STATISTICAL ASSESSMENT OF ICE JAM FORMATION IN CANADIAN RIVERS

by

Semaan Sarraf[†]

ABSTRACT

Ice jam is a major problem in cold climate regions. Million of dollars in tangible losses result every year in areas affected by ice induced floods. Studies have been conducting by a number of researchers in order to understand the mechanisms of ice jam formation and to be able to predict its occurrence, better protect the affected areas and minimize the heavy losses in private and public properties. Methods of predicting and preventing ice jams and the flooding caused by them are essential to solve the problems that occur annually in northern regions. It is intended to develop a general approach in the theory of ice jam formation through statistical investigations. Though, this paper presents few preliminary results, it is important to note that it put more light on the continuous effort to attain the ultimate objective of statistically characterizing and reformulating the ice jam formation problem.

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INTRODUCTION

Ice-jam is a random phenomenon common to rivers and lakes of cold climate regions. It is initiated, when the downstream passage of ice floes being transported is stopped, during Spring ice cover break up. Ice jam lasts from few hours to few days and produces extensive blockage of the river channel causing overflow of the banks sometimes.

Inundation of flood plains, scouring of river channels, obstruction of diversion intakes and damages to structures are some of the problems attributed to ice jamming. The probability of experiencing rise in water level increases dramatically in rivers susceptible to ice jam. Kindervater (1983) study shows that 35 percent of recorded floods in New- Brunswick have been caused by ice-jams, and these events are responsible for 70 percent of the bridges destroyed or damaged as a result of flooding. Channel modifications, construction of pontoon ice-booms and floating structures is implemented to alleviate ice jam flooding to some degree of success.

Ice-jamming is a complex process involving a number of parameters with uncertain nature. Characterization of the event and prediction of the physical laws involved is at its early age of development. Data pertinent to ice jam is scattered in various form and lack systematic documentation. Due to uncertainty of the factors involved in ice jam formation, data obtained from various sources are statistically analyzed to find relation between different variables.

This paper is a preliminary attempt to put into prospective the possibility of assembling existing but scattered ice jam data to initiate a more global and fundamental analysis and discussion (a kind of a unified model) of the ice jam phenomena. The long term objective is a formulation based on statistical approaches to reach an effective solution to the problem to complement deterministic analytical approaches. A simple regression (linear or non-linear) is done to study the degree of association between supposedly dependent and independent variables. The preliminary results of this work shows that a number of relations can be found among the various parameters. Further investigation continues depending on the availability of pertinent data.

ICE JAM PHENOMENON

Two major types of ice jam formation normally occur in cold regions rivers: a) winter ice jam which is formed in calm water, with flow velocity of less than 1 ft/sec. If the flow velocity is greater than 1 ft/sec dynamic types of ice is formed which are initiated as frazil ice and they occur due to heat exchange through the free surface in open water regions. The accumulated and compressed sludge ice (floating frazil slush) could form against an obstacle and become much denser and more compacted than frazil slush, thus stronger ice jam is formed. This type of ice jam is very strong and very hard to break and leads to the formation of surface "sheet" ice cover. At the beginning of freeze up, the actual stage starts to increase followed by a subsequent decrease, while the effective stage continues to drop, reflecting the dynamic nature of ice jam formation and alteration in flow characteristics. The ice cover presence reduces the channel section, thus an increase in depth results although a decreases in discharge is actually occurring. b) In late winter and early spring ice cover break up at different locations due to increase in snow melting runoff. The thermally weakened ice cover starts to desintegrate and break up along the plane of least resistance. The break up is a quick process usually accompanied by ice-jam formation [Michel (1973)]. The uplift pressure and frictional forces on the underside of the ice cover due to an increase in stage or discharge will develop transverse or longitudinal cracks and reduces the contact areas between the ice cover and the channel boundaries [Beltaos (1981)]. Premature break up may also occur caused by rising flow rate with little or no thermal degradation. After the break up, ice is carried by the flow to another location in the open water and at points where man structures exist or the channel narrows, ice jam and flood occur. Ice jams will form if the flow of these fragments is impeded. The accumulation of ice floes at downstream is sudden. While the rate of flow remains constant relatively, the stage increases. The roughness of the underside of the ice cover reduces the velocity of flow which will in turn cause the discharge in the upstream side of the channel to be more than the one at the downstream side. In addition to this, the area of cross section reduces dramatically causing surges and back water flow which could overflow the banks flooding low lying land [Michel (1973)]. Ice jam is affected by The discharge hydrograph, the flow velocity and depths, shear stresses, the channel width and plan geometry, the meteorological conditions [Santeford & Alger (1983)].

