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Canada

STATISTICAL CHARACTERIZATION OF ICE JAMS IN CANADIAN RIVERS

Girma Emissa

A Thesis
in
The Department
of
Civil Engineering

Presented in Partial Fulfillment of the Requirements
for the Degree of Master of Applied Science at

Concordia University
Montréal, Québec, Canada

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ABSTRACT

Statistical Characterization of Ice Jams in Canadian Rivers

Girma Emissa

Ice jam related problems are causing severe economic hardships and socio-economic problems in a number of localities in Canada Prediction of ice jam occurrences and in particular, the knowledge of frequency of events associated with ice jamming will result in better forecasting. Ice jam occurrences in several provinces are set in a database and corresponding hydrometric and meteorologic stations data compiled for the purpose of analysis.

Statistical analysis is performed to isolate and identify those geomorphologic and hydrometeorologic variables that could be used in characterizing and predicting ice jams in Canadian rivers. The results of this analysis recognize the main variables that play the leading roles in the formation and occurrences of ice jams. Further, the results have inabled us to predict the frequency of ice jam occurences. The database can also be used to make proper recommendations for the installation and monitoring of networks of hydrometeorologic instrumentations.

Critical examination of available hydrometeorologic, geomorphologic data and their spatial and time variation is analyzed to identify variables which influence the formation of ice jams. Several hydrometeorological variables have also been examined to predict freeze-up and breakup dates and to find threshold values above or below which the likelihood of certain events can be estimated.

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There are many good friends who shared my ups and downs, who gave me encouragement in my work and were beside me in my ascend up the hill. You will always be in my heart. I am glad that you are also around at the termination of my work and the closing of a chapter.

I dedicate this work to my late father Emissa Kumbi. Without his sacrifice and the special value he held for education, I would not have made it here. He tried to entrench in his family, the importance education has in every day life. I am indebted to you for all that is good in me.

Last but not least, I would like to thank my love Ginette for putting up with my endless work that put every wake of life on hold. Her patience was examplary. Bravo ! we deserve it.

Dedicated to my father - late Emissa Kumbi

who preached the value of education with a missionary zeal

LIST OF SYMBOLS

A	ratio of relative error to the mean
a	cross-sectional area (m^2)
a	constants changing with time
a	degree days factor
$a_1, a_2, ..., a_k$	coefficients of autoregressive and Arima models
AFDD	accumulated freezing degree days (°C)
B	Bowen's ratio
b	constants changing with time
$b1, b2, ..., bk$	coefficients of Arima and moving average models
C	cloud cover, in tenths
c	constant with a value of 0.55
C_o	a statistical constant
d	constant with a value of 0.52
e	relative humidity
e_a	atmospheric emmisivity
e_w	emmissivity of water
$f(C)$	function of cloud cover for solar radiation
$f_1(C)$	function of cloud cover for atmospheric radiation
h	ice thickness (cm)
H_C	heat transfer due to convection
H_{CD}	heat transfer due to conduction ($J \cdot m^{-2} \cdot d^{-1}$)
H_{CE}	convection and evaporation heat transfer ($J \cdot m^{-2} \cdot d^{-1}$)
H_E	heat transfer due to evaporation ($J \cdot m^{-2} \cdot d^{-1}$)
H_{la}	atmospheric longwave radiation ($J \cdot m^{-2} \cdot d^{-1}$)
H_{lr}	reflected longwave radiation ($J \cdot m^{-2} \cdot d^{-1}$)

H_{lw}	longwave radiation from water surface ($J \cdot m^{-2} \cdot d^{-1}$)
H_{nl}	longwave radiation ($J \cdot m^{-2} \cdot d^{-1}$)
H_{ns}	net solar radiation ($J \cdot m^{-2} \cdot d^{-1}$)
H_{si}	incident solar radiation ($J \cdot m^{-2} \cdot d^{-1}$)
H_{sr}	reflected solar radiationn ($J \cdot m^{-2} \cdot d^{-1}$)
K	melt coefficient
M	melt index
M_{ca}	melt due to condensation and advection (mm/day)
M_f	melt factor (mm/°C/day)
M_p	melt due to sensible heat from rain drops (mm/day)
M_q	melt due to conduction (mm/day)
M_{rl}	melt due to longwave radiation (mm/day)
M_{rs}	melt due to shortwave radiation (mm/day)
n	number of observations
n_o	composite roughness
n_1	Manning bed roughness
n_2	Mannning ice bottom roughness
p_a	air vapour pressure (cm of Mercury)
p_w	water vapour pressure (cm of Mercury)
Q	total river flow (m^3/s)
R	reduction constant
r	hydraulics radius (m)
r_1	estimate of a_1
r_2	estimate of a_2
R_t	reflectivity of water surface
S	solar constant
S	standard deviation

s	friction slope
T_a, T_{a1}	air temperature in (^oK) and (^oC) respectively
T_b and	base temperature (^oC)
T_i	index temperature (^oC)
T_w, T_{w1}	water temperature in (^oK) and (^oC) respectively
V	variance
V_6	wind speed at 6m above ground level
V_{15}	wind speed at 15m above ground level
x	a variable
x	mean of x
Y	coefficient of variation of residual errors
Y	ratio of sum of relative errors to the mean
y_c	computed values
y_o	observed values
$y_t, y_{t-1}, y_{t-2}, \ldots, y_{t-k}$	sequence of data
a	experimental coefficient
a	angle of incidence
a	albedo
b_1	absoptivity of water surface
$e_t, e_{t-1}, e_{t-2}, \ldots, e_{t-k}$	independent stochastic component
f	latitude (degrees)
m	mean of y
s	Stephan-Boltzmann radiation constant $(J \cdot m^{-2} \cdot d^{-1}\ ^oK^{-4})$
s_e^2	estimate of standard deviation
x	a constant, with a value of either 0 or 1
y_E	heat transfer coefficient due to evaporation
y_C	heat transfer coefficient due to convection

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CHAPTER I

INTRODUCTION

Spring ice jams are quite common to most Canadian rivers, as well as other sites of temperate climate zones. These random phenomena are primarily the results of river ice breakup during sudden changes in weather conditions, hydraulic parameters or both. The initiation of ice jam takes place when the passage of ice floes being transported down stream, is impeded. It could be either by congestion, or surface restriction. When ice discharge is more than the local transport capacity of the channel surface jam results due to congestion. These type of jams are common at freeze-up (Beltaos, 1988) but also prevail during breakup.

Ice jam occurrences are influenced by man-made or natural obstruction such as flow regulating structures, bridge piers, channel constriction or reaches where there is considerable change in the geometric configuration and cross section such as bends and in front of a stable ice cover. In general, ice jamming is a complex process which is a function of a number of variables and processes which have probabilistic nature evolving in space and time. It is an ultimate result of the interaction of various meteorological and hydraulic conditions.

The formation of ice jam results in extensive blockage, increased hydraulic resistance and reduced flow area. This in turn causes reduction in the conveyance capacity, followed by increase in water level of a river channel substantially, with flooding of low lying areas.

Research in the field of ice jam is fairly recent, spanning over three to four decades. Advances have been made in understanding the interaction between these diverse factors, with theoretical formulation and mathematical description of physical process. Pariset and Hausser (1966), Hausser and Gagnon (1967), Uzuner and Kennedy (1976), Tatinclaux (1978 and 1983), Beltaos (1978, 1982, 1983 and 1984), Michel (1971, 1973, 1975, 1976 and 1984) and Kivisild (1959 and 1976) have made milestone contributions.

Most physical and mathematical ice jam models are based on observation of ice jam processes. Rigorous analytical approach were employed by Uzuner and Kennedy (1976) in explaining the physical laws involved in the theoretical formulation, modeling and prediction of ice jams. In general, these models are simplifications of complicated field conditions. How close these models simulate field conditions remain to be seen, as a result of the scarcity of field data (Prowse, 1985). Collection of data pertinent to ice jam is difficult as the time of occurrence is not known and there is danger associated with it. Furthermore, the prediction and analysis of the phenomenon is relatively cumbersome compared to open channel flow problems. For an idealized formation in a straight channel, stability of ice jam is analyzed using the single block stability (Calkins, 1975). The effects of ice floes entrainment are studied using critical Froude number criterion based on hydrodynamic analysis and moment equilibrium method (Assur, 1973).

Where the winter is severe and breakup is as a result of mechanical failure of the ice cover instead of thawing, the ice thickness and consequently the rise in water is considerable. Where the thawing process advances from middle reaches of the river to the lower end, breakup also advances in the same direction, with high probability of ice jamming at the downstream section (Kamphuis, 1983). Thermal factors which include the intensity of solar radiation and other components of the heat budget as well as mechanical factors, such as thickness of the ice cover during breakup and strength of the ice, the rate of rise of flood wave and the wind force determine the movement and the clearing of ice floes from the river. The strength of ice cover affects the severity of ice jam. Wind speed, air temperature, solar radiation and depth of snow in turn affect the strength of ice cover (Bergdahl, 1978). In addition to the main stream, tributaries have considerable effect on the pattern of ice front movement in the main channel.

In many parts of Canada, frequent flooding due to ice jamming causes damages and destruction to the infra-structure resulting in extensive socio-economic problems. Early settlements along the fertile flood-plains of large number of rivers, have been the most hardly hit, by ice jam flooding. Kindervater's (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 . In New Brunswick, the 1970 ice jams have damaged or destroyed 32 bridges with total economic cost of close to 14 million dollars (1987 price). In 1987, the ice jam flooding below Perth-Andover area resulted in $ 30 millions in damages. Ice jam flooding accounts on an average for approximately $ 4 millions in damages every year in Canada (Atkinson, 1973).

Erosion of river banks scouring of river beds, obstruction of diversion intakes and damages to infrastructures are but a few of the problems attributed to ice jamming. In addition to those mentioned above, the following are among some of the problems related to ice jamming :

- Loss of hydro-power generation during freeze-up because of ice jam congestion.

- Damages to hydraulic structures bridges and piers from ice run at breakup.
- Flooding of communities due to ice jamming.
- Extra cost incurred on infra-structures and resources spent on clearing blockades.

Channel modifications, construction of ice-booms and floating and permanent ice control structures have been implemented to alleviate ice jam flooding to some degree of success.

Events like freeze-up and breakup influence the intensity of the ice jam formation. Brief explanation on this two critical processes is given in the light of shading some facts, as to what takes place prior to ice jam formation. In addition to these processes, the winter ice condition, intensity and duration of spring flood and orientation of the river at large alter the form and features of ice jam significantly (Michel, 1971).

