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STUDY OF RIVER ICE BREAKUP USING HYDROMETRIC STATION RECORDS

by

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MANAGEMENT PERSPECTIVE

River ice breakup may cause floods or costly delays to navigation. Breakup and water levels are a complex combination of meteorological conditions and physical characteristics of the site. Understanding and eventual control depends very much on using historical information which was not obtained to study ice jams. This report is a pilot study to establish the information pertinenent to understanding the phenomena and to providing useful guidance for planning and management.

This report shows that existing data in gauge records of the Water Survey of Canada may be used to obtain useful information which may help in forecasts of future flood levels.

However, before general conclusions can be drawn, other similar studies at sites throughout Canada will be useful if not necessary to obtain progress. It is notable that if the data gathering were to be minimally supplemented that much more could be done with future data records.

T. Milne Dick
Chief, Hydraulics Divison

PERSPECTIVE DE GESTION

Les débâcles fluviales peuvent causer des inondations ou retarder indument la navigation. Les débâcles et les fluctuations de niveau d'eau proviennent d'un ensemble complexe de conditions météorologiques et de caractéristiques physiques du lieu. Leur compréhension et leur contrôle éventuel dépendent étroitement de données historiques qui n'ont pas été recueillies lors d'études d'embâcles. Le présent rapport est une étude pilote visant à établir quelle information est pertinente à la compréhension des phénomènes et peut servir à planifier et à gérer.

Le présent rapport montre que les mesures de jaugeage des Relevés hydrologiques du Canada peuvent servir à obtenir de l'information utile pour prévoir la hauteur des inondations futures.

Or, avant de tirer des conclusions générales, il serait utile, voire nécessaire, d'effectuer des études semblables dans divers endroits du Canada pour faire des progrès. Il est à noter qu'en recueillant un peu plus de données, on pourrait tirer beaucoup plus d'information des mesures futures.

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STUDY OF RIVER ICE BREAKUP USING HYDROMETRIC STATION RECORDS

S. Beltaos[1]

ABSTRACT

The possibility of using hydrometric station records to extract information related to ice breakup forecasting is explored. Methods for interpretation of the records are outlined and utilized to study breakup characteristics of the Nashwaak River at Durham Bridge, N.B. The results are then compared with recent insitu observations of ice conditions. It is concluded that useful but incomplete information can be extracted from existing records and a need for a theoretical framework of breakup processes is demonstrated. The value of records would be enhanced by collection of additional data such as actual ice thickness; one or more discharge measurements during breakup; and wider utilization of local observers for descriptions of ice conditions.

RÉSUMÉ

Les auteurs se sont penchés sur les possibilités d'utiliser les relevés de station hydrométrique pour extraire des données liées à la prévision du déglacement. Ils décrivent leurs méthodes d'interprétation des relevés et ils s'en servent pour étudier les caractéristiques de la débâcle de la Nashwaak à Durham Bridge (N.-B.). Les résultats sont ensuite comparés à de récentes observations sur place des conditions glacielles. Ils en concluent qu'une information utile mais incomplète peut être tirée des relevés disponibles et ils démontrent qu'il serait nécessaire d'élaborer un cadre théorique des processus de déglacement. La valeur des relevés serait augmentée par la collecte de données supplémentaires comme celles qui ont trait à l'épaisseur de la glace, une ou plusieurs mesures du débit pendant la dislocation et finalement, un plus large recours aux observateurs locaux pour la description des conditions glacielles.

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INTRODUCTION

During the summer 1980 meeting of the N.B. Subcommittee on River Ice (formerly: Ad Hoc Committee on Ice and Ice Jams), a question arose as to whether existing hydrometric station records could be utilized to forecast the onset and severity of river ice breakup. To explore this possibility a joint (NWRI/WSC*) study was initiated for the hydrometric station located on the Nashwaak River at Durham Bridge in New Brunswick. The undertaking of this task was facilitated by the fact that a similar study had been initiated by the writer in late 1979 for Ontario rivers, in co-operation with the WSC Guelph office.

Preliminary results of the Nashwaak River study (Beltaos and Lane 1982) indicated that useful, though incomplete, information can be extracted from existing records. This finding prompted the writer to extend the study to include factors not previously considered and assess the resulting forecast methods using insitu ice observations that have since been performed under the auspices of the N.B. Subcommittee and N.B. Environment. The results to date are reported herein.

RIVER ICE BREAKUP

When an ice-covered river basin is subjected to mild weather, two processes generally begin: increased runoff due to rainfall or snowmelt or both; and heat input to the ice cover. The former process results in increased uplift and frictional forces applied on the ice cover; and in increased water stage which, in turn reduces the support provided to the ice cover by the channel banks and provides increased channel width for movement of the cover. Heat input to the ice cover results in reduced dimensions and strength. It follows that during the mild weather spell, the forces applied on the ice cover increase while the cover's ability to resist these forces decreases. If the mild weather lasts for a sufficient time, the ice cover begins to break up which is often followed by formation of large ice jams, major ice runs and eventual clearance of the ice from the reach of interest. This general description of the breakup process includes two extreme cases, i.e., the "premature" and "overmature" breakup (Deslauriers 1968). Premature breakup occurs under conditions of intense runoff with little, if any, deterioration of the ice cover. Clearly, this type of event has the greatest damage potential, other things being equal. On the other hand, conditions of slow or no runoff with intense ice deterioration lead to overmature breakup. This event is characterized by gradual ice disintegration and has minimal potential for damage.

The first question a forecaster might ask would be how to predict whether and when breakup will be initiated. And once initiated, how

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*NWRI = National Water Research Institute
WSC = Water Survey of Canada

severe it is likely to be in terms of magnitude and duration of ice jam stages at various locations.

Concerning breakup initiation, pertinent literature often advocates use of the corresponding water stage, H_B (= height above an arbitrary datum, e.g. gauge height) as a convenient and meaningful index (Shulyakovskii, 1963; Gerard, 1979; Beltaos, 1981, 1982). From our earlier discussion, it would appear that H_B is indeed a desirable parameter because it reflects the ice driving forces as well as the water surface width available for ice movement. Moreover, the above noted literature suggests that, in a given reach, H_B depends on: the thickness of the ice just prior to breakup, h_i; the degree of ice strength reduction caused by thermal effects; and the stage during freeze up when a stable ice cover forms, H_F. The latter is an index of the width of the ice cover and, excepting mature breakup events, has to be exceeded before contact of the ice with channel boundaries is eliminated. As will be discussed later, approximate values of these parameters can be extracted from gauge records. As for ice strength, there is no direct information. The best that can be done at present is to use a meteorological index intended to describe the effects of thermal deterioration.