The orientation of the river has also a considerable effect on ice jamming. In southerly flowing rivers break up begins near the mouth and progresses upstream with lesser chance to break up. While for northerly flowing rivers where upstream portions break up first followed by the downstream are obviously more susceptible to ice jam formation.

There is little work done in trying to predict sites which are more susceptible for ice jamming. However, the general notion is that, at places where there is a change in hydraulic cross section, in bends and deep pools, in large but shallow reaches, or obstruction like bridge piers, debris or the morphology of channel could attribute to stalling of ice mass [Calkins (1975)]. For ice jams that are caused by changing hydraulic conditions, Calkins (1975) determines the critical initiation of the jam, based on Frankenstein and Assur's principle and assuming that the shear stress between the interacting ice pieces to be sufficient to sustain an arch across the stream

Calkins and Ashton (1975) has concluded from their model study of arching of fragmented ice floes that, arching or non arching events are strongly co-related with the ratio of [a (block size) / b (gap width)] to the ratio of (Q_i / V_b), where V_b is exit surface discharge through opening. Taking into consideration the ice discharge coefficient to exceed or equal one, stable arch could be formed, if the Froude number indicates single block stability.

PREVIOUS WORK ON ICE JAM

Based on Shulyakovsky (1963) observation, Beltaos (1981) concluded that the maximum stable freeze up stage (H_f) could be a tentative index for forecasting break up. He shows that H_b (stage at break up) increases with increase in H_f. Increase in depth is more pronounced when the ice thickness is also increasing. To quantify the effects of the basin morphology, Beltaos relates the channel geometry with the length and strength parameters of the ice cover formation. He also suggested the use of stage at freeze up as a tentative index for forecasting break up could yield results only if relevant data are at hand. To collect those data, continuous monitoring of river stages, ice thickness at break up and discharge is important. In addition, other dependant factors which influence the stage relationship such as thickness of ice and strength are unlikely to be quantified at the desired level of accuracy.

Zhukova (1979) deduced, on the basis of extensive statistical data on ice jams from Baykal Amur Mainline (in USSR) that sites where ice jams form vary from year to year. the frequency, prevalence and the height of rise in water level due to ice jam are interrelated to each other. The rise in water level has two components: a) The rise due to ice jam (ΔH_{jam}), and b) The rise due to a change in discharge. In this work, the long period mean low flow level is taken as a reference plane when considering H_{jam} and H_{Qjam}. The long period mean value of $\Delta H_{jam}/H_{jam}$ defines the rise in water level and its value was found to vary from 0.2 - 0.9. It also was found that where jams are frequent, the relative rises in water level are not high. In addition, Ice jams are dangerous in river reaches with H_{Qjam} / H_{Qmax} ratio of 0.7 - 0.9 and the maximum annual discharge is observed mostly soon after break up. There is an inverse relation between $\Delta H_{jam}/H_{jam}$ and H_{Qjam}/H_{Qmax}. Zhukova used this relation to develop methods for forecasting ice jam, despite the fact that this relation is generally weak. She stated that the ice cover thickness and the strength of ice during break up influence the ice jam formation considerably. The higher the thickness of the ice cover likewise will be the values of ΔH_{jam}. Such a relation is observed in 1/5 of the ice jam reaches and is typical of large rivers. However, trying to relate ice cover thickness with maximum height of jam rises is of little importance, since this parameter solely relies on meteorological factors. Instead, the ratio of ice thickness (H_I) before break up to a long period mean river flow during break up is compared to the frequency of ice jam. It was found that when this ratio is <0.20, ice jams are frequent. If the value of $H_I/H_{Qjam}>0.8$ the probability of occurrence of ice jam is 24%. For thick and strong ice cover, the break up takes considerable flood wave. In such cases the value of $\Delta H_{jam}/H_{jam}$ can reach 0.8-0.9 and the stages can be very high. This is typical of small and medium river reaches. In large rivers where the orientation of the river flow coincides with the direction of break up front the strength and thickness of ice cover contribute more to the ice jam formation than the ratio of $\Delta H_{jam}/H_{jam}$ does. In rivers where the ice winter discharge is low and velocity is high, there is no relation between the rise in water level during freeze up and break up. Freeze up could only be used to determine possibility of ice jam occurrence, not the magnitude of the rise in water level.