1. 1 FREEZE-UP AND BREAKUP

During the winter season, as the air temperature starts to decline, the temperature at the water surface also dips. A strong wind blowing over the water surface generate waves that have, a cooling effect as heat exchange takes place between the cooler air mass and warmer water body. The less denser bottom layer replaces the one above. This accelerates the temperature gradient at the bottom of the river to drop further, inducing formation of the frazil ice crystal, at ice free super-cooled turbulent zones. Much of the frazil agglomerates into slush and pancake ice floes. The supercooling temperature ranges 0.02 to 0.05 ^{o}C below freezing temperature. Border ice will form at the banks of a river, where the stream velocity is low (Michel, 1971).

Freeze-up is initially noted by an increase in flow depth, followed by a subsequent decrease. The appearance of the first ice floes is initiated as a result of thermal heat transfer at the water-air interface. Shore ice is the dominant feature accounting for most of ice cover formation in small rivers and brooks (Michel, 1971) and calm section of large rivers. If these ice floes are impeded from movement, consolidated ice cover will form (Beltaos, 1979). If the wind velocity is low floating ice cover forms (Shuliakovskii, 1963). Where border ice forms, the growth occurs either laterally or vertically. Initially the growth is fast and is in lateral direction followed by vertical direction, with the thickness being greatest at the bank and decreasing towards the center of the river. The lateral growth is by juxtaposition of the incoming floes. The ice thickness/depth ratio or the Froude number is the limiting value beyond which equilibrium conditions do not exist and the ice cover progress is stopped as external forces become significantly greater than the internal resisting forces. Pariset, Hausser and Gangnon (1966) suggest the limiting Froude number to be 0.33.

When the floating ice moving with the flow stalls, the ice cover bridges across the channel increasing the wetted perimeter and the resistance to flow significantly. If the shear stress available is sufficient to sustain an arch across the stream, the slope of the energy grade line drops, resulting in reduced velocity. Consequently the backwater effect is maximized with increase in depth upstream such that the resistance imposed by the ice and the channel bed is reduced (Santeford and Alger, 1983).

For ice covered flow, Manning's open channel flow formula with modification to roughness coefficient values can be used to determine discharge.

$$Q=\left(\frac{a\,r^{2/3}s^{1/2}}{n_o}\right) \tag{1. 1}$$

where, Q is discharge, a is cross-sectional area, r is hydraulic radius, s is friction slope and n_0 is Manning roughness coefficient. In general, the roughness coefficient due to ice cover is greater than roughness coefficient of ice free flow. The ice roughness is high at the beginning, but recedes and stays invariably due to thermal effects and smoothening of the underside. In general, the winter roughness coefficient n_1 varies from 0.010 for smooth ice formation to 0.025 for rough ice formation (Calkins, 1975). For smooth ice formation, n_1 varies from 0.010 to 0. 012 at the beginning of freeze-up and 0.08 to 0.010 in the middle of winter (Michel, 1971). Sabaneev (1948) formula is used for determining the composite roughness of the channel.

$$n_o=\left(\frac{n_1^{3/2}-n_2^{3/2}}{2}\right)^{2/3} \tag{1. 2}$$

where, n_0 is composite roughness, n_1 is bed roughness and n_2 is roughness of the ice cover underside.

For a river with an ice cover, the net discharge is lowered as a result of increased flow resistance. Reduction in discharge, up to 27%, is possible. Discharge estimates, in the presence of ice cover, are based on open water rating curves. Once stable ice cover forms, back waters from downstream station interfere with the flow at hydrometric stations, as a result, discharge estimates at most are arbitrary, except in cases where field measurements are made. Less direct methods such as winter index station method, the modified backwater method, the ice-factor method and the winter rating curve method could be used to estimate discharge where the effect of backwater is noticeable (Pelletier, 1988). All these methods are somehow dependent on open-water stage-discharge relationships and correlations of meteorological data and the backwater effects. If there is a station upstream or downstream, with open water or well defined ice cover characteristics, then the known discharge value can be extrapolated to the location in question (Andres, 1989).

Ice freeze-up depends on meteorologic conditions and hydraulic characteristics of the river channel; mainly thermal components, wind speed and geomorphology of the river basins. The formation of ice cover results in the dynamic alteration of flow characteristics (Santeford and Alger, 1983). Where the depth of flow is significant and the flow velocity is low stratification is inevitable. Otherwise, the temperature remains the same along the depth. The rate of heat loss is less once the ice cover forms, since it serves as an insulation piece. The relation between water level and discharge is very well defined during ice free period and starts to have a scattered nature at maximum stages during freeze-up. The degree of distortion of this relationship is primarily dependent on the form, thickness and roughness of the accumulating ice cover.

Beltaos (1979) suggests that the maximum stable freeze-up stage may be used as a tentative index for breakup stage. Some of the factors which influence this relationships, like ice thickness and strength of ice are parameters unlikely to be quantified at the desired level of accuracy. The precision of water level measurements at freeze-up and breakup is also questionable. Therefore, relating freeze-up stage to breakup stage depends on the way in which breakup and freeze-up depths are extracted.

Freeze-up date is considered to be the last day of a period during which the ice has no measurable effect on the flow (Beltaos, 1979). Streamflow summary yearly reviews are used to determine freeze-up date. It is considered to be a day after the ice effect is indicated at the hydrometric station. For ice jam cases prior to 1960, relevant data was taken from Allen (1977). Allen considers freeze-up date to be the day after first permanent ice is observed. In some cases the freeze-up date is directly incorporated, from publications we referred to extract date of ice jam.

The breakup of an ice cover is a quick process characterized in some instances by ice jam formation. Initiation of ice cover breakup could be caused by many factors which have either thermal or mechanical nature (Beltaos, 1979). If normal river stage is less than the maximum winter stage, the shear stress and the downstream component of the ice cover weight are very small to cause breakup.

When ice breaks up as a result of non thermal parameters, forces and stresses between the water flow and the ice cover are responsible for ice cover breakup (Shulyakovskii , 1968). An uplift pressure, on non-uniform ice cover, due to an increase in channel depth or discharge, will develop transverse or longitudinal cracks along the plane of least resistance. Frictional forces on the underside of ice cover reduce the contact areas between the ice cover and the channel boundaries. The width of the river will increase to accommodate the broken ice cover making more room for movement (Beltaos, 1979).

On the other hand, intense solar radiation results in decay of the ice cover and increased snow and ice cover melting, with augmented run-off and stage. Reduced ice cover strength and size are the outcomes of considerable heat input. Ice cover breakup and movement in the downstream direction will then follow. When stream runoff is low and ice cover deterioration is due to an increase in temperature, the initiation of breakup could occur even when normal river stage is less than the maximum winter stage. But it is not expected to cause any serious damage to the infra-structure (Beltaos, 1979)

Premature breakup is caused by rising flow rate with little or no thermal degradation. It is initiated when the ice cover is lifted from its confinement by shore fast ice. The necessary condition for the initiation of this type of breakup is that, the depth of flow have to increase by an amount equivalent to the thickness of the ice cover and there must be an increase in storage at the neighborhood of the control section under consideration (Santeford and Alger, 1983). In addition to the above necessary condition there are two sufficient conditions to complete the whole process of breakup. First, the presence of a place for the fragmentation to move into. Second, the incoming discharge must change substantially to compensate for the dewatering effect of the ice cover movement, which otherwise will cause the ice sheet to drop into a locked position. This occurs when a drop in stage upstream is caused as a result of acceleration of the flow due to the decrease in resistance at the section where the ice sheet is released. The main factors governing breakup severity seems to be discharge and ice competence. (Gerard, 1986)

If the ice breakup is associated with rise in water level, the breakup stage at which the ice push occurs can be estimated from the ice cover at the highest position during the winter (Shulyakovskii, 1963).

Beltaos (1979) states that, stages at breakup rise if there is increase in stage at freeze-up. Where ice thickness is considerable, the rise in stage is more pronounced. Beltaos used the relationship between the differential of breakup and freeze-up stages versus ice thickness to arrive to this conclusion. To verify the results continuous monitoring of ice thickness, river stages and discharge at breakup is important. Other dependent factors which influence the stage relationship such as ice thickness and strength parameters are unlikely to be quantified at the desired level of accuracy.

Breakup in each river and part thereof is distinct from one segment of the channel to the other, as a result of different influential zones of tributary rivers and differential warming zones. Breakup of a tributary often acts as a trigger initiating breakup in the major river. The outcome of breakup will vary from mild to very destructive cases depending on the combination of meteorological parameters. Where the ice cover is strong, discharge is the most determinant factor causing ice breakup (Michel, 1971). Breakup date for most part is directly taken from observations or determined from Allen (1977). In cases where observational data is absent, the breakup date is considered to be the time at the base of the rising limb of water level fluctuation. Where both methods were not applicable use isopaths of average dates of breakup date is implemented.

The severity of breakup depend upon the water level at the time of freeze-up (Beltaos, 1979), the extent of winter season, the rate of thawing and the slope of the river. Breakup is affected by the runoff hydrograph, heat input flow velocity and depths, shear stresses, and the channel width and geometry. Hydrologic influences on the breakup of ice cover are attributed to the effect of solar radiation and air temperature on snow and ice melting. These influences determine the volume of water in the river during the high water level period and the volume of flood wave. Where the effect of tributary is minimal, warming trend on a river can be described by air temperature (Burdokiya, 1970).

At lower end of rapid sections, accumulation of ice floes occurs. When one or more of these accumulations break through the ice cover, they will be carried away by the flow and start moving in a closely packed formation along the gap between cleavages. Due to impacts with channel boundaries or other floes there will be fragmentation of the ice blocks and the ice cover strength is reduced. Larger floes have more momentum with a tendency to move downstream, but as a result of their size and limited passage ice jam occurrence is more likely. Where the slope is gentle and velocity of flow is low, or at places where there is obstruction, the progress of these fragments is impeded or completely stopped resulting in ice jam formation. But if the breakup is caused due to thermal deterioration over-mature breakup takes place. In this process melting is the governing factor.