With regard to the severity of breakup, one would ideally wish to predict the complete stage hydrograph during the breakup period at any given location. This appears to be too ambitious a task at present; it is thought more practical to limit the goal of the study to forecasts of the maximum stage during breakup, H_m. This stage can be easily identified on gauge recorder charts and is usually caused by a nearby ice jam. Theoretical considerations and field data (Pariset et al, 1966 Beltaos, 1983) have shown that the maximum stage that can be caused by an ice jam occurs when the jam has attained a condition of equilibrium and fully affects the site of interest. This equilibrium stage depends mainly on discharge, channel slope and width. During any one breakup period, H_m may or may not reach the equilibrium jam stage owing to one or more of the following reasons. (a) Ice jam located far downstream of the gauge site. Even if this jam attains equilibrium, the gauge site will experience a fraction of the jam's effect on stage. (b) Ice jam is located far upstream of the gauge site. The gauge site will again experience a fraction of the jam's effect on stage owing to attenuation effects during the jam's release. (c) Unstable jam that releases prior to attaining equilibrium. (d) Overbank flooding. Water and ice spread out onto the flood plain so that the jam's potential is dissipated. This case could be viewed as a particular instance of the unstable jam case. Considering that a major factor contributing to ice jam formation is the original ice cover itself, it is reasonable to expect that not only discharge but also competence of this cover may influence the value of H_m (see also later discussion).

DESCRIPTION OF DATA

The main data source has been the WSC record of gauge height versus time for the period 1965-81. Supplementary information consisted of daily discharge data (WSC); meteorological data (Atmospheric Environment -"Monthly Records"); channel hydraulics in the vicinity of the gauge (B.Burrell, N.B. Environment); and recent ice thickness measurements (P.Tang, N.B. Environment). From these "raw" data, several parameters thought to be characteristic of the ice regime have been extracted as described below.

Maximum Stable Freeze Up Stage (H_F)

A typical but not universal configuration of the daily average stage hydrograph near the start of the ice season is sketched in Figure 1. The solid line represents the actual stage whereas the broken line gives the "effective" stage (=stage that would have occured had the flow been unaffected by ice). At a certain time which may be termed the beginning of freeze up, the actual stage starts to rise while the effective stage continues to drop. Eventually, the actual stage attains a peak and then declines. This sequence reflects the dynamic nature of ice cover formation in rivers. With the onset of cold weather, frazil ice forms and is initially transported freely. The effect of this moving ice on the water stage is small. As more and more frazil is produced, it begins to agglomerate into slush and pancakes. Eventually, the ice transport is impeded somewhere downstream of the gauge (due to border ice growth or other constricting feature) and an ice cover begins to propagate upstream. The presence of the ice cover causes a local stage increase which eventually begins to be "felt" at the gauge site. The gauge height then increases until the time when the edge of the ice cover arrives at the gauge site. Subsequently the gauge height decreases due to decreasing discharge and thermal smoothing of the underside of the cover. The peak stage (H_F) during this period is considered an important factor influencing the succeeding breakup because it defines the stage at which the ice cover is formed; the width of the cover is approximately equal to the channel width at the stage H_F. To eliminate brief peaks during which there is little time for freezing, H_F is defined as a daily average value. It is recognized that this definition of H_F only provides an index for the width of the stable ice cover and could, perhaps be improved by taking an average over a number of days after the peak. While this is a matter that should be investigated in the future, it was considered an unnecessary elaboration for the present exploratory study.

Moreover, it should be kept in mind that the above described freeze up process occurs frequently but not always due to occasional presence of complicating factors, e.g., severe flow and stage controls; incomplete ice cover; very rapid drop in discharge that suppresses occurrence of a peak on the stage hydrograph. Because of these and possibly other unforeseen difficulties, H_F should be determined in conjunction with consultations of prevailing weather conditions and (if available) local observers' reports* while keeping in mind its physical

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* At many gauge sites, local observers are temporarily employed by the operating agency to provide brief descriptions of ice conditions at a specified frequency.

significance as outlined earlier. In the present study, interpretation of freeze up stage records presented little difficulty except on a few occasions where H_F determination was designated "uncertain".

"Winter" Peaks.

Occasionally, a brief thaw may occur during the winter period. If such a thaw causes sufficient runoff, the gauge record will show a peak which may or may not initiate breakup. In the latter case, the peak stage represents a lower limit for the stage required to initiate breakup at that time. The term "winter" peak is used conventionally and includes any peak that does not initiate breakup. While such peaks usually occur in the winter, there are instances where "winter" peaks occur a few days before the spring breakup.

Stage at Initiation of Breakup (H_B).

Usually,when a thaw does lead to breakup of the ice cover, the stage begins to rise from its fairly steady winter value and shortly after exhibits spikes and peaks that can only be caused by breaking or broken ice effects (Fig.2). A probable value of the stage at the initiation of breakup, H_B, may be fixed at the first significant spike* . Unfortunately, this definition is not always objective or meaningful. Only a probable range of H_B can then be determined, by considering: (a) the latest time for which it can be confidently assumed that there still was continuous ice cover; and (b) the earliest time for which broken ice effects became evident on the stage hydrograph. Difficulties may be experienced in cases of absence of spikes owing to very rapid stage increases caused by intense runoff or release of upstream ice jams; "misleading" spikes caused by discharge reductions due to upstream jam formation; or "overmature" breakup events where breakup can be initiated during constant or even decreasing stage conditions.

Because of such complications, H_B determination should utilize all supplementary information, e.g., prevailing weather conditions, local observers' reports and prior experience of local ice conditions. For the present study no overmature events were encountered, with the possible exception of the 1964-65 event which has been designated "undefinable". This circumstance compensated somewhat for the lack of local observers' reports that have proved extremely helpful in other studies (Beltaos, Unpublished Data).

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* Initiation of breakup is defined herein as the instant when a sustained movement of the ice cover begins. When the cover is set in motion, the resistance to flow is reduced and the stage should tend to drop thus producing a spike on the stage hydrograph. Sometimes, however, the stage rise may be so steep as to suppress spike appearance. Only a slowdown in the rate of rise would then be evident.

Maximum Breakup Stage (H_m)

This is the maximum stage reached during the breakup period and its determination is straightforward (Fig. 2).

Effective Stage and Maximum Ice Effect on Stage (ΔH_m)

The ice effect on stage is the difference between the actual stage and the effective stage. The time of maximum ice effect can usually be determined by simple inspection (Fig. 2) and does not necessarily coincide with the time of H_m.

Daily average discharge values are estimated by WSC based on interpolations between discharge measurements as well as on such evidence as upstream and tributary flows, runoff and weather conditions, etc. Such estimates may involve considerable error. This has repercussions on the accuracy of the effective stage which is determined by joining daily values plotted at noon of each day. For the Nashwaak R. at Durham Bridge, very little confidence can be placed on discharge estimates during breakup conditions (Beltaos and Lane 1982).