In narrow river reaches without a flood plain, ice jam occur frequently and the values of

$\Delta H_{jam} / H_{jam}$ are identical in narrow river reaches with or without flood plain. The change in shape of a channel determines the most probable location where ice jam forms while the magnitude and frequency of ice jam are predicted based on spring flood characterstics. This is shown by the inverse relation between ice jam frequency and coefficient of variation of maximum spring flood.

Rudnev (1978) used aircraft observation data in typifying ice jam as ice impasse, ice dam and ice plug. Regardless of where the reach they form, probabilities of rise in water level due to ice jam, computed for each gauging post is found to be similar for the same type of ice jam. The probability distribution and the long period probability of rises in water level is obtained by combining all the rises due to ice jam of a given type at different observation points into a single series. On this basis composite empirical probability curves of rises in water level due to ice jam were drawn. The analysis of these curves shows the probability of exceedence of rises in water level for different types of ice jam and the highest probability of ice jam produced rises. The absolute rise in water level for each point is computed from: $\Delta H_{jam} = H_{fr} + \Delta H_p$; where H_{fr} is the water level the day preceding the initiation of ice cover movement; ΔH_p is the most probable rise in water level corresponding to the type of ice jam.

Rudnev argues Zhukova's method of determining the rise in water level due to ice jam is insufficiently accurate, since separating rise in water level due to individual component is unreliable. To locate probable sites for ice jam formation, Uzuner and Kennedy (1972) analysis based on stability of ice blocks is sufficient at places which is not inhibited.

STATISTICAL ANALYSIS

The analytical approaches proposed by various researchers, in trying to predict in advance the break up up depth, to make sure whether ice jam is going to occur or not and if so to describe the severity quantitatively, are mostly site specific. The extension of this analysis to other river basins needs long time well documented informations regarding ice jam process at the site.

In general statistical analysis would be the most sought after approach to analyse events which are related to ice jams. In the present work, the variables pertaining to ice jam are freeze up depth, discharge, break up depth, ice thickness at various moment in winter, and water depth before and after the jam formation. Also, there are other factors which influence the form and the feature of ice jam, but there bound to be difficulties in quantifying them. At the moment, the aim is to search for possible useful relations among the different parameters. Since at this stage it is difficult to specify which is the independent or dependant variable, every variable is looked at in both categories. In addition and in order to serve the ultimate objective of the work, the identification of the principle parameters and the ability to relate these parameters together is required. Among the major parameters, the following are noted here:

a) meteorological Parameters: dates of freeze up, air temperatures at various stages of ice evolution, degree-days after thawing, date of Ice jam occurrence and failure;

b) geomorphologic Parameters: direction of flow, cross section characteristic..etc;

c) hydrological Parameters: flow variables (v, Q, H,...).

These variables could be detected through gauge stations and continuous observations, channel cross sections, erosion, basin area, precipitation, bank configuration, slope and type of bed, Froude number (rise in water elevation back surface profile), thickness and strength of ice cover, jam length, downstream ice conditions (thickness, strength), relative distance of ice jam from permanent opening, especially recurrence points if ice jams, ice production rate.

Thus relating these parameters together and defining a combination of variable is the first step in defining the relationships that may exist among these parameters. Certainly a number of defined equations had been found. It should be noted here that since the long term aim of this work is to provide a general and not a site specific characterization of ice jam in canadian river, it is most appropriate to convert and help composing through dimensionless analysis into a number of non-dimensional but representative parameters.

Hydrometric station records obtained from Environment Canada, Sector Urgence Environment, and other sources are used to analyse and investigate similarities between the results and some theoretical formulations given by other researchers. Extrapolation of these results to the specific sites, where an ice jam forms is going to be explored in the future.

The first three graphs basically illustrate to some extent the compliance of the present results with Beltaos explanations of ice jam formation. Unfortunately, due to the lack of data at break up, the core of his theoretical foundation; which states that the tendency of increase in stage at break up with the increase in stage at freeze up is left unexplained. Fig. 1 explicitly shows that the relation between maximum stage and ice thickness is not linear. Fig. 2 show that the increment of the jam depth with increase in ice thickness is pronounced at low values of ice jam caused increase. At higher values the drop in depth increment could be caused when the thickness of ice is still decreasing. One has to be at guard as so many parameters play roles in this complex phenomenon. Fig. 3 shows that, at the beginning, the maximum stage increases with the stage at freeze up, but the later this trend is reversed. Because of lack of data the range of values of $\Delta H_{jam} / H_{jam}$ was not examined .This could have in a way described the frequency of occurrence of different jam depths.