1. 2 OBJECTIVE OF THE STUDY

The objective of this study is to examine the effects of hydro-meteorologic as well as geomorphologic parameters on the process of ice jam formation in Canadian rivers. The compiled data is to be analyzed using statistical approach to isolate and identify those indices which could be used in characterizing and predicting ice jams. One of the goals of this study is to identify among the many variables which ones play the leading roles that affect the occurrences of ice jams and to evaluate how many percent of the time these relationships are conclusive and take place within certain percentage of confidence interval.

Several hydrometeorological variables have been examined to predict freeze-up and breakup dates and to find threshold values above or below which the likelihood of certain events can be estimated.

Prediction of ice jam occurrences solely relies on analysis which is stochastic in nature. Therefore, any correlation between variables that might be useful tools in the prediction of ice jam related events is investigated. Furthermore, the relative importance of each variable with regard to the occurrences of ice jam is examined.

A data base for variables with relevance to ice jam occurrences is to be developed for use in forecasting models. It can be used by researchers and those involved in planning processes. This could lead to certain recommendations regarding ice monitcring networks.

CHAPTER II

HISTORICAL DATA OF ICE JAMS IN CANADA

Available data pertinent to ice jam in Canada is scattered in various form and lack systematic documentation. The absence of central body collecting relevant data has caused some inconsistencies in the format and the quality of the data. Existing federal and provincial agencies, do not specifically collect ice jam related information, except in cases where special programs have been implemented for the sole purpose of research. Participation of private sector is negligible, contributing to the scarcity of data. Sometimes, even available information could qualitatively be of no practical value for scientific and engineering application. The guidelines stipulated by New Brunswick ice committee (1983) to standardize the data collection procedure is one step in the right direction.

Except for the Yukon river where water level, discharge records and the sequence of freeze-up and breakup events since 1896 are available, most Canadian rivers with the potential for ice jamming are with little or no documentation on freeze-up, breakup or ice jam processes, unless significant flooding is associated with it.

The lack or total absence of stream gauging during winter seasons or meteorological stations representing the surrounding area at the periphery of ice jam location is notable in the most northerly locations. Sometimes to avoid damages to instrumentation agencies involved in collecting data try to locate hydrometric stations at sites where the ice effect is minimum. Scarcity of data is also attributed also to limited funds as well as dangers associated with winter and breakup measurements. In general, quantitative field information relevant to ice jams are scarce and dramatic changes are not to be expected in foreseeable future. For winter operations, water-stage recorders of the pressure gauge or air bubbler type designed for cold weather operation and housed in an insulated box-type protective structures is recommended. This type of gauges endure extreme pressure from the surrounding and allow holes to stay open, at exceptional weather conditions (Michel, 1973).

In recent years, efforts have been made to study the flow regimes during freeze-up, breakup and consequently ice jams. This include aerial reconnaissance and field surveys done by different agencies through federal and provincial involvement in flood reduction programs. In New Brunswick, through Canada works program, information on ice jam induced flooding and their consequential damages has been gathered from different sources.

In this study, hourly hydrometric station records at the vicinity of ice jam location, and field notes are used to extract relevant information which are representative of freeze-up, breakup and ice jam characteristics for the purpose of statistical analysis. The quality of streamflow data is checked by comparing them with upstream or downstream hydrometric station measurements, and temperature measurements.

2. 1 INFORMATION SOURCES FOR ICE JAM LOCATIONS AND TIME OF OCCURRENCES

Historical documentation and newspaper coverage of ice jams and related events dates back to early 18th century and its destruction renowned by early settlers. In this study, sites and time of ice jam occurrences are established based on wide variety of information obtained from different sources like local archives, reconnaissance works done by different agencies and researchers during freeze-up and breakup period on several Canadian rivers. These studies as well as newspaper description of ice jam phenomenon is extensively used to extract time and space coordinates of these events. Some of the sources that have been used to extract information with regard to location and time of ice jam occurrence are :

- In Alberta, field studies done by Andres, Rickert and Doyle on Athabasca river and its tributaries (1977 to 1979, 1984 and 1985).
- In Yukon, flood study conducted by Fenco (1974 and 1976), Orecklin (1979, 1980 and 1981) and historical documentation presented by Dawson city museum and historical society (1981) and work done by kivisild (1959 and 1975).
- In N. W. T., on Liard an Mackenzie rivers work done by Prowse (1985) and Lasalle Hydraulic Laboratory (1981 and 1982).
- In New Brunswick, study conducted by Kindervater (1984) and Lebrun-Salonen (1984 and 1985) and Beltaos (1982).
- In Ontario, work done by Beltaos on grand river (1982) and Thames river (1981, 1982, 1983 and 1985).
- In Quebec, work done by Trembley on St. Charles du Berger (1978) and Aux Vaches river (1979).

Pertinent information from these works have been directly incorporated in the present study. Additional data was compiled for each case of ice jam, from Environment Canada; Water Survey and Atmospheric & Environment Service (AES) branches. Among all ice jam cases where hydraulic, geometric, meteorologic and geomorphologic parameters could be quantified are only considered. Once the cases are established, the next step was to determine the hydrometric and meteorological stations at the upstream and downstream vicinity of the ice jam location. Agencies responsible in collecting information of the nature described above, are then contacted for specific data.

In general, observations of ice jams usually result in data values that are time dependent or of relatively constant characteristics. Hydraulic and meteorological variables fall under the first group and geomorphologic variables under the latter. The basic meteorological data obtained from AES vary from station to station. The data obtained consists of :

- Daily maximum, minimum and mean temperature
- Daily maximum and minimum relative humidity
- Six hourly precipitation ending at 12:00, 18:00, 00:00 and 06:00 hour GMT
- Total rainfall, snowfall and precipitation
- Snow on the ground
- Global solar, sky, reflected, net all wave, total shortwave and longwave radiation
- Wind direction and speed

The basic data obtained from hydrometric station records for the purpose of this study are :

- Hourly freeze-up and breakup water level variations
- Hourly freeze-up and breakup discharge variations

- Ice thickness (average, maximum and minimum)
- Area of cross section at hydrometric stations

All hydrometeorologic data were extracted from stations within reasonable distance from the ice jam location. The data obtained in meteorologic cases date back to 1890 while for others only few years of data was obtained. For each year data was collected between the month of November and June. For some of the parameters AES, monthly weather reviews were consulted to obtain the records of meteorological variables associated with ice jamming. But for the most part, data was obtained on a magnetic tape or floppy diskettes.

2. 2 REGIONS OF STUDY

The region of study from where ice jam occurrences in terms of time and spatial location was extracted, is divided province wise. They are: Alberta, British Columbia, New Brunswick, North West Territory, Ontario, Quebec and Yukon Territory. For hydrometric station data, Water survey of Canada branches in each region were contacted. In Ontario, regional agencies like Grand River Conservation Authority and Thames River Conservation Authority have taken part in supplying data.

Alberta

Most of the literature concentrate on the Athabasca river and its tributaries such as Pembina, Clear-Water, and Mackay rivers. The freeze-up and breakup observations made on Athabasca was formerly undertaken by Andres and Doyle (1977 & 1979) and later by Andres and Rickert (1984 to

1987) of Alberta Research Council. The study concentrated on the lower Athabasca river at the vicinity of Fort McMurray spanning from Pelican rapids to sites upstream of clear water river mouth, with detailed description on the movement of ice fronts. Some quantitative values and characterization of ice jams and a scanty detail on winter meteorological conditions are also presented.

British Columbia

Available literature is based on the seasonal publication of B. C. Hydro. Ice observation on Peace river are conducted during freeze-up season with no information at the time of breakup and ice jamming.

New Brunswick

In New Brunswick, among several studies done, works by Kindervater (1985) and Lebrun Salonen (1983-85) were used to extract basic information on Saint-John river valley, Restigouche, Miramichi, Kennebecasis, and Canaan rivers. Both references, have documented in detail descriptions of ice jam damages and their cost to the public and the business sector.

North West Territories

The Mackenzie river at the confluence of Liard in the vicinity of Fort Simpson region, during the winter as well as breakup season was studied by Prowse(1984-86), Parkinson (1982) and Mackenzie river basin committee

(1981). The hydrometeorological conditions during the study period were documented elaborately.

Ontario

In Ontario, the Grand river with its upstream boundary at Legatt and its downstream at West Montrose and Lower Thames river from the mouth to Middlemess reach were studied during Freeze-up and breakup season for several years. For Lower Thames the slope ranges from zero to an average of 1.2 ft per mile near Delware. It has little relief with dominant sand and clay plains. Average annual flood damages were calculated to be over 1.5 Million dollars (1975 dollars) Bruce (1983). Ice thickness, description of ice movement front, and characteristics of ice jam were given in detail in a reports published by Beltaos (1980-85).

Quebec

In Quebec, there are several studies conducted by the Environnement Québec in variety of river reaches. Works done by Barabé (1979) on flooding problem at Richmond, Carbonneau and Desforges (1970), Michel (1971) on Chaudière river, and Tremblay (1975) on St. Charles and Du Berger rivers are among the references used to extract the relevant data.

Yukon

In Yukon, the Yukon river Klondike river and Stewart river have a long standing detailed historical documentation of breakup and freeze-up processes dating back as far as the 18th century. Ice jam triggered flooding of Dawson area is compiled by Dowson Museum society (1981). The exact date of ice breakup since the beginning of early nineteenth century is also compiled by Dowson Museum society. Field work done by Fenco (1974 and 1976), Orecklin (1979, 1980 and 1981) and later by Klen Klhoff (1986) has resulted in a long list of ice jam occurrences with associated water level and discharge. There were some ambiguities with regard to ice related water level elevation on a report produced by Fenco which was later rectified by Klen Klhoff, the explanation given being the discrepancy as a result of changes in the bench mark by Water Survey of Canada.

2. 3 SELECTION OF HYDROMETRIC AND METEOROLOGICAL STATIONS

With the help of topographic maps correlations of ice jam occurrences with the nearest hydrometric and meteorological stations were established. Since in this study, the date of ice season spans over sixty years, it is obvious that hydrometric and meteorologic stations at the vicinity of ice jam locations sometimes might have been added, deleted, or temporarily moved to new locations. For continuity of records, alternative stations within closer proximity, latitude wise and to a lesser degree longitudinally are searched to fill gaps or missing data. This is due to the fact that, meteorological parameters have considerable variability in magnitude when the alternate stations are further apart latitude wise from the originally selected stations. Selection of the alternative station is facilitated with the help of Water Survey of Canada's hydrometric map supplement (1987).

