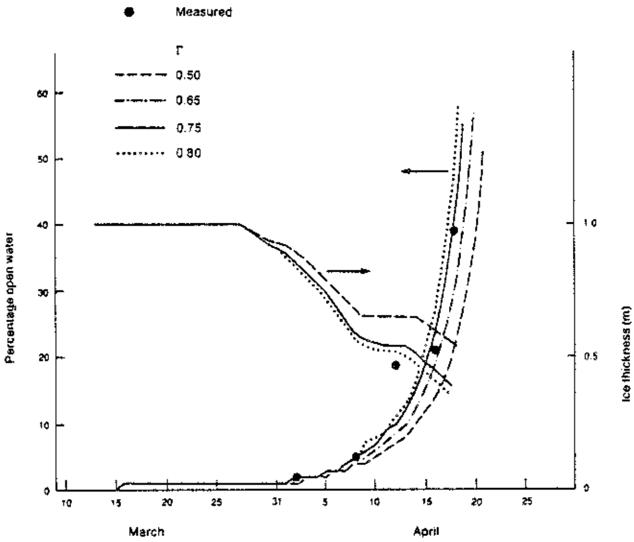

Figure 5. Calibration of the exposure factor and sensitivity of the ice thickness to variations in the exposure factor

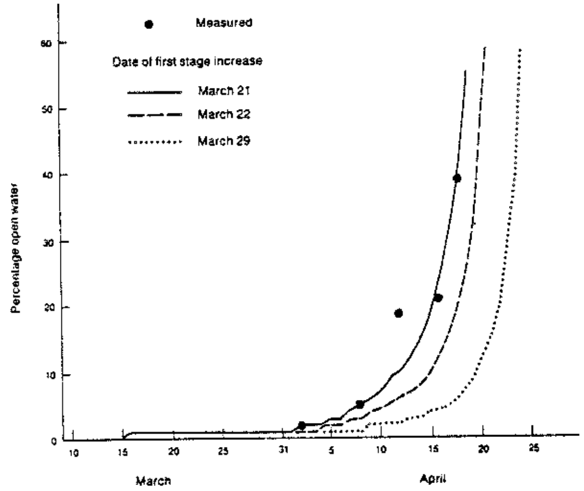

Figure 6. Sensitivity of the rate of open water generation to variations in the date of first stage increase

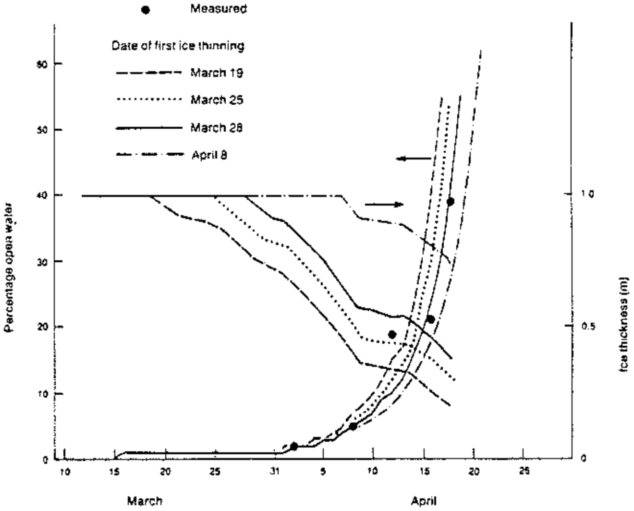

Figure 7. Sensitivity of the rate of open water generation and ice thickness to variations in the date on which the ice cover begins to melt

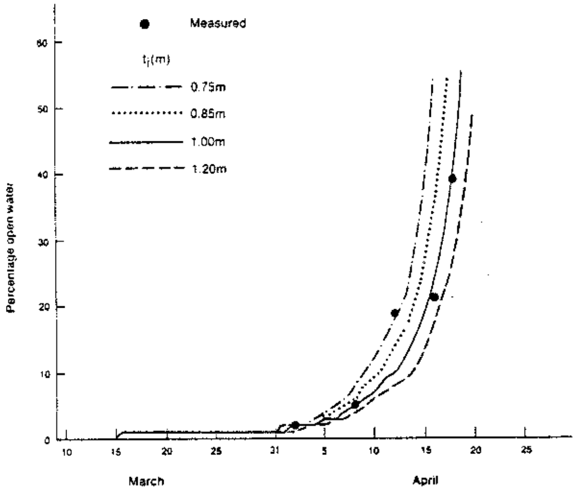

Figure 8. Sensitivity of the rate of open water generation to variations in the initial ice thickness