Fig. 4 shows how the relation between the maximum stage due to discharge. The data from Chateauguay river has enabled as to see contrary to Rudnev's explanation, there is a strong relationship between the stage during winter flow and discharge. This is depicted in figure 11. Even though there is disparity between figures 7 and 11 overall it should be realized that there is still a good relationship between stage and discharge.

Study Example: Chateauguay River

The Chateauguay River, located in south west Quebec, has long been plagued by ice jam and related flood problems. The flooding, generally in March or April, is related to several factors that affect the river capabilities to handle the large flows associated with spring thaws. Input such as large runoff quantities and high rainfall rate as well as impedance and blockage of the river due to ice cover and ice jams all contribute to cause floods. Much more work will be required to establish the relationships between ice jams and the factors that affect them known that each river has its own environment that affects the ice break up and ice jams. However, a great deal more observation is required in problem areas to help putting together a viable solution. The stage-discharge curve is formed through data collection of the discharge of a river 1/3 at corresponding times the stage is recorded. The frequency distribution of each discharge group was recorded and plotted in Fig. 8. As was expected the distribution closely resembles a normal distribution with the peak frequency of discharge about an elevation between 21.95 and 22.10m.

An integrated histogram of the flow at or above the indicated flow is given in Fig. 9. This curve closely resembles a smooth ogee curve. From this graph it can be seen that 82% of recorded flows were greater than the average and 38% were greater than double the average flow. Also, Fig. 10 shows that the most common date for a jam would be on or around the 27th of March, with the probability increasing to this date and decreasing after. The maximum discharge record for March and April displays a similar shape of frequency curves (Fig. 8). The curve, however, lags that of the jam occurrence by 2-3 days. This would seem to indicate that the jam causes the maximum flow. The occurrence of each maximum is plotted vs. the discharge (Fig.11). It can be seen that only one maximum, occurring on March 2nd precedes the date of earliest jam. It can also be seen that it is a low value and it is probable that no jam or flooding occurred that year. Some of the maximums occur long after the latest jam, such as the 26th of April. These highs however could be due not to thaws and jams, but to the high rainfall about that time of the year.

The exact distribution of the dates of the maximum can be seen from the frequency histogram. Its shape, although not perfect due to a small number of points, conforms closely to a normal distribution. This relationship seems likely as the jams occur downstream of the station and then the backwater rises to affect the readings. However, such a long lag time seems unlikely. The knowledge of the probable date of occurrence and the lag to the time of flooding will certainly help in predicting and protecting against future flooding. In addition the amount to which the upstream level will change can help in the design procedure of any structure to counter flood flows.

CONCLUSION

The biggest problem that still facing hydrologists, remains the lack of data and observations on which to base their work. Though, researchers have done a great deal of good with their elaborated techniques which are mostly site specific the need for all ice jam information and observations available or could be found for better chance of succeeding in understanding the problem. When this is completed then the damage caused by ice can be lessened through the proper design of structures to contain the destructive power of the river.

Some progress had occurred through the years of continuous researches to tackle ice jam formation problem yet still is a long way to go in satisfactorily solve the problem. Though, this paper presents few results, it is important to note that it put more light on the continuous effort to attain the ultimate objective of statistically characterizing and reformulating the ice jam formation problem.