Ice Thickness (h_i)

Ice thickness can be estimated from WSC discharge measurement notes. Such notes give the distance from the water surface to the bottom of the ice which, under free flotation conditions, represents about 92% of the total ice thickness. However, this assumption may or may not be valid depending on whether there is significant bank support of the ice or snow cover which may cause the free water surface to rise above the top of the ice. The presence of a slush deposit under the solid ice may render thickness values completely unreliable because the notes would then show the distance from the water surface to the bottom of the slush. Another source of error may be (unreported) instances when "water surface" has been used nominally, i.e., substituted by a more convenient datum such as the top of a deep snow layer.

Usually, a few ice thickness values will be available during any one winter season. These can be plotted versus time and extrapolated to the start of the mild weather spell that led to breakup. Where the winter season involves highly variable weather conditions, it may be preferable to extrapolate using a more complex correlation, e.g., h_i versus accumulated degree-days of frost. Such procedures would generally give fair indications of h_i at the time breakup starts but ignore thickness reductions that may occur during the pre-breakup period (onset of mild weather spell to onset of breakup). This assumption is considered adequate for the present in view of (a) the crudeness of the other data involved; and (b) the partial accounting of this effect by introducing a meteorological index of heat input to the ice cover.

Meteorological Index of Ice Strength

Few data on ice strength at the time of breakup are available and the manner of ice strength reduction by thermal effects is not well understood at present (Frankenstein, 1961; Korzhavin, 1971; Butyagin, 1972). In general, it is reasonable to expect that ice strength will decrease with increasing amounts of heat absorbed by the ice cover but there is no consensus on the most appropriate index for the latter. A very simple and well known index is the accumulated degree-days of thaw, S_T (see for example, Williams, 1965; Bilello, 1980). However, S_T can only be satisfactory in cases where the time of year when breakup occurs and the number of "thawing" days do not vary appreciably. Otherwise, the important effect of solar radiation will not be considered. For example, a sunny day in April would be much more effective in weakening the ice than a cloudy day of the same average air temperature in January. To fully account for thermal effects on ice strength, several parameters are needed in addition to air temperature, e.g., short wave radiation, cloudiness, wind speed, water temperature, snow cover, ice composition, etc.

Unfortunately, not all of this information is usually available and even if it were, it would be impractical to attempt multiple correlations with so many parameters. Shulyakovskii (1963) suggested the use of a calculated value of heat input to the ice cover from the surface, thus ignoring heat transfer from the water since water temperature is, as a rule, unknown. A similar but somewhat simplified approach was suggested by Williams (1965). Bulatov (1972) outlined a method for computing ice strength based on theoretical and experimental correlations with radiation effects. However, Bulatov's paper was too general to permit application of his method by others. Ashton's (1983) analysis is similar to Bulatov's and shows that the main agent of deterioration is the penetrating solar radiation, once the ice has been warmed to 0°C. Additional radiation absorption causes melting at the grain boundaries with a resulting decrease in strength. However, Ashton's analysis cannot be applied to the data under consideration because information on snow cover, albedo and ice structure is lacking.

Evidently, only empirical indices of ice strength can be employed at present. Some of the simplest ones are accumulated degree-days of thaw, hours of sunshine and solar radiation but their simultaneous consideration would complicate the analysis. Shulyakovskii's (1963) single heat input parameter, $\sum q$, has the advantage of simplicity as well as a background of practical usage and was thus utilized by Beltaos and Lane (1982). However, there is no theoretical evidence that this parameter adequately accounts for the qualitatively different effects on ice strength of the various heat components involved.

ANALYSIS OF DATA

Table 1 summarizes the data for the Nashwaak R. at Durham Bridge (Fig.3). Of the 21 freeze up - breakup events that occurred during the period of record (1965 -81), one has proved impossible to interpret, while six presented serious difficulties. At the time of writing the report by Beltaos and Lane (1982), only a few ice thickness values were available and thus no attempt was made to consider h_i in the analysis. Subsequently, additional ice thickness data were made available to the writer by P. Tang of N.B. Environment which enabled determination of h_i for many of the events under consideration. For events without any thickness measurements h_i was estimated via a correlation between measured values and time from H_F. This procedure involves errors as large as 30%. Water surface to bottom of ice distances quoted by WSC have been divided by 0.92 to obtain h_i though this is recognized to be a first approximation. $\sum q$ values quoted by Beltaos and Lane (1982) have been revised to account for daily variations of associated heat input coefficients but only in a few instances did this result in substantial changes.

Initiation of Breakup.

Beltaos and Lane's analysis (1982) followed Shulyakovskii (1963), after some initial verifications of the basic premises. First, H_B was plotted versus H_F where a trend for H_B to increase with H_F was indicated. However, there was considerable scatter suggesting additional effects. Next, the difference $(H_B - H_F)$ was postulated to depend on h_i and $\sum q$, the total amount of heat input to the ice cover per unit surface area. The latter is an accumulation of daily heat fluxes (q) during daylight hours until the time of breakup initiation; heat transfer from the water is ignored. Calculation of $\sum q$ involves many simplifying assumptions so that $\sum q$ must be viewed as a mere index of the true amount of absorbed heat (see Beltaos and Lane 1982 for details of the calculation). A plot of $(H_B - H_F)$ versus $\sum q$ indicated the expected trend but exhibited considerable scatter. To explore the possible effects of h_i, the following procedure was adopted. First, $(H_B - H_F)$ was plotted versus h_i by noting the value of $\sum q$ beside each data point. This indicated an increase of $(H_B - H_F)$ with h_i and a decrease with $\sum q$. The upper envelope of the data points, assumed representative of the case $\sum q \simeq 0$, was then described by the straightline $(H_B - H_F) \simeq 2.5\ h_i$*. Next, the deviation of any one data point from the upper envelope $[= 2.5\ h_i - (H_B - H_F)]$ was computed and plotted versus $\sum q$, as shown in Fig. 4. Data ranges in Fig. 4 indicate instances where only ranges for H_B could be identified; vertical ranges indicate cases where lower and upper limits of H_B occurred within a short time period so that the corresponding $\sum q$'s were nearly equal. Data points with arrows denote winter peaks or otherwise known limits for H_B; such points are occasionally of little value (e.g., two uppermost points at $\sum q = 0$) but often give useful indications as to how a correlation line should be drawn.

Fig. 4 confirms the anticipated trends but with considerable scatter. The latter can be partly attributed to the crudeness of H_B determinations (no local observers' reports) and the empiricism introduced in the analysis (lack of a theoretical framework for breakup processes). A compensating feature is that even a large error in predicting H_B usually translates to acceptable error in forecasting

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* Linear plots of this kind have also been found by the writer at other sites but with different numerical coefficients (Beltaos, unpublished data).

the time of H_B because the prevailing temporal gradients of stage are usually large.