SUMMARY

The observations of breakup summarized herein have lead to the development of a model to predict the rate of open water development contributing towards incipient instability and breakup of a non-regulated ice covered stream. The observations indicate that for even slightly below normal snowfall, the breakup process is largely dominated by thermal processes and seems to be initially independent of the runoff. The initial open water is generated by a stage increase resulting from the melting of the snowpack. This can occur before the snowpack is entirely removed and contributes to a decrease of the average albedo of the stream/ice surface. This results in a more efficient transfer of energy (heat) across this surface and promotes the development of open water.

The ice cover begins to thin once the snow cover on the ice has been melted. The combination of a progressively thinner cover and a greater heat flux at the stream surface leads to an exponential increase in the fraction of open water. The processes by which this occurs are quite straightforward, and all can be rationalized quite easily except for the physics of the development of open water. This leads to the one crucial assumption in the model; all the heat that is absorbed by the fraction of open water goes to the melting of a proportional amount of ice cover.

A numerical model, developed to account for these processes, was tested against one year of observations and was found to describe the change in the fraction of open water relatively well. Using measured values of daily air temperature, solar radiation and discharge and initializing the model by defining the maximum winter ice thickness, the day of the first consistent stage increase and the last day of accumulated snow on the ice cover, it was found that the observations of open water could be calculated using an exposure factor of 0.75, an albedo of ice and water of 0.3 and 0.05, respectively, and a convective heat transfer coefficient over ice and water of 10 W/m^2-°C and 15 W/m^2-°C, respectively.

Sensitivity analysis suggested that the variations of the albedos and the heat transfer coefficients within appropriate and accepted limits did not significantly alter the model performance. It was most important to have a good definition of the maximum winter ice thickness, the date of first thinning (last day of a substantial snow cover) and the first day of appreciable rise in stage. For this specific location, it appears that an exposure factor of 0.75 is the most appropriate.

It should be noted that this model describes the process by which an ice cover goes from a very solid competent state to one so deteriorated that instability sets in and breakup occurs. For this specific year, the critical fraction of open water appeared to be about 0.40. However, in all likelihood, the critical value is a function of the snowmelt runoff. For years with a low snowpack and, hence, low flow increases, it is probable that Θ_c is relatively high. On the other hand, if there is a significant snowpack and considerable runoff develops, the fraction of open water needed to produce unstable

conditions is probably less. Definition of the critical value, as function of runoff (or of the combination of snowpack and meteorologic conditions) can be done by looking at a number of years, applying the model to get a theoretical or computed Θ_c for the day prior to breakup and then for each of those years correlating Θ_c with the runoff or runoff potential.

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Mike Saxton, Manitoba Hydro

Could the analysis given in this presentation be extended to the case of a regulated river under constant upstream flow release?

Reply by D.D. Andres

This type of analysis could be extended to the case of the regulated river. In fact, in the development of breakup models at the Alberta Research Council, a numerical procedure was developed first for a regulated river (Peace River downstream of the Bennett Dam) because the processes are considerably less complicated (Andres, 1984; see references and end of paper). Some of the things which make a regulated river simpler to model include: (1) a well defined discharge which is usually maintained steady enough so as not to mechanically destroy the ice cover and (2) a usually continuous stretch of open water upstream of the ice head. This serves as a heat sink whose stored energy systematically causes the ice front to progress in a downstream direction at a rate equivalent to the rate at which energy is delivered to the ice cover by the flowing water.

Greg Snyder, WMS Associates

Was a comparison made to other models used to forecast breakup; specifically the model used on the Nashwaak River in New Brunswick? The bottom line for any model is that it is useful in accurately predicting breakup on the river of interest, hence by definition the model must be site specific. How site specific is the model?