Table 1. Meteorologic stations used in the statistical analysis

Station	Province	Latitude	Longitude	Type of data
Aroostook	New Brunswick	46.78	67.73	1
Beechwood	New Brunswick	46.53	67.67	1
Campbellton	New Brunswick	48.00	66.68	1, 3
Centreville	New Brunswick	46.43	67.68	1, 3
Charlo A.	New Brunswick	48.00	66.33	1
Charlo Falls	New Brunswick	N/A	N/A	1
Chatham A.	New Brunswick	47.02	65.45	1, 3
Chipman	New Brunswick	N/A	N/A	1
Doaktown	New Brunswick	46.55	66.15	1
Edmunston	New Brunswick	47.37	68.33	1
Fredericton A	New Brunswick	45.87	66.53	1
Fredericton CDA	New Brunswick	45.92	66.62	1
Fredericton UNB	New Brunswick	N/A	N/A	1
Harvey Station	New Brunswick	45.73	67.00	1
Kedgwick	New Brunswick	47.65	67.35	1
Minto	New Brunswick	46.05	66.00	1
Pointe Lepreau	New Brunswick	N/A	N/A	1
Royal Road	New Brunswick	46.05	66.72	1, 3
Sussex	New Brunswick	45.72	65.52	1
Upsalquitch	New Brunswick	47.45	66.42	1
Woodstock	New Brunswick	46.15	67.58	1
Waldemar	Ontario	43.88	80.28	1
Ferg. Shand Dam	Ontario	43.70	80.38	1, 3
Delhi	Ontario	42.87	80.55	1, 3
Elora	Ontario	43.65	80.42	1
Simcoe	Ontario	42.85	80.27	1, 3
Harrow CDA	Ontario	42.03	54.90	1
Fort Nelson	B. C.	58.83	122.58	1, 2, 3
Fort McMurray	Alberta	56.65	111.22	1, 3
Mildred Lake	Alberta	57.03	111.60	1

Table 1. Continued..

Station	Province	Latitude	Longitude	Type of data
Smith RS	Alberta	55.17	114.03	1
Grande Lo	Alberta	56.30	112.22	1
Cross Lake	Alberta	54.63	113.90	1
Wandering River	Alberta	55.20	112.50	1
Calling Lake	Alberta	55.25	113.18	1
May Lo	Alberta	55.62	112.35	1
Athabasca 2	Alberta	54.82	113.53	1
Edmonton Stony	Alberta	53.55	114.10	1, 2
Bitumont	Alberta	57.37	111.53	1
Ells Lo	Alberta	57.18	112.33	1

Sometimes, topographic or other types of maps reveal very little detail as to the occurrences of ice jam, in which case we have opted for an assistance from meteorologists and hydrologists to give as details on the nearest station for collecting meteorologic, hydraulic and geomorphologic data. In the case of meteorologic data, stations with continuous data record at the proximity of ice jam occurrences were ignored, when within reasonable range of distance an alternative station with more variety of meteorological data is available.

Various physiographic regions of Canada which have unique hydrographic characteristics and stream flows within each region generally respond to the same natural stimula. Canada was initially divided into six physiographic regions. They are Arctic, Cordillera, Interior Plains, Canada Shield, St. Lawrence Low Lands and Appalachian Region. These approximately correspond with the physiographic region except for the Southern interior plains which are designated as the Prairie Region, which could be delineated as a separate region (Hare and Thomas, 1974). The stations from which data is obtained correspond to five zones. Homogeneity test and regional regression analysis performed for each region.

Table 2. Hydrometric stations used in the statistical analysis

Station No.	Description	Province
01AD002	Saint John river at fort Kent	N. B.
01AD004	Saint John river at Edmunston	N. B.
01AF002	Saint John river at Grand falls	N. B.
01AG003	Aroostook river near Tinker	N. B.
01AH002	Tobique river at Riley brook	N. B.
01AH003	Tobique river at Plaster rock	N. B.
01AJ001	Saint John river near east Florenceville	N. B.
01AJ003	Meduxnekeag river near Belleville	N. B.
01AJ008	Saint John river at Hartland Saumon pool	N. B.
01AJ009	Saint John river at Simonds	N. B.
01AK003	Saint John river at Fredericton	N. B.
01AK004	Saint John river at Mactaquac	N. B.
01AK007	Nackawic stream near Temperance Vale	N. B.
01AK009	Saint John river at Mactaquac genereting stn.	N. B.
01AL001	Nashwaak river at Penniac	N. B.
01AL002	Nashwaak river at Durham bridge	N. B.
01AL008	Nashwaak river at Stanley	N. B.
01AL009	Nashwaak river at Nashwaak bridge	N. B.
01AL010	Nashwaak river at Taymouth	N. B.
01AM001	North branch Oromocto river at Tracy	N. B.
01AM002	Oromocto river near French lake	N. B.
01AO002	Saint John river at Maugerville	N. B.

Table 2. Continued..

Station No.	Description	Province
01AP002	Canaan river at east Canaan	N. B.
01AP004	Kennebecasis at Apohaqui	N. B.
01AP005	Saint John river at Saint John	N. B.
01AQ002	Magaguadavic river at Elmcroft	N. B.
01AQ009	Lake Utopia at canal	N. B.
01BC001	Restigouche river below Kedgwick river	N. B.
01BE001	Upsalquitch river at Upsalquitch	N. B.
01BJ007	Restigouche river above rafting ground brook	N. B.
01BK003	Nepisiguit river at Nepisiguit falls	N. B.
01BO001	SW Miramichi river near Blackville	N. B.
01BP001	Little Southwest Miramichi river at Lyttleton	N. B.
01BQ001	Northwest Miramichi river at Trout brook	N. B.
02GA014	Grand river near Marsville	Ontario
02GE003	Thames river at Thamesville	Ontario
02GE004	Thames river at Chatham	Ontario
02GE006	Thames river at Dutton	Ontario
Upper Belwood	Grand river at upper Belwood	Ontario
Waldemar	Grand river at Waldemar	Ontario
Fergus dam	Grand river at Fergus Shand dam	Ontario
Legatt	Grand river at Legatt	Ontario
07BE001	Athabasca river at Athabasca	Alberta
07BC002	Pembina river at Jarvie	Alberta
07CD001	Clearwater river at Draper	Alberta
07CD005	Clearwater river above Christina river	Alberta
07DA001	Athabasca river below McMurray	Alberta
07DA017	Ells river near the mouth	Alberta
07DB001	Mackay river near Fort McMurray	Alberta
07DD001	Athabasca riverat Embarras airport	Alberta

CHAPTER III

DATA CLASSIFICATION AND TREATMENT

The fact that the collected ice jam data are fairly diversified and extracted from rivers with different climatic and physiographic region leads to qualitative and quantitative differences. Therefore, the data treatment techniques should reflect the uncertainties brought by subjective judgment in the process of grouping data before analysis.

Data screening is used to detect blunders in key punching or coding error, as well as to locate outliers. Probability distribution properties of each variable is explored using univariate and bivariate screening. Where meteorologic and hydrometric stations were moved to downstream or upstream part of the reach, care has been taken not to combine the data into a single series but segregate in accordance with location and to combine the final curves if necessary. At sites where records have been interrupted the frequency curve is approximated using synthetic records.

In describing parameters which are relevant to ice jamming the distinction is made of those parameters which are function of time and change over an area continuously, parameters which describe the transport process along the river and parameters which describe process distributed over the area but in a mosaic like pattern because of their step-wise changes due to discontinuities.

Most parameters associated with ice jam are random in nature and vary significantly in space and time. When variables are changing at a faster rate with time areal density of observation points and the frequency of sampling intervals should be increased. The spatial variability of variables depends on physiography of river basin to greater extent, while temporal variability is generally characteristics of the event.

In case of large rivers, the variation of ice transport can be sufficiently described by direct observation. The variation in parameters at stations with no data can be shown by constructing longitudinal profiles of variables at known location and interpolating the curve.

Available data is classified under hydraulic, geomorphic and meteorologic parameters. After grouping, these parameters are set in non-dimensional form to allow interchange of information among rivers under consideration.

3. 1 HYDRAULIC PARAMETERS

The location of site for hydrometric station depends on physical characteristics of the channel such as cross section area, slope and roughness. A straight stable channel far enough from confluence of a river, upstream from rapids or riffle, with easy wading, where depth and velocity are uniform, cross currents and frazil ice effect is minimum is preferable. This kind of location is suitable for installation of artificial control. Availability of telephone and hydropower and accessibility in winter are other factors to be taken under consideration in selecting sites. For the confluence of an important tributary, hydrometic stations must be located either at the major river or at the major river and tributary upstream or downstream of confluence.

The daily gauge reading and temperature values are used in interpolating the discharge hydrograph. Most discharge estimation methods give more or less accurate results for large rivers (Michel, 1973).

The accuracy declines with decrease in size of the river. If the flow is affected by ice jams, the stability of rating curves and longitudinal surface water slope change as a result of backwater effects due to lodgment of ice and debris at a control. The nature of depth versus discharge relation results in scatter points. Therefore, in addition to gauge and shift correction, correction for back-water effect should also apply. Where ice effect is felt at the station it is marked as B, on streamflow summary. Missing records can be due to plugged intake caused by silting or freezing, frozen float resting on the bottom of the well, or slippage of beaded wire caused by surging.

The discharge estimates are arbitrary for most of the winter as field observation is done few times in the winter. Where there is open water or well characterized ice cover at upstream or downstream of station discharge values can be extrapolated to the desired station; provided there is inter station losses (Andres, 1991)

An ice jam could last from few hours to several days at a location and variability in terms of average daily water level and discharge could be inappropriate to represent the progress of the event. Therefore, the discharge and water level estimates used were the mean hourly values reconstituted from charts by WSC.

Information pertaining to gauged location can be transferred to ungauged sites within the area using flow duration curves or regional regression analysis. Flow duration curves are also used to transfer discharge values from long term gauged sites to adjacent locations with short term data.

Hydrometric station records of open water flow are frequently used as a source of information in flood frequency analysis to determine the maximum water level and discharge. The outcome of this analysis is directly integrated in the design of hydraulic structures. Unfortunately the worst cases of flooding have been associated with ice jams and nearly all designs preclude to take into consideration water level and discharge induced by ice jams.