It may be noticed in Fig. 4 that two data ranges are plotted for the 1979 event, designated (1) and (2). The former reflects the interpretation given by Beltaos and Lane (1982) and involves serious uncertainty; it plots far off the band of the other data. Later on, it was discovered (P. Tang, personal communication) that a site visit by WSC staff in March 1979 indicated the presence of intact ice cover which dictated the following revision. What was originally thought to have been breakup initiation was in fact a winter peak whereas breakup was initiated later in March. The event designated 1979(2) reflects the new interpretation and plots at a much improved position. This result illustrates the importance of local observers' reports.

Maximum Breakup Stage

As discussed earlier, flow discharge is a major factor influencing H_m. However, discharge data for the Nashwaak River study are uncertain so that the plot of Fig. 5, showing H_m' (=H_m - stage at zero discharge) versus prevailing discharge is of qualitative value. It is noted that some of the data points in Fig. 5 represent conditions of maximum ice effect, ΔH_m, in instances where the latter did not occur at the same time as did H_m. Also plotted in Fig. 5 is the theoretical relationship between equilibrium jam stage and discharge for comparison (Beltaos 1983). The latter is seen to provide a satisfactory upper envelope up to a certain discharge, but to consistently overpredict the stage beyond this discharge. This is a typical trend, reflecting the fact that increasing discharge reduces the probability of equilibrium jam formation (Beltaos 1983). For practical purposes, an upper envelope of the data points could be drawn and used to forecast potential H_m values. Whether and how closely the potential H_m is to be realized in a given season depends on the number and stability of ice jams that form near the gauge site, as discussed earlier. In turn, such effects are controlled by channel and floodplain configuration as well as the competence of the ice cover during breakup. The former factor is difficult to assess at present because the behaviour of ice jams is unknown once the bankfull stage is exceeded (see also Calkins 1983). On the other hand, experience suggests that the competence of an ice cover should be an important factor influencing H_m and this possibility is considered next.

Since the competence of an ice cover can be defined in terms of its strength, thickness and width, it may be of interest to explore $\sum q$, h_i, and H_F (rough index of ice cover width) as possible factors influencing H_m. Fig. 6 shows H_m plotted versus H_F. The data points define an upper envelope that increases with H_F. The deviation of the observed value of H_m from the corresponding upper envelope value is plotted versus $\sum q$ in Figure 7. This results in another upper envelope that confirms the anticipated trend. It thus appears that H_F and $\sum q$ define a potential or, an upper limit for, H_m. Whether and how closely this potential will be realized in any one breakup event, depends on a number of other factors, e.g., discharge, local jamming conditions, etc. One would expect that h_i should also be relevant here but, owing to discharge uncertainties, this possibility has not been investigated herein, though h_i effects on H_m have been discerned elsewhere (Beltaos, Unpublished Data). Moreover, it is noted that strictly speaking, $\sum q$ should be calculated to the time of H_m. However, the value used in Fig. 7 applies to the time of H_B. This was thought sufficient given that the present study was exploratory.

Frequency of Occurrence of H_m

A simple frequency analysis on H_m values was also performed by Beltaos and Lane (1982). The fact that, occasionally, there have been two breakup events in the same season was ignored and all events were assumed to be independent so as to increase the effective length of record. This may or may not be valid but more data are needed to clarify this point. For the present study, it was found that the above approach resulted in a frequency curve that differed very little from the one obtained by use of only the highest breakup stage in any one season.

For convenience of plotting, use has been made of, $H_m' = H_m$ - stage at zero discharge. In this manner, the event $H_m' \geq 0$ has a probability of 1. After performing the frequency analysis, H_m' can be plotted versus probability on various types of charts as a means of exploring the mathematical form of the H_m' distribution. Gerard and Karpuk (1979) suggested that the log-normal distribution is a possible candidate and found a linear relationship after plotting their data on log-normal probability paper. Figure 8 shows that only in the range $0.1 \leq P \leq 0.9$ do the present data adhere to a linear relationship.

Limitations

Clearly, the results presented so far are site-specific and empirical. Therefore, extrapolation to other sites or hydrometeorological conditions different from those covered by the years of record is not justified. Accumulation and comparison of several case studies such as the present would facilitate development of more general forecasting methods.

COMPARISON WITH OBSERVATIONS

Since 1981, ice conditions in the Nashwaak River near Durham Bridge are monitored under the auspices of the N.B. Subcommittee on River Ice and N.B. Environment. The results of the field observations are used in this section to assess the effectiveness of the relationships derived so far.

1981-82 Event

Ice effects on stage commenced on Dec. 26, 1981, and a value of 2.18 m was chosen for H_F on Dec. 28. Breakup was initiated at about 1100 h on Apr. 1, 1981, with H_B = 2.50 m and H_m = 3.00 m occurring at 1800 h on Apr. 3. From measurements, h_i was estimated as 0.61 m and $\sum q$ was calculated as 5784 J/cm^2. The quantity 2.5 h_i - (H_B - H_F) is 1.21 m and inspection of Fig. 4 indicates that the data point for this event would not fit the trend defined by the historical data. To explain this discrepancy, a close examination of the weather records was undertaken and revealed a highly atypical sequence of events: A warming trend began on Mar. 11 and continued until Mar. 20. Subsequently, the weather turned cold but q values remained positive, excepting the dates Mar. 22, 27, 28 and 29. A total of 15 cm of snow fell during the period Mar. 19-22. A continuous warm trend began on Mar. 30 and led to breakup. Between Mar. 11 and 29, a net of 34.3°C - days of frost was accumulated. This sequence of events suggests that sustained thermal ice deterioration would have started on Mar. 30 even though the value of $\sum q$ up to Mar. 29 was 3789 J/cm^2. This illustrates a shortcoming of Shulyakovskii's $\sum q$ calculation. The latter only accounts for heat exchange during daylight hours and would thus seriously underestimate recovery of ice strength during a cold spell that intervenes between two warm ones. If $\sum q$ were accumulated from Mar. 30 on, a value of 1995 J/cm^2 would be obtained. This would improve the plotting position of the 1981-82 event in Fig. 4. However, such a correction involves a measure of arbitrariness and the writer cannot see how to improve this situation without resort to a theoretical model of ice deterioration. Though some research has been done in this regard (Bulatov 1972; Ashton 1983), it has not advanced to the point where it can be applied in practice. For the present, it can only be hoped that the forecaster would recognize atypical events and make necessary allowances based on experience.

With $\sum q$ = 5784, Fig. 7 indicates that the quantity (H_m - 1.22 - 1.18H_F) should not exceed -0.68 m which gives H_m < 3.11 m, as was the case (H_m = 3.00 m). If $\sum q$ were taken as 1995 J/cm^2, Fig. 7 would have given H_m < 3.63 m. In cases where reliable discharge data are available, a plot such as Fig. 5 could also be used to improve forecasts of the potential H_m value. However, this is not possible in the present study owing to the serious uncertainties associated with breakup discharges.