ACKNOWLEDGEMENTS

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REFERENCES

1. Ashton, G. D., (1974 b), *Froude criterion for ice block stability*, Journal of Glaciology. Vol. 13, No. 68.
2. Beltaos, S., (1981), *Ice freeze up and break up in the lower thames river 1979 -1980 observations*, NWRI Canada center for inland waters.
3. Beltaos, S., (1983), *River ice jams : Theory, case studies and application*, Journal of hydraulic engineering, ASCE Vol. 109, HY 10, pp. 1338-1359.
4. Calkins, D. J., (1975), *Probable ice jam sites in a river system - fragmented floes*, Technical notes.
5. Calkins, D. J. and Ashton, G. D., (1975), *Arching of fragmented ice covers*, USA, CRREL Special report.
6. Kivisild, H. R. and Penel, J., (1975), *Ice jam related to climatological and hydraulic parameters-Yukon river*, Rem seminar on therm regime of river ice, Ottawa.
7. Kindervater, A. D., (1985), *Flooding Events in New Brunswick A Historical Prespective*, Water Planning and Management Branch, Inland Water Directorate (Atlantic Region), Environment Canada, N.S.
8. Michel, B., (1971),*Winter regime of rivers and lakes*, CRREL monograph lll - B1a.
9. Michel, B., (1973), *Theory and simulation of ice jams at break up*, Proceedings of seminar on ice jams in Canada, NRCC, Technical memorandum No. 107, pp. 36-54.
10. Rudnev, A. S., (1978), *Use of typification from air craft observation data in forecasting maximum stages in the Lena river*, Soviet Hydrology-Selected papers, vol. 17, No. 1.
11. Santeford, H. S. and Alger, G. R., (1983), *Effects of an ice cover - A conceptual model*, Conf. on frontiers in hydraulic engineering, Cambridge, Mass., USA.
12. Uzuner, M. S. and Kennedy, J. F., (1974), *Hydraulics and Mechanics of Ice Jams*, IIHR Report, No. 161, Univ. of Iowa.
13. Williams, G.P. (1972), *The characteristics of ice jams*, N. R. C.,Ottawa.
14. Zhukova, M. A., (1971), *Formation of ice jams and their distribution*, Soviet Hydrology-Selected papers, Vol. 18, No. 1, pp. 7-13.

NOTATIONS

Q	Discharge
C	Coefficient of concentration
B	Width of the stream
Q_i	Surface ice discharge
Q_{ie}	Exit ice discharge
D	Function of thickening process
X	Ratio of ice surface flux
A	Area of stream cross section
HMD	Hydraulic mean depth
t or HI	Ice thickness
F_{cr}	Critical Froude's number
F_0	Flow Froude's number
H_f	Stage at freezeup
H	Flow stage
H_b	Stage at breakup
ΔH_{jam}	Stage at jam
HQ_{jam}	Stage due to discharge at jam
H_{jam}	Total depth at jam ($\Delta H_{jam} + HQ_{jam}$)
H_{max}, H_m,	Maximum stage
H_{Dis}, H_O	Stage due to discharge
R	Hydraulic mean radius
Q_1	Discharge with ice coverage
S	Slope of the river bed
N	Roughness coefficient
N_1	Roughness coefficient due to ice cover
g	Acceleration due to gravity
ρ_i	Density of ice
a / b, Y_m	Hydraulic mean depth

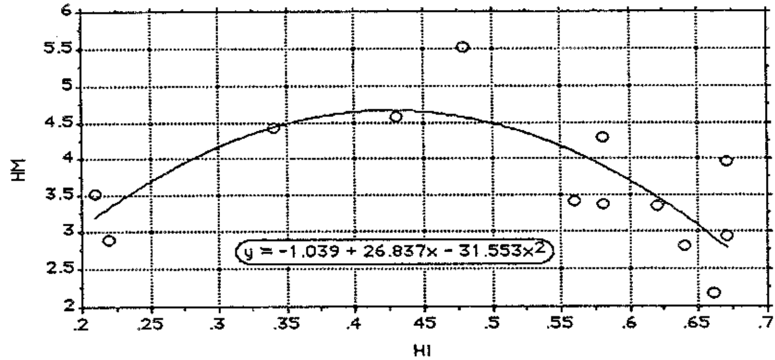

Fig. 1 - Maximum Stage vs. Ice Thickness (Meduxnekeag river)

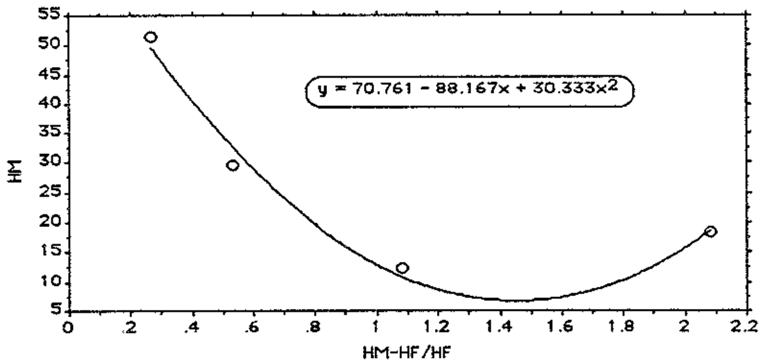

Fig. 2 - Maximum Stage vs. Stage Increase / Freeze-up Stage (Liard Mackenzie)