3. 2 METEOROLOGIC PARAMETERS

Among meteorological parameters accumulated, degree days, heat exchange at the water-air and ice-water interface, precipitation and solar radiation, to the greater extent, affect the formation of ice jam. The larger the freezing degree days after a permanent ice cover forms, the stronger and the thicker the ice cover and the higher the water level during ice jam formation will be. The ice cover thickness and the strength of ice during breakup influence the intensity of ice jam formation considerably. Their combined effect is accounted for, in terms of their product. Spring breakup of the ice cover can be caused by mechanical factor, thermal factor and high intensity of rainfall or combination of these factors. Solar radiation has a marked influence on snow melting and the state and strength of ice cover. Thawing degree days also influence melting of the snow and ice cover and could be used as a measure of the thermal effects on ice jam formation in addition to heat budget equations.

3. 3 GEOMORPHOLOGIC PARAMETERS

The basin area, the latitudinal and longitudinal location of each hydrometric station is established from surface water data reference index, published by WSC. Distance from the source of the river to different hydrometric stations and the orientation of the flow direction for each river are extracted manually from a topographic map. Drainage pattern and drainage density, slope of the river bed and shape factor were calculated for each hydrometric station.

Channel morphology is determinant as to the location of ice jam occurrence. It also to a larger extent determines the unique water resource characteristics among drainage basins. Geomorphology and topography are relevant features in determining conveyance capacity of a river system. The crossing of a river from homogeneous physiographic region to some other distinct regions affect the conveyance capacity of the main channel. In addition to this the drainage pattern influence the movement of ice blocks. The movement of ice blocks in a long and narrow river channel is very much different compared to confluence of a river. The topography at the vicinity of the confluence determinant as to the location of ice jam formation.

3. 4 DESCRIPTION OF VARIABLES USED IN REGRESSION AND MULTIVARIATE ANALYSIS

This data was used to extract relevant information related to break up, freeze-up and ice jam characteristics that could be eventually used in multivariate statistical analysis, forecasting, and development of threshold values for likelihood of significant events.

The size, slope, land use, vegetation and the volume of flow in the channel affects the formation of ice jams. Among a number of parameters drainage area, shape, water shade channel length, slope, drainage pattern, channel roughness and cross-sectional properties and time of flow parameters are considered to be the most important ones. This parameters in general define the characteristics and the nature of ice transport.

3. 4. 1 *Hydrometeorologic Variables*

Hydrometeorologiclic variables that are used in regression and multivariate analysis with the exception of the last three elements, are summarized as follows. Heat budget is elaborated separately in the next chapter.

- Ice thickness; average minimum, and maximum
- Degree days of thaw and freezing accumulated over the winter
- Precipitation
- Snow on the ground
- Heat budget calculated 10, 20, 30 days before breakup or ice jam
- Date of freeze-up, breakup, complete ice cover formation, and other related events
- Maximum depth at freeze-up, break up and ice jam
- The change in water level between maximum flow depth at freeze-up and breakup

3. 4. 1. 1 *Ice thickness*

Air temperature data show that negative monthly temperature prevails from October to April, allowing for considerable ice formation in rivers. Increasing ice thickness in downstream direction of northerly flowing rivers is attributed generally to climatic conditions, although water velocity, freeze-up jamming and frazil ice accumulations are also contributing factors.

Estimating ice thickness has a prime importance in structural design in cold regions as well as operational activities of hydraulic structures. River ice cover varies with space and time and is generally the thickest at times prior to spring ice breakup. Ice breaking boats or vessels are used in drifting ice thickness measurements, for stable ice cover ice drillers or augers are employed. Measurements pertaining to ice thickness are open to error in measurements, sampling and interpretation. Winter climate pattern, air temperature, wind speed, snow cover and density, channel geometry, configuration and slope influence the thickness of ice cover. Snow cover slows the growth of ice thickness by insulating it from cold. Contrary to this, it also increases ice thickness by forming snow ice. Snow cover is governing parameter in spring snow melt peak.

Ice thickness can only be accurately characterized with observations over a long period of time. Available data, is however, of short duration and limited spatial extent. Therefore, ice thickness data has been extended from empirical formula developed by Stefan (1889) that is based on air temperature observation and overall winter freezing degree days as:

$$h = 2.54\,\alpha\sqrt{\frac{9}{5}\,\mathrm{AFDD}+32} \qquad (3.\ 1)$$

where, h is thickness of the buoyant ice in cms, α is experimental coefficient determined previously at the site. AFDD is accumulated freezing degree days in ^{o}C days. α has a value of 0.4 to 0.5 for an average river with snow and 0.2 to 0.4 for sheltered small river with rapid flow.

3. 4. 1. 2 *Degree days*

The degree days concept is vital in the study of ice formation accretion breakup and most of all in ice forecasting techniques. Accumulated freezing degree days can also be used as an indicator of severity of winter. In contrast, thawing degree days could be used to study breakup characteristics. Degree days are also an index of other meteorological parameters with more complex nature that are often difficult to apply in practice, i.e., cloud cover, radiation, albedo, and heat transfer to and from the atmosphere.

Degree day is defined as a measure of the departure of the daily mean temperature from a given standard. It is accumulated and used as an index to evaluate the effect of temperature variations over a period of time. Negative departures may be considered zero, contributing nothing to the accumulated total, or having negative values. Heating and growing degree days are calculated assuming the first case; freezing and thawing degree days the second (Boyd, 1980). Degree days below and above freezing in change over months is critical in the outcome of the ice breakup and jamming process. Thawing degree days are calculated from this date to breakup or jam date. Where parameters need to be normalized for transposing results to other locations the annual freezing degree days over 30 years is used as a quotient. Thawing degree days are calculated for the whole winter. It is also accumulated 5, 10, 20, 30, 60 days ahead of ice jam date and integrated in the database for statistical analysis.

3. 4. 1. 3 *Precipitation*

Precipitation is in the form of rain and snow. It denotes the magnitude of the gross input and Changes with space and time of the runoff process. It is sampled at discrete points and averaged over an area. Wind direction, topography, distance from the sea, vegetation, etc are the major factors affecting the amount of precipitation.

3. 4. 1. 4 *Snow on the ground*

This parameter denotes the magnitude of spring floods due to snow melt. For rivers, in Ontario, Snow on the ground (SOG) was determined from isoline maps published by the Ministry of Natural Resources (1984). The values of SOG were either directly from daily mean discharge for each station converted to an equivalent depth or a map of run-off isolines based on the geometric centroid of each basin.

3. 4. 2 *Geomorphologic Variables*

The geomorphologic variables which are summarized below include:

- Basin area
- Water shade relief
- Shape factor
- Channel length
- Drainage pattern
- Drainage density

- Shape of the basin
- Latitudinal and longitudinal locations of hydrometric stations

3. 4. 2. 1 *Basin area*

Drainage area affect breakup through the changes in surface run off. The relief and vegetation of the river basin also plays great role on the time of ice breakup of small rivers as a result of shorter flow time of the run off. This variable is a strong indicator of the potential flow volume that can be generated from rainfall. Assuming uniform depth of rainfall across the basin area the run-off volume is the product of basin area and rainfall depth.

3. 4. 2. 2 *Water shed relief*

They are channel slope, water shade slope and hydrometric curve. For the whole basin instead channel slope index is a better approximation since slope is varying from section to section. Slope of the channel is an indicator of the potential velocity at which runoff can be conveyed to the gauge location, and is expected to influence peak daily flows. Channel slopes were determined from longitudinal profiles. Elevations and distances were measured along the main channel from the gauge to the uppermost drainage boundary. For some ice jam cases, the slope is calculated using Modified Equivalent Slope Method. The distances between contours crossing the main channel and between contours and boundary adjacent to the upstream drainage boundary and the gauge are measured. Stream slopes are determined between these contours and boundaries.

3. 4. 2. 3 *Basin shape Factor*

This variable helps to account for the effects of drainage basin configuration on the daily flow characteristics. The drainage basin main channel length and area were used to compute this parameter as follows

$$\text{Shape factor} = (\text{Channel length})^2/\text{Basin area} \qquad (3.2)$$

If the basin perimeter is known shape factor can be evaluated also as Basin area/Basin perimeter.

3. 4. 2. 4 *Channel length*

Distance measured along the main channel from outlet to basin divide. Location of the end point of the channel depends on the level of flow when the map was drawn. Therefore, this quantity requires subjective assessment, which often leads to certain degree of inaccuracy. While drainage area indicates potential for rainfall to provide a volume of water, length is used in measuring time parameter associated with the flow. This variable may also be taken as an indicator of the degree of attenuation of daily flow and was determined from 1: 250 000 scale map of Canada.

3. 4. 2. 5 *Drainage pattern*

A number of parameters, ratio and laws have been developed by Horton (1942) to define drainage pattern. Horton's law are indicators of geomorphological characteristics of the basin. It reflects the volume of water that can be generated from rainfall. Assuming uniform depth of rainfall across the basin the runoff (volume) of water produced is a product of basin area and rainfall depth.

3. 4. 2. 6 *Drainage density*

It is the ratio of total length of streams within a basin to the total area of watershed. High drainage density value indicates dense stream. Most watershed characteristics reflect the timing of run-off in addition to volume of water which is indicative of flood hazard. In developing a system of classifying methods for estimating time parameters the input parameters were separated into 4 roughness of flow resistance, slope, watershed size and water input. Land cover and use also affect the rate of evaporation.

3. 4. 2. 7 *Shape of the basin*

Shape of the basin reflects the way the run-off concentrate at the outlet. Circular water shed would result in run off from different parts of the basin reaching the outlet at the same time. Elliptical shape will allow the runoff to spread over time.

3. 4. 2. 8 *Geodetic locations*

The latitude and longitude of the gauge location were both included as variables in multi-variate and regional regression analysis.

CHAPTER IV

DERIVED PARAMETERS

From collected hydrometric data, several parameters were derived based on empirical relationships. Elements of heat budget fall into this category.

4. 1 THE ENERGY BUDGET FORMULATION

The seasonal variation of air temperature is represented by a single harmonic function with periodicity of one year (Shen and Ruggles, 1982). Water temperatures in a river also follow the same pattern, but the temperature could drop only close to 0 ^{0}C. If atmospheric conditions are such that periods of super cooling prevail, the heat exchange at the surface leads to significant cooling of water resulting in ice cover formation in calm reaches or production of large quantities of frazil in open high velocity turbulent reaches. Atmospheric conditions will govern the rate of thickening of ice cover.