1982-83 Events

Ice effects on stage commenced on Dec. 13, 1982, while a value of 2.50 m was chosen for H_F on Dec. 19. A mild weather spell in January led to breakup with H_B = 2.65 m at 0900 h on Jan. 12 and H_m = 3.83 m at 1500 h on Jan. 12. The values of h_i and $\sum q$ are estimated as 0.24 m and 375 J/cm^2 respectively. It follows that 2.5 h_i - (H_B - H_F) = 0.45 m and this would plot satisfactorily in Fig. 4. Use of Fig. 7 gives H_m < 4.24 m, as was the case (H_m = 3.83 m).

The peak stage during the January event was caused by a local ice jam that did not release but froze in place as cold weather resumed. A new H_F of 2.55 m occurred on Jan. 16. Breakup was initiated at 1000 h on Mar. 22 with H_B = 3.30 m, $\sum q$ = 3669 J/cm^2 and H_m = 3.97 m at 1800 h on Mar. 22. No ice thickness measurements are available for this event, hence h_i can only be estimated, as follows. If other years' experience is used and the presence of the frozen jam is ignored, h_i would be estimated as 0.61 m. On the other hand, the thickness of the jam at the time it formed is estimated to have been about 1.2 m, (see for example, Beltaos 1983). Calkins (1979) has shown that ice growth is accelerated in the presence of a porous ice accumulation under the lower boundary of a solid ice cover. If, as a first approximation, h_i is assumed to increase as the square-root of degree-days of frost, then a factor of $\sqrt{1/p}$ should be applied to the normally expected ice thickness (p = porosity). For $p = 0.4$, this gives $h_i \approx 0.61/\sqrt{0.4} = 0.96$ m. With this, the value of $2.5\ h_i - (H_B - H_F)$ becomes 1.66 m which would plot satisfactorily in Fig. 4. Use of Fig. 7 gives $H_m < 3.83$ m. The observed H_m was 3.97 m, i.e., 0.14 m higher than would have been thought possible from the historical data. This is very likely due to the extremely thick ice cover caused by the freezing of the January jam.

CONCLUSIONS

The present results indicate that useful though incomplete information can be extracted from existing gauge records. This information can be utilized in forecasting the onset and potential severity of breakup, subject to the limitations outlined next.

The present analysis is empirical and site-specific; hence, it cannot be extrapolated to other sites or to hydrometeorological conditions that are not covered by the years of record. While studies similar to the present can be used as an aid to forecasting, it was shown that some reliance on experience would be necessary for unusual events. The lack of a theoretical framework for breakup processes is considered a major obstacle to eliminating empiricism from pertinent forecasting methods. Accumulation and comparison of additional case studies would contribute toward this goal.

As a by-product of this study, several instances were identified where moderate increases of the gauge operation effort would greatly increase the value of records for breakup-related studies. These include measurement of the true ice thickness and, where applicable, delineation between solid and slush ice layers; wider utilization of local observers and increase of reporting frequency during freezeup and breakup; and performing one or more discharge measurements during breakup events.

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Table 1. Summary of Breakup Characteristics

				h_i (cm)			
Season	H_F (m)	H_B (m)	H_m (m)	From Measurements	Estimated ±30%	$\sum q$ (J/cm^2)	Remarks
1964-65	2.56	>2.20	NA		55	2125	Breakup undefinable
1965-66	1.40	1.58	2.23		73	5420	
1966-67	1.80	1.71	1.73	70		5944	
1967-68	2.34	3.25	3.87		43	425	
-"-	3.35	>2.78	NA		52	3748	
-"-	3.35	2.71	3.40		52	6246	
1968-69	2.25	>1.84	NA		38	0	
-"-	2.25	1.87	1.87		74	4240	H_B uncertain
1969-70	3.44	1.98-5.31	5.31		41	511	H_B uncertain
1969-70	2.29	1.43-1.80	2.05	37		4782	H_B uncertain
1970-71	1.65	>2.07	NA	40		197	
-"-	1.65	>1.83	NA	64		2119	
-"-	1.65	0.90-1.31	NA	64		6819-7359	
1971-72	1.19	>1.34	NA	18		251	
-"-	1.19	>1.43	NA	50		0	
-"-	1.19	>1.59	NA	60		1370	
-"-	1.19	>1.74	NA	79		0	
-"-	1.19	1.62-2.19	2.49	79		978-1467	
1972-73	2.72	>2.79	NA		50	241	
-"-	2.72	>2.16	NA		60	3251	
-"-	2.72	1.91-2.35	2.61		60	5294	
1973-74	2.20	>2.22	NA		75	2900	
-"-	2.20	1.56-2.19	2.19		76	5353-7162	
1974-75	2.19	>2.15	NA		70	2205	
-"-	2.19	1.48-1.68	1.68		70	4642-6267	H_B uncertain
1975-76	2.44	>3.38	NA		59	338	
-"-	2.44	2.19	2.94	73		3933	
1976-77	1.89	>2.69	NA	30		0	H_F and H_B uncertain $H_F \doteq 2.29$ m might be better
-"-	1.89	>1.91	NA		70	3897	
-"-	1.89	1.49-1.53	2.29		72	7442	
1977-78	1.82	2.15-2.51	2.51		25	21	
-"-	2.74	1.42-1.54	1.76	64		8176	H_F uncertain
1978-79	1.10	<1.93	2.57	30		293	
-"-	3.40	>3.26	NA	34		1074	
-"-	3.40	>3.12	NA	61		2650	
-"-	3.40	2.07-2.56	3.20	61		6234-6719	
1979-80	2.25	2.71-3.01	3.03	55		658	
1980-81	2.41	1.81-2.11	2.12	52		736-2542	