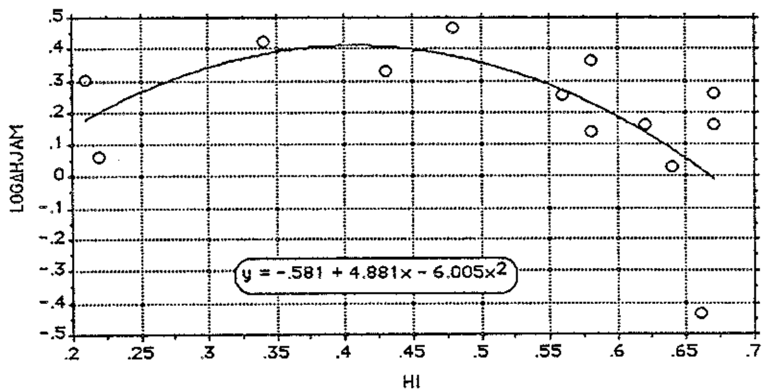

Fig. 3 - Stage Due to Ice Jam vs. Ice Thickness (Meduxnekeag River)

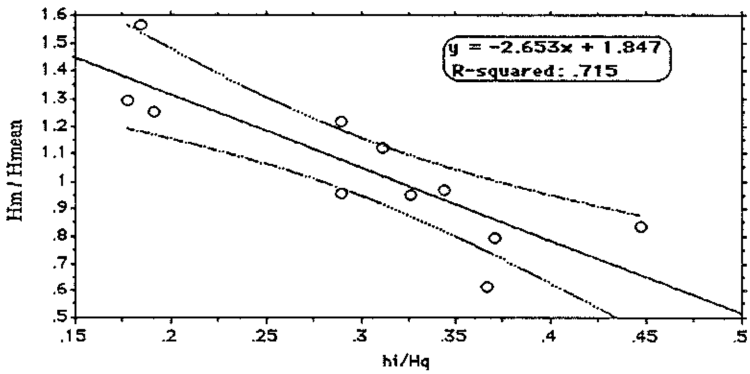

Fig. 4 - Stage Due to Ice Jam vs. Ice Thickness (Meduxnekeag River)

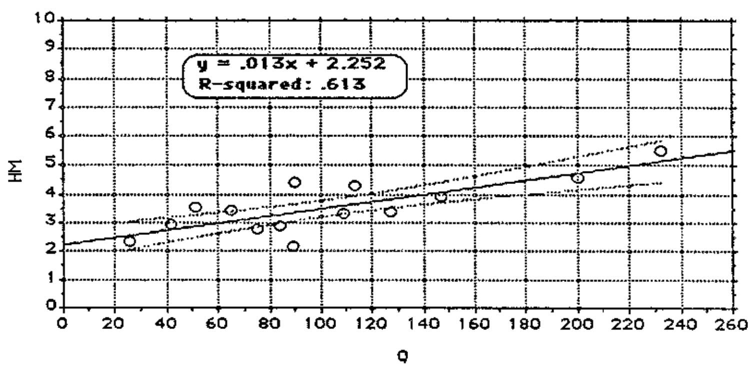

Fig. 5 - Max. Stage vs. Discharge (Meduxnekeag River)

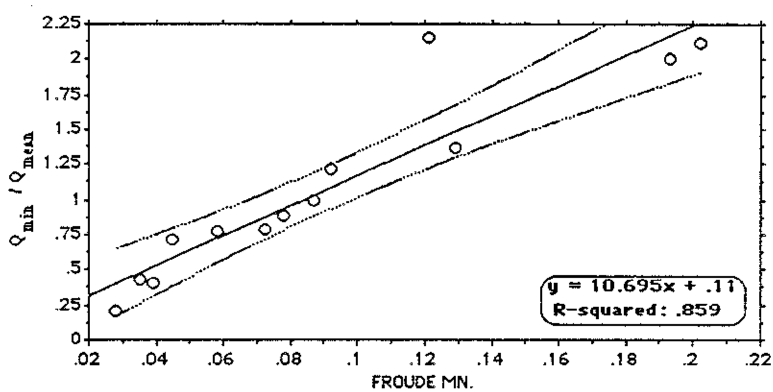

Fig. 6 - Minimum Discharge Vs. Minimum Froude Number (Yukon River)