The energy balance of ice cover is examined to study the growth and decay of an ice cover. The rate of change of temperature in the ice cover depends on the change of certain meteorologic parameters such as wind speed, air temperature, solar radiation and albedo of the ice cover. Among these parameters solar radiation plays the most important role in the energy balance. The average cloudiness at 60^{0} N latitude reduces direct radiation at approximately 60 %. The effect of radiation is 1.5 times as much on clear sky days compared to overcast (Burdykina, 1970).

Surface heat, frictional heat and heat transfer through the channel bottom contributes to the heat budget. Green and Outcalt (1985) suggested that heat flux to the ice cover is more sensitive to variation in water temperature than changes in meteorological conditions.

The heat exchange through the free surface is important for open water reach, while the heat dissipation by means of bed heat influx dominates in the case of ice covered reaches (Shen and Ruggles, 1982). Bed heat flux and frictional heat represent important contributions to the total heat budget of ice covered reaches. The net heat exchange and the direction of heat flow depends on the temperature difference between water body and the surrounding (Shen, 1981). Heat exchange across the water surface is controlled by different mechanisms of heat transfer that depend upon different climatological factors. The major climatological factors that contribute to the heat exchange process are barometric pressure, solar radiation, air humidity, wind velocity, sun and cloud conditions and precipitation. The simplest model calculate the heat input into the ice cover from sunshine hours, mean daily air temperature and wind speed.

The principal surface heat exchange process consists of absorption of short wave radiation, the emission and absorption of long wave radiation, convection, latent heat in the form of condensation, evaporation and fusion of water, snow and ice.

Heat may also be transferred through the river bed either by contact or infiltration or both, from geothermal heat supply of the earth by advection and heat generated by friction at the river bed. Exchange of sensible heat between the air or the ground and the ice cover, and the transfer of sensible heat from melting snow and precipitation, heat due to geothermal energy are small sporadical and can be ignored (Paily, 1974).

Most energy budget formulations depend on water temperature data. In this study alternative methods of net heat transfer and heat loss calculation based on routine weather records supplied by AES, has been chosen over other formulations. Detailed investigation of various terms of energy budget is given below.

4.1.1 Heat transfer due to Radiation

Solar radiation is directly transmitted (33%), reflected, absorbed (14%), diffused and scattered (53%) in the process of passing through the atmosphere. Certain percentage of the scattered radiation reaches in diffused form (20%) to earth to be absorbed and reflected (33%). All in all 43% of the radiant energy is reflected. It is reported on a daily basis and measured in langlay units. The angle at which the sun rays are incident on the earth determines the quantity of solar radiation obtained. The maximum being at equator and decreasing with an increase in latitude. The heat gain as a result of radiation is the difference btween short- wave and long-wave radiation.

4. 1. 1. 1 Heat transfer due to short-wave radiation(H_{ns}) and long-wave radiation(H_{nl})

In general, the net solar radiation is defined as the difference between incident and reflected solar radiation. The net incident solar radiation is a function of aspect of water surface and shading from either valley wall or vegetation. The heat input due to short wave radiation can be determined if clear-sky solar radiation, cloud cover and reflected radiation are known. In absence of observational data the heat gained per unit surface and time from incident solar radiation can be estimated from tables and radiation charts [Bolsegna(1964), Moon(1960), Koberg(1964)] or empirical formula as follows :

$$H_{si} = \beta_1 \, S \, R \sin \alpha \; f(C) \tag{4. 1}$$

where, β_1 is the factor of absorptivity of water. β_1 depends on the incidence and wave length of radiation and experimentally determined to be 0.83 for clear-sky conditions. S is the intensity of solar radiation outside the atmosphere at normal incidence with approximate value of $5 \times 10^6 \ J \cdot m^{-2} \ day^{-1}$. R is a reduction factor that takes into account the dispersion of radiation by the atmosphere and absorption by water vapor and ozone. The integrated values of $SR\sin\alpha$, considering the most probable value of the concentration of the dispersant is given by Threlkeld and Jordan (1957) in a tabular form. The function of the cloud cover f(C) is calculated from empirical relations given by Kennedy (1944) :

$$f(C) = 1 - 0.0065 \, C^2 \tag{4. 2}$$

Cloud cover in tenths, C, is a measure of degree of cloudiness and its value is 10 for overcast skies. The daily short wave solar radiation can be computed also from hours of bright sunshine. But the values obtained are on the higher side.

Reflected solar radiation is obtained by multiplying incident solar radiation by reflectivity (R_t). Reflectivity is given as a function of solar altitude, amount of cloud cover and height of clouds. Density, amount and height of the cloud cover affect the radiation exchange. Based on averaging of Koberg (1964) equations representing clear-sky and cloudy conditions the reflected solar radiation can be expressed as (Dingman et al., 1967) :

$$H_{sr} = 4520.88\, H_{si} - 2.8322\, H_{si}^2 \tag{4. 3}$$

The net radiation loss is therefore the difference between the incident and reflected solar radiation and is expressed as :

$$H_{ns} = 0.11574\left[a - b\left(\phi\text{-}50\right)\right]\left(1 - \alpha\right)\left(1 - 0.0065\, C^2\right) \tag{4. 4}$$

ϕ is latitude of location under consideration in degrees, α is albedo of the ice cover, a and b are constants varying with time. The units both for a and b is in $J{\cdot}m^{-2}{\cdot}day^{-1}$.

The effective long-wave radiation is the sum total of atmospheric long-wave radiation reaching the water surface, portion of atmospheric radiation reflected by the water surface and the long-wave radiation emitted by the water surface.

The amount of heat received by a horizontal water surface from the surrounding is estimated by clear sky atmospheric long-wave radiation as given by Stefan-Boltzman law modified by the emmisivity of the atmosphere:

$$H_{la} = e_a\, \sigma\, T_a^4\, f_1(C) \tag{4. 5}$$

Stephan-Boltzmann constant, σ, is equal to $4.9 \times 10^{-3}\ J{\cdot}m^{-2}{\cdot}day^{-1}K^{-4}$. T_a is the air temperature, in ^oK. The emmisivity of the atmosphere, e_a, depends on the degree of cloudiness and its value is 0.96 for cloudy sky. But for clear sky several formulas exist. Among them the most widely used is suggested by Brunt (1932):

$$c_a = \left(0.52 + 0.0065\sqrt{0.01p_a}\right) \qquad (4.6)$$

where, p_a is vapor pressure of the air in N/m^2.

The amount of heat quantity emitted by long wave radiation from the water surface is estimated by :

$$H_{lw} = e_w \, \sigma \, T_w{}^4 \qquad (4.7)$$

T_w is the absolute water temperature. The emissivity factor for water, e_w, is 0.97. If surrounding objects and air have the same temperature, then the reflected long-wave radiation for emmisivity of 0.97 is given as :

$$H_{lr} = 0.03 \, H_{lw} \qquad (4.8)$$

Therefore, the total quantity of heat gained or lost by water body through long wave radiation is given by :

$$H_{nl} = e_w \sigma \left[T_w{}^4 \left(1 + 0.017C^2\right)\left(c + d\sqrt{0.01p_a}\right) T_a{}^4 \right] \qquad (4.9)$$

c and d are constants which have an approximate value of 0.55 and 0.052 respectively.

4. 1. 2 *Evaporative Heat transfer* (H_E)

The heat loss due to evaporation, convection, and conduction can be computed from meteorological measurements of air temperature, wind velocity and vapor pressure. The heat and mass transfer due to evaporation and conduction can be calculated based on Prandtl (1926) velocity distribution of the boundary layer and Reynolds analogy to heat and mass transfer. The amount of heat lost by evaporation is approximately equal to the amount of heat gained by radiation (Williams G. P., 1965) . It is the sum of heat lost due to latent heat of vaporization and the evaporated water mass and is calculated using modified Meyer's (1915) formula:

$$H_E = 3.16 \times 10^3 [\psi_E(p_a - p_w)] \qquad (4.\ 10)$$

$$\psi_E = 400\, V_{15} \qquad (4.\ 11)$$

where, H_e is heat loss by evaporation in $J \cdot m^{-2} \cdot day^{-1}$, V_{15} is wind speed in Km/hr, p_a and p_w are the air and water vapor pressure in N/m^2. All the three elements are mesured at 15m above the water surface. ψ_e is heat transfer coefficient due to evaporation. Equation 4. 10 do not hold true for natural convection and low wind velocity. Latent heat of vaporization is a function of air temperature. For a given temperature the air and water vapor pressure p_a and p_w can be determined from a table or graph. Since we are confining our study to cases where the water temperature can be assumed to be at freezing point, p_w is constant and is taken to be $611 N/m^2$.

4. 1. 3 *Convective heat transfer* (H_C)

The convective heat transfer is used to describe temperature related heat transfer in one lump. The magnitude of convection loss depends on the difference between water and air temperature and the wind velocity at the water surface. For quiescent air over a flat body the heat loss due to convection ranges from 7.6 x 10^4 to 1.5 x 10^5 $J{\cdot}m^{-2}{\cdot}day^{-1}{\cdot}{}^{o}C^{-1}$, for a temperature difference of few degrees to 38 ^{o}C respectively. For all practical purposes, where the range of temperature differential is between 10 to 38 ^{o}C the value of H_c is considered to be 1.2 x 10^5 $J{\cdot}m^{-2}{\cdot}day^{-1}{\cdot}{}^{o}C^{-1}$.

$$H_C = \psi_E\left[6.92 \times 10^3\left(\left(T_{a1}-T_{w1}\right) - 32\right)\right] \tag{4. 12}$$

$$\psi_C = 4.4\ V_{15} \tag{4. 13}$$

where, H_c is heat loss by convection in $J.m^{-2}$ day^{-1}, T_{a1} and T_{w1} are the air and water surface temperature in ^{o}C, the measurement being taken at 15m above the water in case of air temperature measurements. ψ_c is heat transfer coefficient due to convection. For practical purposes wind velocity, 0.5 times the actual wind velocity is used. The combined heat loss by evaporation and convection is given by Michel (1971) as :

$$H_{CE} = 8.2 \times 10^4\ V_{15}\left[\left(32 - \left(0.66 + 0.33\ e\ \xi\right)\frac{5}{9}\left(T_a - 32\right)\right)\right] \tag{4. 14}$$

where, $\xi = 1$ for $T_{a1} >$ zero or $\xi = 0$ for $T_{a1} \leq 0$. H_{ce} is in $J.m^{-2}$ day^{-1}, T_a is in ^{o}C, e is the relative humidity 15 m above water.