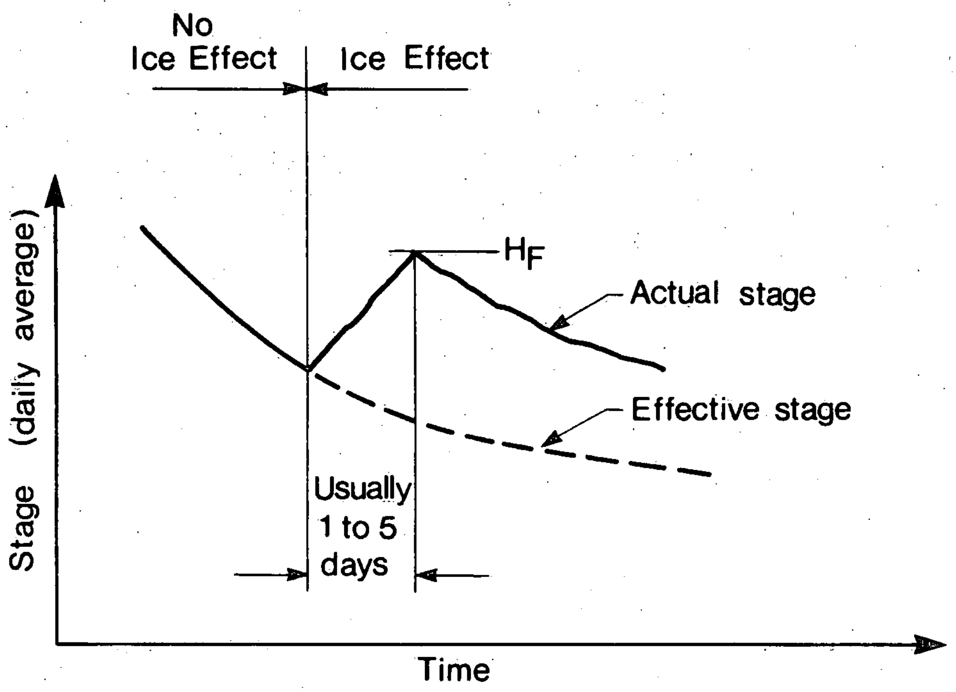

Fig. 1 Schematic illustration of daily stage variation with time during beginning of freeze up.

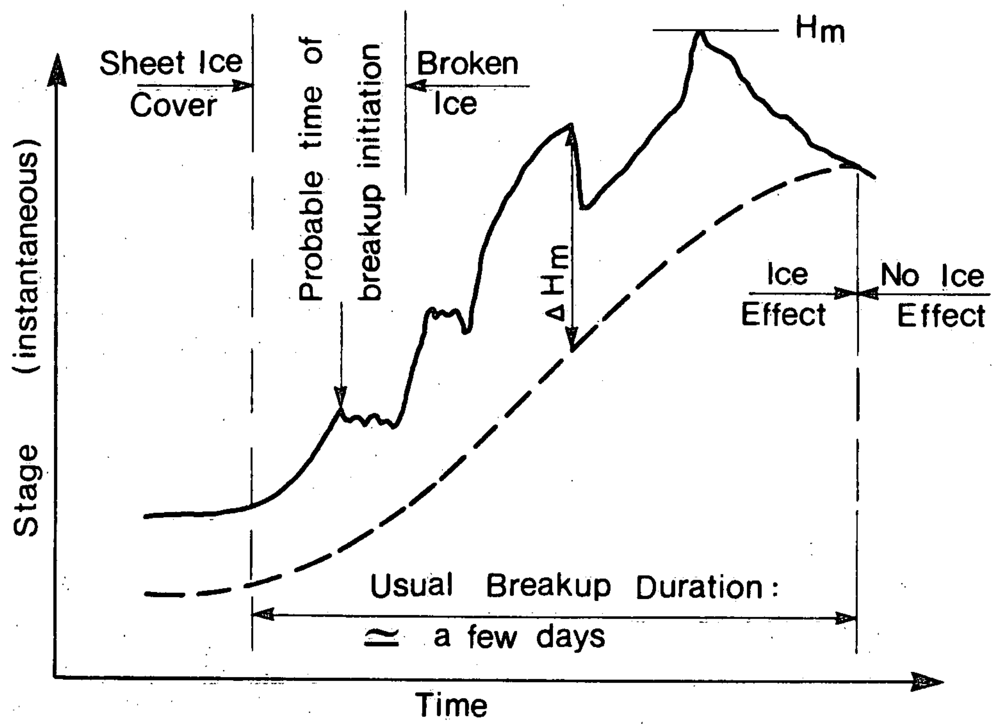

Fig. 2 Schematic illustration of instantaneous stage variation with time during breakup.

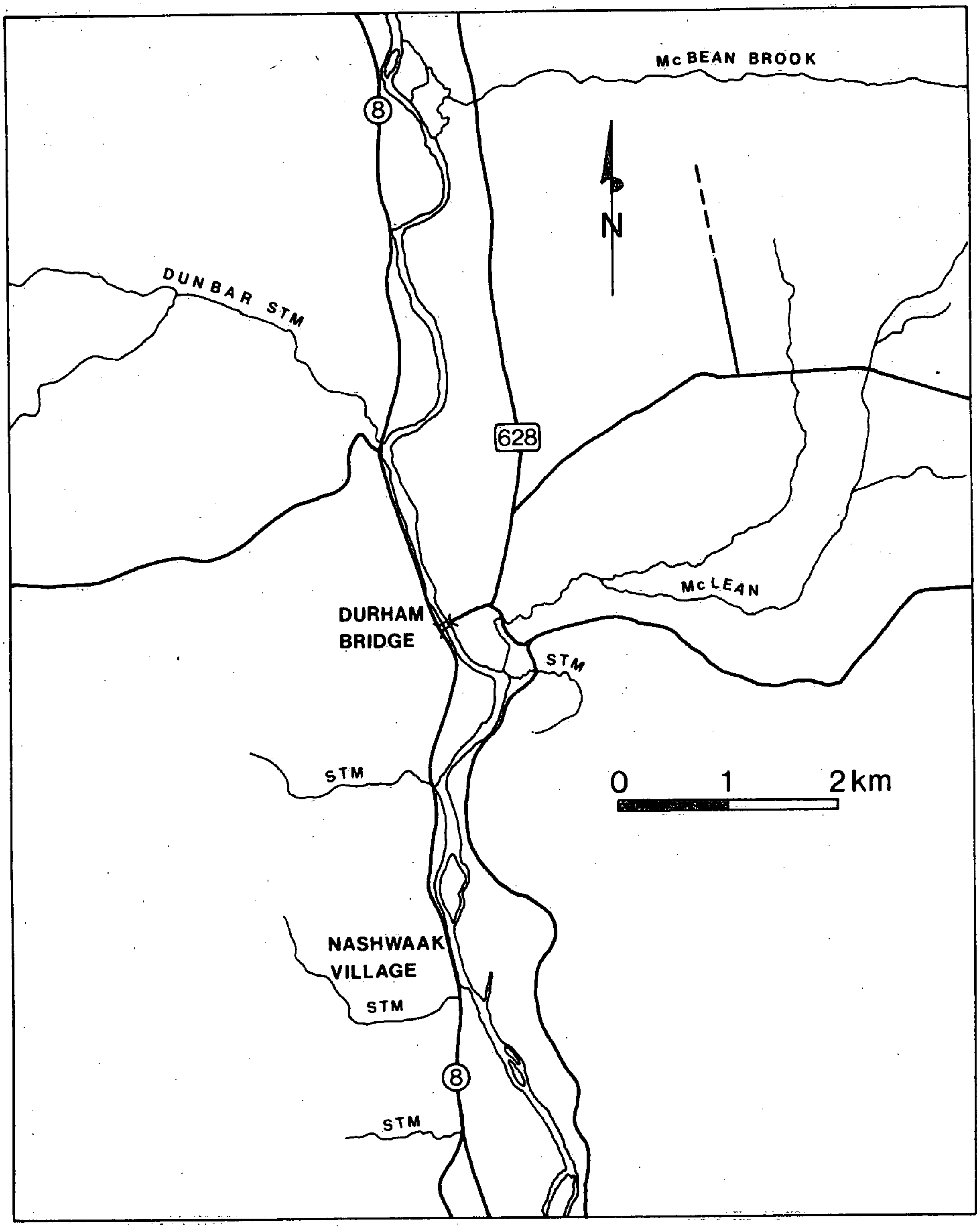

Fig. 3. Plan of Nashwaak River in the vicinity of Durham Bridge.