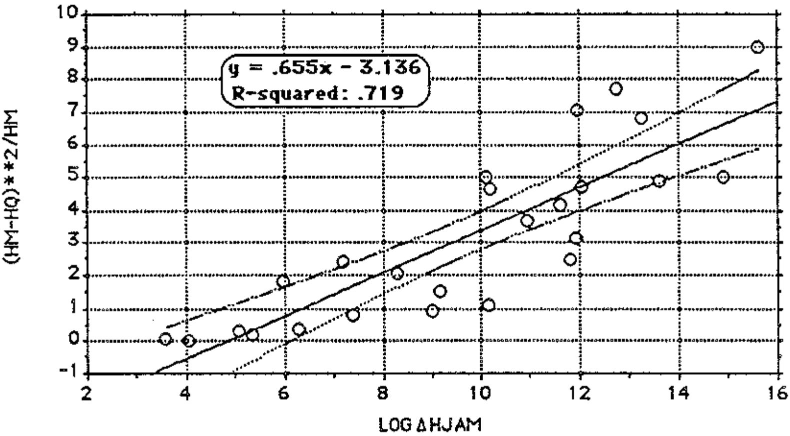

Fig. 7 - Logarithmic Regression between Stage Increase vs. Max. Stage at Jam (all rivers)

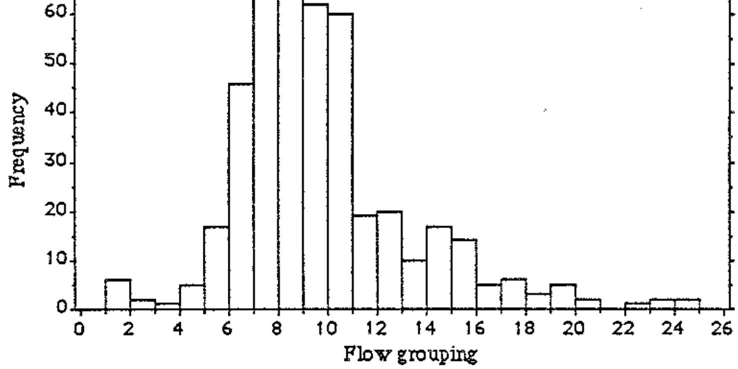

Fig. 8 - Frequency of Ice Jam Occurrence vs. Flow Grouping (Chateauguay River)

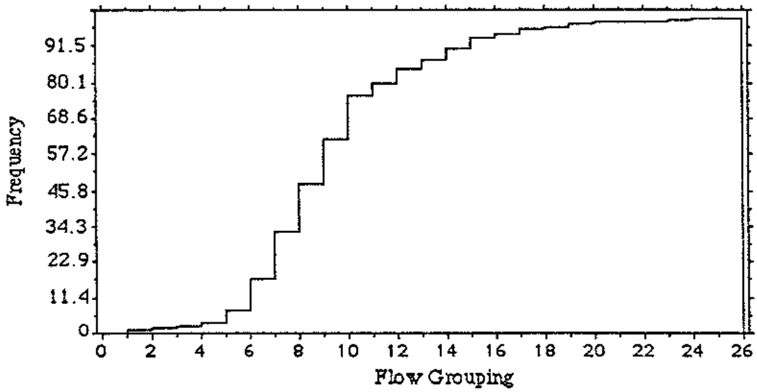

Fig. 9 - Cumulative Percentage Distribution Histogram (Chateauguay River)

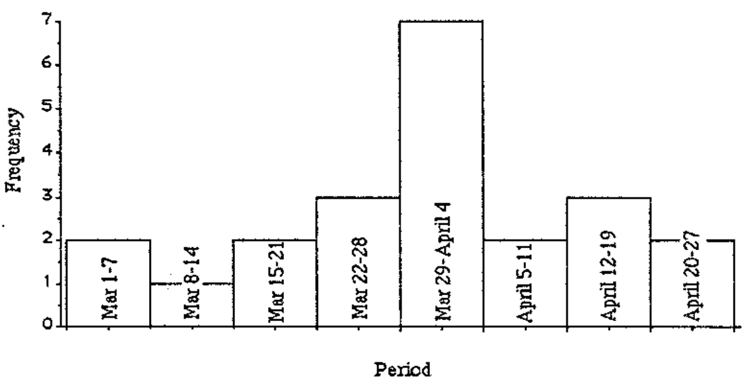

Fig. 10 Frequency Histogram of Maximum Flow (Chateauguay River)