4. 1. 4 *Heat transfer due to conduction* (H_{CD})

The sensible heat lost by conduction from water surface is expressed as a ratio of heat flux due to the process of evaporation known as the Bowen's ratio. Hence the heat transfer by conduction is expressed as :

$$H_{CD} = B\,H_E = 1.3 \times 10^{-6}(K + 0.36\,V_6)(T_w - T_a) \qquad (4.\,15)$$

H_{CD} is heat loss due to sensible heat transfer by conduction in $J.m^{-2}\,day^{-1}$, V_6 is wind velocity at 6 meters above the water surface in Km/hr and K is a coefficient determined from :

$$K = 0.926 + 0.04\,(T_w - T_a) \qquad (4.\,16)$$

Energy budget calculations have been performed on daily, weekly or monthly accumulations of a number of indexes of meteorological parameters.

4. 2 SNOW MELT INDEX

Snow melt is a thermodynamic process determined by the snow cover energy budget. The amount of water content in snow can be determined using methods such as energy budget, partial season method, Snow storm maximization and statistical analysis of snow cover. Temperature index method is one of the simplest method for estimating snow melt. In this case, snow melt is quantified using statistical correlation between temperature of the air and the melt as estimated from run-off based on meteorological variables. Relationship of this nature is linear (Pugseley, 1981). Snow melt is expressed as :

$$M = M_f(T_i - T_b) \tag{4. 17}$$

where, M_f is melt factor, T_i is index air temperature which is either maximum or minimum daily temperature, T_b is base temperature usually taken to be the freezing temperature. If an interval of one day is used for calculating melt factor, it is called degree-day factor. The melt index mainly serves to characterize the intensity and consequently the duration of snow melt and the date on which the snow cover will disappear.

The advantage of these models is they require only temperature data. Their disadvantage is that they are based on the theory that all energy exchanges can be reduced to a function of single variable, temperature. In actual fact, however, the closer the radiation, wind and humidity conditions are to normal, the more accurate will be the estimates of snow melt. These models underestimate high melt and overestimate low melt rates. They produce better results for shaded areas such as forests. They are much less accurate in open areas.

For better results the above general equation is modified for open or partly forested basin. It also incorporates wind speed and rainfall conditions into the model. The energy budget method is based on conceptual model in which each of the principal exchanges is represented by mathematical relationships. The basis of these model is given by the following equation.

$$M = M_{rs} + M_{rl} + M_{ca} + M_p + M_q \tag{4. 18}$$

M_{rs} = melt due to short wave radiation

M_{rl} = melt due to long wave radiation

M_{ca} = melt due to condensation of atmospheric water vapor and advection of warm air

M_p = melt due to sensible heat of rain drops

M_q = melt due to conduction of heat from the ground.

The most commonly used method in estimating snow melt is rational approach based on degree days method. The accumulated snow depth M in mm is given by :

$$M = a\,T_a \qquad (4.19)$$

where, a = degree days factor. Its values range between 2 and 7, i. e, 5 for non forested area, 1.7 to 1.8 for coniferous wood, 3 to 4 for sparse wood, 1.4 to 1.5 for dense coniferous wood. If snow melts during period of heavy rain, long-wave radiation, convection and condensation with turbulent mixing is a major source of heat.

The above model could be modified for combination of different effective fraction of the basin covered by the forest and rain or no rain conditions. Louie and Pugsley (1977) state that the most appropriate degree days model is good enough for the desired accuracy. In our study simplified mathematical equations of temperature index methods are used to estimate snow melt as a result of lack of energy budget data.

CHAPTER V

METHOD OF ANALYSIS

In this study, potential ice jam parameters data are collected from a large number of river basins. This data, obtained from Water Survey of Canada, Atmospheric and Environment Service and other regional agencies, is analyzed using a statistical techniques to determine the degree of relationship among hydraulics, meteorological and geomorphologic parameters associated with ice jams. Compared to open water flow ice jam data is fairly diversified and qualitatively different. Therefore, standardizing the record, is the first step taken to eliminate inconsistencies between various sources. The multidimensionality of available data necessitate the use of advanced statistical procedures.

Uncertainty in ice jam data arises due to the stochastic nature of hydrometeorologic processes. More often the quantities which are uncertain have to be expressed by their expected values or median values. These values are needed if deterministic approach is employed, or the variation is not large enough to affect the performance of the parameters under study.

Most ice jam related studies have concentrated on the physical description of ice jams and their evolution. But, due to uncertainty of the factors involved, statistical analysis is the most appropriate tool to analyze events related to ice jams. The methodology, based on multivariate statistical methods applied to time and space dependent data variability is particularly suited to large data.

The overall analysis requires also the critical examination of available data and description of spatial variation of some of the parameters with regard to ice jamming process. The nature of analysis employed generally depends on the type of data. The major distinction is based on whether tne data is dependent on time or space.

5. 1 SPATIALLY VARIED DATA

The available data is reduced into meaningful form using statistical means. Some of the parameters sush as ice thickness and heat budget parameters were estimated to fill data gaps. Several procedures were used to test the hypotheses about the population and characteristics of data.

The ice jam data was analyzed to derive probability density functions for each of the variables under investigation. Frequency diagram was constructed for parameters such as basin area, shape factor, latitude, longitude and length of channel from source for both upstream and downstream hydrometric stations. Graphical methods of frequency analysis are inferior compared to analytical methods, but are advantageous in a sense of visual comparison of observed data and computed result.

The corresponding distribution model was selected by comparing alternative density functions with frequency diagram. Chi-Square tests were conducted to select the family of density functions that best fits the frequency diagrams for each variable. The parameters of the density functions were estimated from data using the method of moments, where sufficient information was available, and through the use of Bayesian Statistics where data was scarce such as in the case of ice thickness, hourly water level and discharge variation. For normally distributed variables, the parameters of density functions are estimated from:

$$\text{Mean} = \bar{x} = \sum_{i=1}^{n} \frac{x_i}{n} \tag{5. 1}$$

$$\text{Standard deviation} = S = \sqrt{\frac{\sum (x - \bar{x})^2}{n}} \tag{5. 2}$$

$$\text{Variance} = V = S^2 \tag{5. 3}$$

In case of hydraulic structure design streamflow populations should reflect the extreme nature of the breakup water levels and discharges. Ice jam related stages or discharges are very near the upper limit of expected phenomenon. As a result, their probability distribution was found not to follow any particular distribution and also it is most unlikely that it could be extrapolated on the basis of any standard statistical distribution.

In the first round of statistical analysis most hydraulic, meteorologic and geomorphologic variables were included to study in depth the contribution of each parameters with regard to ice jam formation and occurrence. Parameters with short records were excluded to avoid bias. The quality of streamflow data at a particular location is checked by comparing them with upstream or downstream hydrometric station measurements.

The method of analysis varies from basic descriptive statistics to complex multivariate analysis. Simple and multiple regression analysis is performed to study the degree of association between supposedly dependent and independent variables. A number of possible relations among the variables were explored to understand the effect of change of one or more independent variables on dependent variables. Several combinations of parameters were attempted to carry out different types of regression procedures.

Statistical procedures are implemented in screening data to obtain homogeneity among data of various kinds to account for factors affecting ice jam formation. To reflect variability of hydrometeorologic parameters from station to station, regional regression is implemented. Several hypotheses of the stochastic parameters and homogeneity test is conducted for hydrologically homogeneous region. The accuracy of each regional regression equation was compared using the coefficient of determination, R^2. Where the data is known to have non-homogeneous nature, it is reduced and classified into different groups by means of cluster analysis.

Spatial homogenization of data was also be achieved by removing effects that are relevant to specific stations, applying recentering of data. Recentering is accomplished by subtracting from the mean. Dividing this outcome by standard deviation of the population transforms data into unitary variance and eliminates the scale effect of spatial fluctuations. This facilitates comparison of time dependent fluctuations of one parameter at a given station.

Multivariate analysis was found to be an efficient technique to define relationships between variables and describe the statistical interdependence between relevant variables affecting the occurrence of ice jam. The techniques are descriptive rather than prescriptive. Multivariate analysis isolate the contribution of one variable among several intertwined array of independent variables. Mostly probabilistic models with elementary descriptive techniques are used to describe stochastic process. In some cases a set of statistical modeling tools which are multivariate techniques like component analysis, regression on principal components, factor analysis, stepwise regression and canonical analysis has been used in analyzing data and describing statistical interdependence and relationships between variables.

Principal component analysis is used to reduce the number of variates, resulting in economy of representation and developing a rank list for the importance of several variates. Linear transformation of the given data is the first step in a series of procedures for component analysis. Where linear transformation leads to non-linearity logarithmic transformation is assumed. Regression on principal components defines the numerical values of cause and effect expressions in linear models.

Factorial analysis estimates the model pertinent parameters for given set of data and helps in defining additional components to modify the model and improve the result by virtue of alternate formulation and testing. Factor analysis is an aid used in extracting cause and effect relationships among different variables. In combination with component analysis and regression on principal components, factor analysis helps in reaching a sound conclusion on the relationships among independent variables.

Canonical correlation analysis selects one variable from each set of variables, that have a stronger relationships in a stepwise manner till all the pairs that are highly correlated are exhausted. This method is merely an extension of multiple correlation analysis or multiple correlation analysis can be viewed as a special case of canonical correlation analysis.

The objective of stepwise regression is to develop a prediction equation relating dependent variable to one or more independent variables and set a criteria to measure importance among the variates. It is not truly a multivariate technique, as the dependencies among the independent variables is not totally removed. In addition to calibrating prediction equation, stepwise regression sets statistical criteria for choosing independent variables to be used in the final regression. There should not be no inter dependency among the independent variables to be used in the analysis.

5. 2 TIME DEPENDENT DATA

The main purpose of time series analysis is to understand the mechanism that generates the data and apply this mechanism to be able to extend the sequences to produce the most likely outcomes of this random event over a short time interval or what we call short range forecasting. This can be achieved by making inferences regarding the underlying laws of the stochastic process that fits the data from sequences of recorded observations, after analyzing components of time series.

The history or movement of variables such as flow rate and water level fluctuations and other hydrological variables are characterized by variability in space and time. Time based variability is studied using Correlogram, Spectrum and other methods of time series analysis (Kottegoda 1980). A time series is analyzed for the purpose of formulating and calibrating a model that is used to explain the time dependent characteristics of a hydrologic variable. However, it differs from bivariate form of regression in that it assumes independence among residuals. Time and space are not casual properties. They would be regarded as convenient parameters by which we bring true cause and effect into proper relationships.