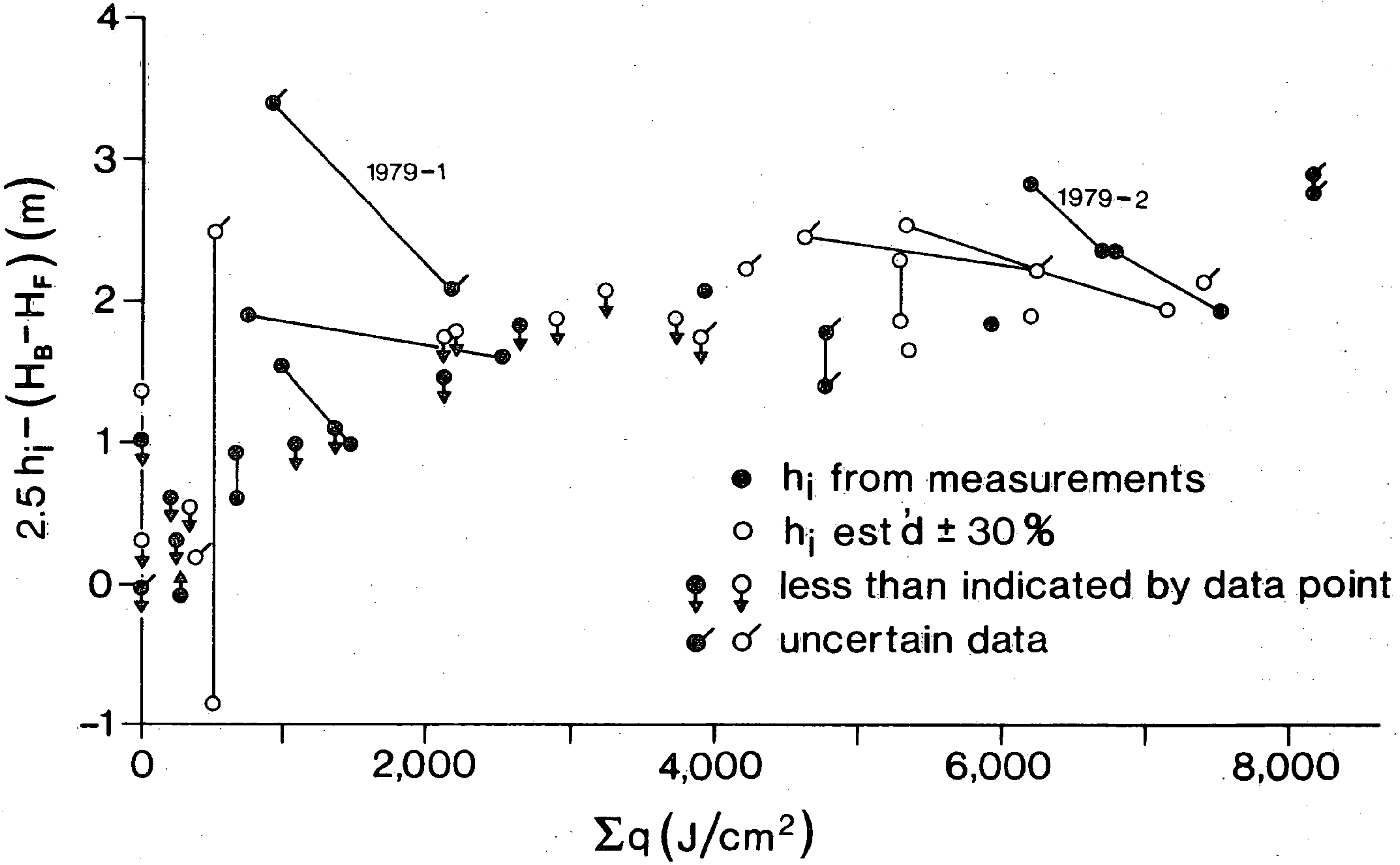

Fig. 4. Variation of $2.5h_i - (H_B - H_F)$ with Σ_q

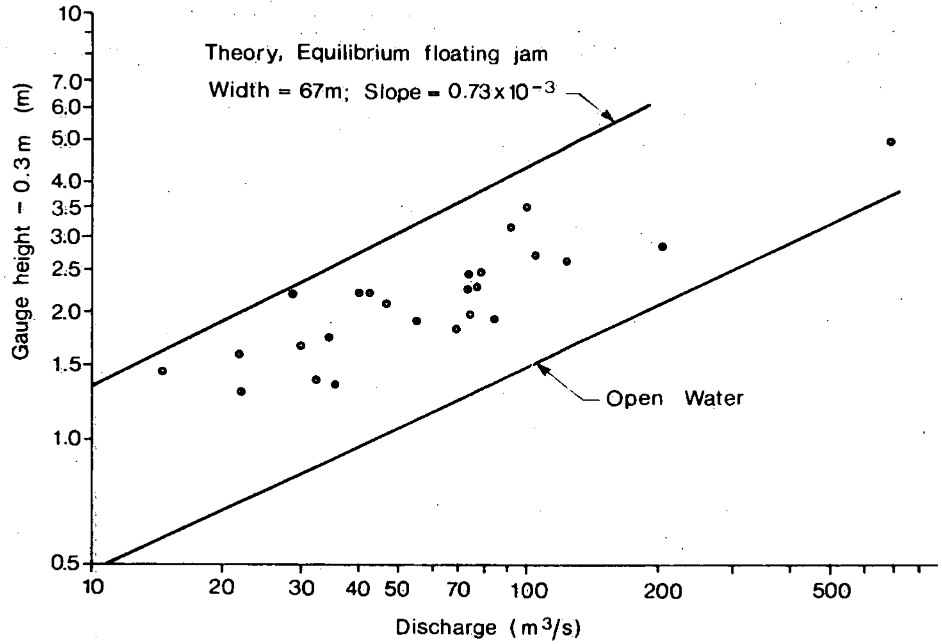

Fig. 5. Effect of discharge on breakup stage.