I would like to commend you on trying to keep it as simple as possible and based on standard meteorologic data. I think this leads to a more usual model which could ultimately become part of a regular forecast system.

Reply by D.D. Andres

Thank you very much for your comments. With respect to your first question, no comparison was made to other breakup models such as the one used on the Nashwaak River. The model described herein does not model breakup in the same way as the Nashwaak model which is extremely site specific. The Nashwaak model predicts breakup on the basis of correlations between meteorologic conditions and the stage necessary to produce breakup at one singular location. These correlations are done without regard for the more generalized physical processes which drive the reach-scale phenomenon of breakup and do not differentiate the effect energy input has on the weakening of the ice cover and the increase in stage.

The Athabasca River model, on the other hand, does attempt to account for the physical processes which lead to breakup and therefore it is much less site-specific and applicable to a variety of rivers, provided the channel characteristics are known and the processes are typical of a natural stream (non-regulated). I should like to add that the model, as described in the paper, is not complete because it only addresses the physical processes which lead to breakup and defines the rate at which these processes occur. The critical condition when breakup occurs is a function of the snowmelt runoff and can be determined only by a number of years of observation. However this last step in the development of a complete model is not complicated and relatively straight forward. Also, this latter step is probably the only truly site specific component of the model.

T.D. Prouse, National Hydrologic Research Institute

Incoming longwave radiation usually increases as more of the sky is obscured by the surrounding land mass. Under some meteorologic conditions this increase may even more than offset the decrease in the short wave radiation. Did you account for this in your calculation of what is commonly referred to as the "view factor"?

Reply by D.D. Andres

The analysis of heat transfer at the surface of both the ice and water was simplified by considering two processes: (1) the solar radiation which is independent of the air temperature and (2) all the other heat transfer terms (including long wave radiation) which are dependent largely on the temperature difference between the air and the ice or water. These temperature depended terms were all lumped together and described by a heat transfer coefficient. By differentiating the known rates of heat transfer at a water or ice surface between the known short wave solar radiation and the unknown temperture-related terms, the appropriate heat transfer coefficient could then be calculated to account properly for the latter processes. The heat transfer coefficient was assumed to be constant for any solar radiation/shading condition and the "exposure factor" or "view factor" was then adjusted within reasonable limits to account for total transfer or energy.

It should be mentioned that for long river reaches such as those considered on the Athabasca River it is very difficult to accurately model the view factor on the basis of the sun angle, the height of the valley walls, and the orientation. Thus it seems more appropriate to develop a simple but rationally based coefficient to use as a calibration reference.

R. Gerard, Department of Civil Engineering, University of Alberta

How does your forecasting technique compare to that developed by C. Doyle in his 1987 M. Sc. thesis entitled "Hydrometeorological Aspects of Ice Jam Formation at Fort McMurray, Alberta."

Reply by D. D. Andres

Very briefly, Doyle (1987) attempted to look at three issues. First, he related the accumulated degree days of thaw and the hours of bright sunshine on a daily basis to estimate discharge at breakup. Second, regression techniques were applied to forecast the maximum ice jam stage on the basis of discharge, recognizing that as the amount of bright sunshine increased the strength of the ice decreased, hence leading to reduced ice jam severity. Finally, he attempted to estimate the time of breakup by looking at a variety of meteorologic variables, including the antecedent upper atmospheric synoptic patterns and flow over Fort McMurray, but the results here were inconclusive.

In the above analysis input (meteorologic variables) was related to output (ice jam stages or flooding at Fort McMurray) and no observations of the processes were made. Hence the relationships and the techniques basically became statistical. This is very similar to the Nashwaak River model, except in Doyle's work the processes are somewhat better understood and more clearly rationalized.

In comparing the two models, I think that the comment I made with respect to Snyder's question would apply to equally well here. From an operational view point, the Athabasca River model allows one to better understand the processes and hence deduce what is happening on the river. Also, It allows one to get a feel for how the antecedent conditions such as ice thickness and snowpack will determine the date of breakup in a deterministic way. On the other hand, the Doyle models allow for a crude assessment of the ultimate condition at Fort McMurray from a statistical point of view. When those two approaches are used together a more confident interpretation of the final outcome is inevitable.