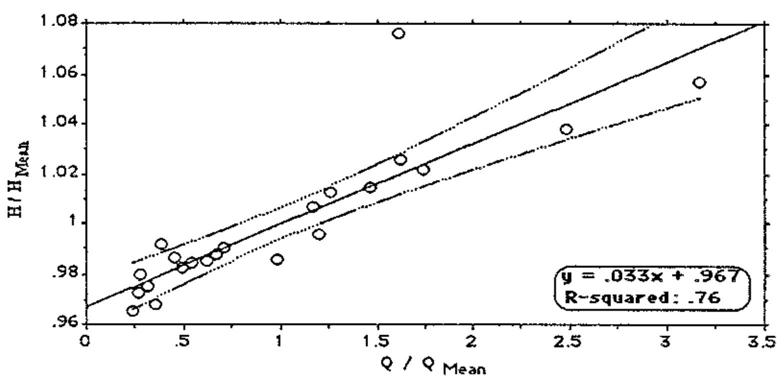

Fig. 11 - Stage vs. Discharge (Chateauguay River)

5th Ice Workshop

Discussion Form

PAPER: Statistical Assessment of Ice Jam Formation in Canadian Rivers
AUTHOR: Semaan Sarraf
QUESTION BY: Doug W. Brown

QUESTION/COMMENT:
Is it really feasible to attempt an assessment of ice jams in all communities in Canada. Inventories of smaller areas - i.e. Kindervater for New Brunswick and Kriwoken for 9 MacKenzie communities and ~20 Indian settlements in northern Ontario were in themselves major undertakings.

Response:

Statistical assessment of ice jam formation is certainly a major undertaking and this paper does not pretend achieving that. Though it presents few preliminary results, it is important to note that it puts more light on the continuous effort to attain the ultimate objective of statistically characterizing and reformulating the ice jam formation problem. The characterization of the event and prediction of the physical laws involved is at its early stage of development. In addition, data pertinent to ice jam are scattered in various form and lack systematic documentation. Efforts will first be directed towards accomplishing this task.

5th Ice Workshop

Discussion Form

PAPER: Statistical Assessment of Ice Jam Formation in Canadian Rivers
AUTHOR: Semaan Sarraf
QUESTION BY: K.S. Davar

QUESTION/COMMENT:
Use of statistical approaches can be helpful for engineering analyses, such as this one, but deserve caution. The data base is generally non-stationary and more data does not necessarily imply convergence toward an 'ideal relation'.
Perhaps, a good analogy is to consider such statistical approaches as a scaffolding for building a physical-deterministic model and eventually forget the scaffolding.

Response:

Statistical analysis would be the most sought after approach to analyse events of uncertain nature related to complex phenomena such as ice jams. This paper is a preliminary attempt to put into prospective the possibility of assembling existing but scattered ice jam data to initiate a more global and fundamental analysis and discussion (a kind of a unified model) of the ice jam phenomena. The long term objective is a formulation based on statistical approaches to reach an effective solution to the problem to complement deterministic analytical approaches. The biggest problem that still faces hydrologists, remains the lack of data and observations on which to base their work. Much more work will be required to establish the relationships between ice jams and the factors that affect them known that each river has its own environment that affects the ice break-up and ice jams.

5th Ice Workshop

Discussion Form

PAPER: Statistical Assessment of Ice Jam Formation in Canadian Rivers
AUTHOR: Semaan Sarraf
QUESTION BY: Doug Hodgins, MacLaren Plansearch

QUESTION/COMMENT:
You have made an interesting start on a long and challenging project, and I wish you success. I have certain doubts about the value of statistical analyses for forecasting, for example, but feel that your analyses have great potential for directing attention toward the parameters which should be examined in deterministic modelling.
Can you comment on this, given the recent thrust toward numerical ice modelling?

Response:

Methods of predicting and preventing ice jams and the flooding caused by them are essential to solve the problems that occur annually in northern regions. The long term goal to develop a general approach in the theory of ice jam formation through statistical investigations. In fact, there is little work done in trying to predict ice jamming. The aim is to search for possible useful relations among the different parameters. For example, the knowledge of the probable date of occurrence and the lag to the time of flooding will certainly help in predicting and protecting against future flooding. In addition the probable amount to which the upstream level will change can help in the design procedure of any structure to counter flood flows.