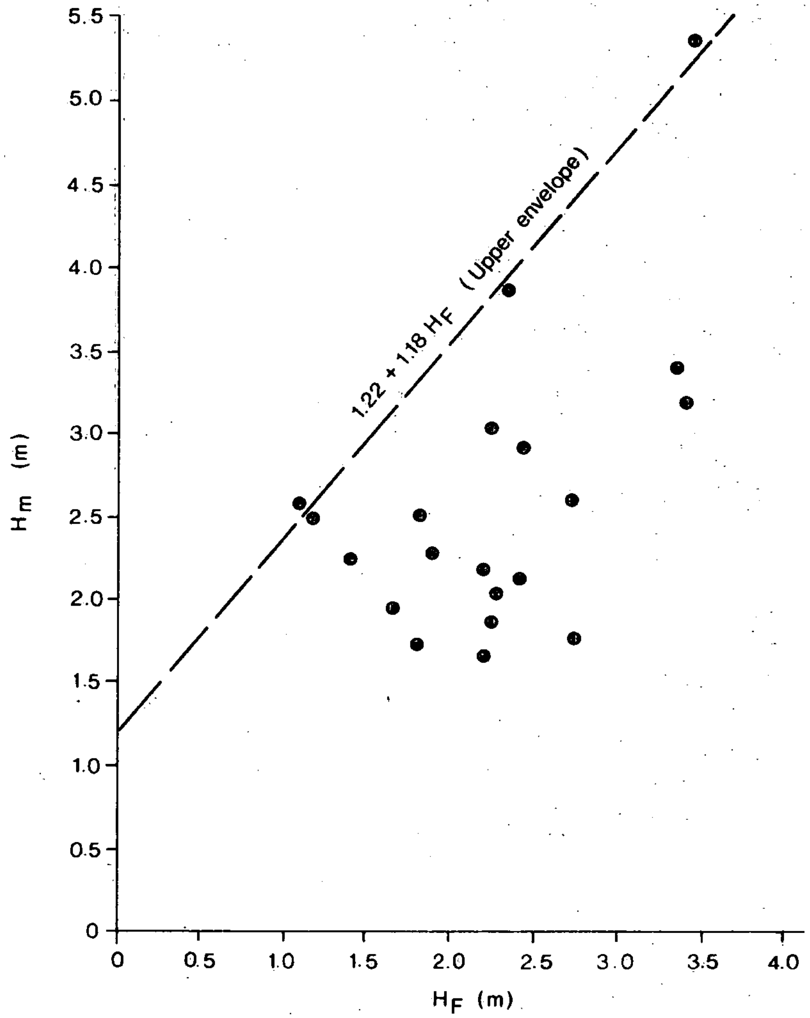

Fig. 6. Maximum stage during breakup versus H_F.

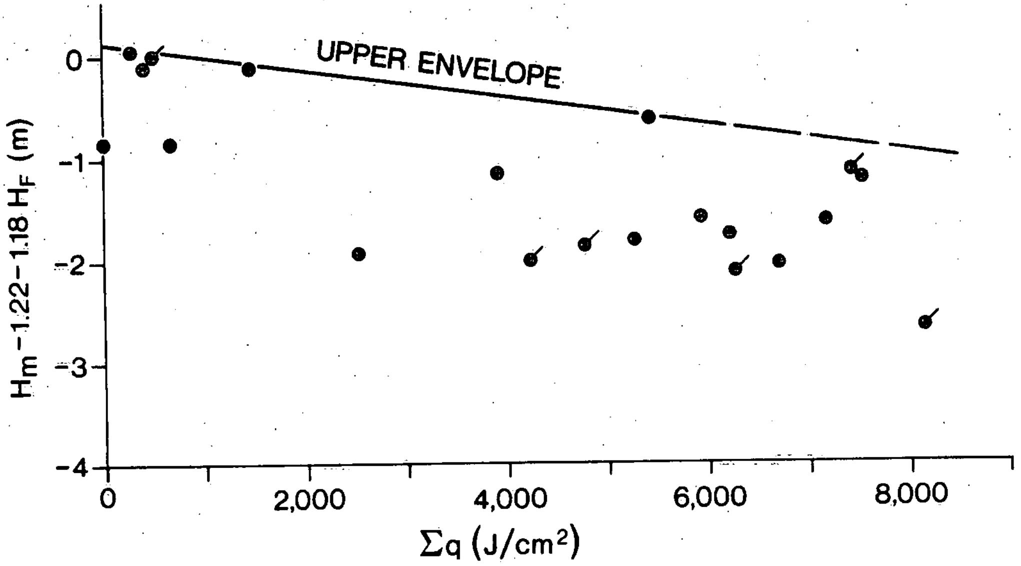

Fig. 7. Effect of Σ_q on H_m; legend same as for Fig. 4.

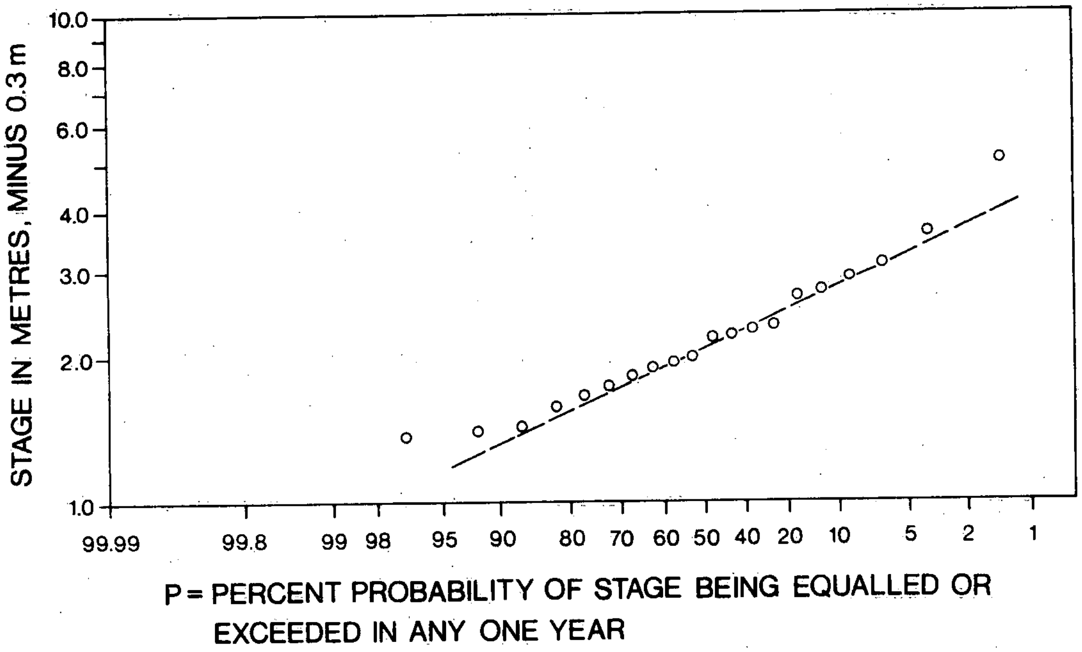

Fig. 8. Frequency curve of breakup peak stage.