In this study, continuous automatic gage measurements of discharge and water level from a chart are transformed into discrete series using a basic sampling interval of one hour, for handling of data effectively. The hourly water level and discharge data used in the analysis is without shift corrections. As mentioned above, this is as a result of highly variable conditions surrounding the occurrence of ice jamming events. The hourly data collected was checked for sequential dependence and randomness using turning point test. The auto-correlation function and the spectral function were determined for a variance density of 10% of the spectral value, at the upper limit of frequency range. The information contained in a discrete series is greatly affected by the choice of sampling intervals. The choice mostly depends on the objectives of the project. In principle, the basic sampling intervals are determined from limit frequency and sampling intervals. Limit frequency is inversely proportional to sampling interval.

Stochastic models fitted to streamflow series are often used to generate synthetic data where shortage of data is evident for planning and execution of a hydraulic structure design project. The models are not only useful in prediction, but also explaining ice jam process and behavior.

The mean and variance of the streamflow and water level time-series were checked to see if they are constant with time. If the mean and variance change with time, the time-series is not constant or stationary.

Probabilistic evaluation of ice jam phenomena which generally have multiannual periodicity requires a long series of observation.

Area interpolation of data gives results within reasonable accuracy only for gradually changing meteorological and river basin parameters. The accuracy of interpolation suffers set back due to the stepwise changes in variables over an area. The statistical relationship between series of data observed at neighboring stations can be used in improving interpolation. For a parameter to be interpolated, it should represent a continuous process and be from sites where there are sufficient number of gauges in the vicinity. Measurements of parameters which are subject to discontinuities are to be regarded as point values instead of being assumed to be having local area distribution. Point values can not be transferred to other points and are valid only at vicinity of observation points.

The result of time series analysis is used to forecast the expected future behavior of processes and supply information for planning and design of hydraulic structures. The time of occurrence of hydrologic phenomena, is determined by computing the value of one independent factor as a function in terms of others (Starsolosky 1980).

5. 3 FORECASTING

The combination of synoptic and hydrological variables were used in establishing forecasting dependencies and long range forecasting of break up characteristics of rivers. For fairly reliable results the analysis depends on long historical data. Long range forecasting of rise of flood wave were done by studying the air temperature pattern in spring, as it is indicative of rate of melting and intensity of run-off.

Short range forecasting is based on heat budget analysis. It combines theoretically and empirically determined heat transfer rates with meteorological forecasts of air temperature, humidity, cloud cover, wind speed and direction, and hydrological prediction of river stage and discharge.

Prediction can be improved by increasing the number of observation points and quality of observation of ice phenomena. Precipitation during fall period plays an important role and can influence the length of the ice cover period (Lebedeva 1972). The magnitude of degree days accumulated over the preceding heating season could be used as an index to predict the appearance of first ice and the extent of ice cover during winter season (Richards 1963). Only local forecast of ice cover formation should be used for the purpose of prediction.

Overall forecasting methods contain methods derived from the laws governing the movement of water in the channel, such as approximate techniques of flood routing and hydrodynamic methods which form the basis of short-term forecasting. Methods derived from the analysis of meteorologic and hydrologic process in the river basin, such as water-budget methods of water supply forecasts, and methods derived from the analysis of heat transfer processes in rivers and reservoirs, are the basis for short-term forecast for ice formation and ice breakup. The latter method employs weather charts and meteorological observational data and is used for long term ice forecasts.

Prior knowledge of meteorologic conditions increases the scope, accuracy and reliability of forecasting. Meteorologic forecasts constitute an important and essential input to methods used in forecasting hydrologic variables. Optimum sampling intervals were determined to avoid redundancy of data and increased cost.

The date of river ice break up is established from plots of negative degree days versus the calendar day. It is a measured staring from the point of maximum cumulative negative degree days. For cases where the break up occurs before the date of maximum cumulative negative degree days a value of zero is entered for time. In estimating river ice break up there are always inherent problems with accuracy of discharge measurement. For better results the mean hourly values of discharge around the approximate date of ice break up was taken under consideration. The shorter the time interval in a generated sequence, the harder it is to find a simple model that describe the hydrologic variable under study. Some of the models that are used for forecasting purposes are elaborated below.

5. 3. 1 *Autoregressive models*

For a given set of observed sequences of water level and discharge data an autoregressive model of k^{th} order was fitted as :

$$y_t - \mu = a_1 \left(y_{t-1} - \mu\right) + a_2 \left(y_{t-2} - \mu\right) + \ldots + a_k \left(y_{t-k} - \mu\right) + \varepsilon_t \qquad (5.\ 4)$$

where, μ is mean of y, a_1, a_2, a_3, ..., a_k are autoregressive coefficients and e_t = the independent stochastic component. The independent stochastic component has normal distribution with zero mean and variance. The first order autoregressive model can be expressed as :

$$y_t - \mu = a_1 \left(y_{t-1} - \mu \right) + \varepsilon_t \tag{5. 5}$$

The second order autoregressive model for discharge and water level contains the first two terms from the general autoregressive model and is given by :

$$y_t - \mu = a_1 \left(y_{t-1} - \mu \right) + a_2 \left(y_{t-2} - \mu \right) \varepsilon_t \tag{5. 6}$$

The parameters of the first and second order autoregressive model are estimated in the following manner.

step 1 - Calculate the mean from

$$\bar{y} = \sum_{t=1}^{n} \frac{y_t}{n} \tag{5. 7}$$

step 2 - Estimate r_1

$$r_1 = \frac{\sum_{t=1}^{n} \left(y_t - y \right) \left(y_{t+1} - y \right)}{\sum_{t=1}^{n} \left(y_t - y \right)^2} \tag{5. 8}$$

step 3 - Calculate a_1 and a_2 where

$$\bar{a}_1 = \frac{r_1(1 - r_2)}{(1 - r_1^2)} \qquad \bar{a}_2 = \frac{(r_2 - r_1^2)}{(1 - r_1^2)} \tag{5.9}$$

step 4 - Calculate S^2

$$S^2 = \frac{\frac{n-1}{n}(1 - r^2)\sum_{t=1}^{n}(y_t - y)^2}{n - 3} \tag{5.10}$$

$$\sigma_\varepsilon^2 = \left[\frac{n-2}{n-5}\right](c_0 - \bar{a}_1 c_1 - \bar{a}_2 c_2) \tag{5.11}$$

The strength of persistence is estimated from lag one serial correlation and is determined by a_1. Both stationary and non stationary sequences are represented by autoregressive and moving averages.

5. 3. 2 *Moving average models*

In these models the deviation of a variable y_t from its mean is expressed as weighted sum of independent distributed random variable ε_t.

$$y_t - \mu = \varepsilon_t + b_1 \varepsilon_{t-1} + b_2 \varepsilon_{t-2} + \ldots + b_k \varepsilon_{t-k} \tag{5.12}$$

k denotes the order of the scheme. To describe the persistence, k+2 variables must be estimated.

5. 3. 3 *ARIMA models*

ARIMA models are a hybrid of moving average models and autoregressive models developed by Box and Jenkins in 1976.

$$(y_t - \mu) + b_1 (y_{t-1} - \mu) = \varepsilon_t + a_1 \varepsilon_{t-1} \tag{5. 13}$$

The parameter of the Arima model a_1 and b_1 is roughly estimated from the following relationships.

$$r_1 = -\frac{(b_1 - a_1)(1 - a_1 b_1)}{1 - 2a_1 b_1 + a_1^2} \tag{5. 14}$$

$$r_2 = b_1 r_1 \tag{5. 15}$$

Using the above as initial starting values and applying iterative procedures mentioned by Box and Jenkins has given better results. Early warning systems can reduce destruction and flood damage.

The theoretical basis for extrapolating hydrometeorologic data beyond duration of the record is that the maxima can be assumed to be the maxima of independent samples from the population of all possible events. Some of the statistical forecast errors estimate that can be expected are :

- Coefficient of variation of residual of errors :

$$Y=\frac{\sum\left[(y_c-y_0)^2\right]^{\frac{1}{2}}}{y_0} \qquad (5.16)$$

- Ratio of relative error to the mean :

$$Y=\frac{\sum(y_c-y_0)}{ny_0} \qquad (5.17)$$

- Ratio of relative error to the mean :

$$A=\frac{y_c-y_0}{n\overline{y}_0} \qquad (5.18)$$

where, y_0 and y_c are observed and computed values, n is total number of observations and $\overline{y_0}$ is the mean.

CHAPTER VI

RESULTS AND DISCUSSIONS

The hydrometric and meteorological stations and the river basins with high frequency of ice jam occurrences that are used in these study are illustrated using figure 1 to 7. The frequency of ice jam occurrence is the highest in Saint John river valley, followed by Athabasca, Thames and Nashwaak river as shown in figure 80. All in all, there are 119 cases of ice jam incidents in N. B., 26 cases in Ontario, 16 in N. W. T., 35 in Alberta and 15 cases in Québec that were recorded and used in this study.

Hydraulic and meteorologic parameters have strong effect on ice jam formation. Among hydraulic parameters, the most important parameter that influence the formation of ice jams are freeze-up depth, breakup depth, discharge and ice thickness. Meteorological parameters such as AFDD indicate the degree the severity that could be associated with ice jams and thereby indicate the level of damage due to flooding that could be associated with the rise in water level. There are other factors which influence the form and the feature of ice jam. But there bound to be difficulties in quantifying them.

The cumulative frequency of discharge for winter flow is depicted in figure 72. For variable level of greater than probability the corresponding discharge can be easily determined from the graph.

The probable date of ice breakup on the Yukon river at Dawson city was determined from frequency analysis, as shown in figure 61, to be May 9. This parameter show strongly that it is normally distributed.

The probability distribution of maximum water level and discharge for the winter season, for Yukon river at Dowson, is shown in figure 69 and 70 respectively. Both parameters, more or less, follow normal probability distribution. Figure 63 shows the frequency distribution for improved shape factor. The mode value for this parameter is 0.25 which happen to coincide with the maximum probable value. The modified shape factor is obtained by taking into consideration the upstream, downstream or the mean of both, depending on the location of ice jam with regard to hydrometric station. Other hydraulic and morphologic parameters such as the basin area, channel length, latitude and longitude of hydrometric relation, depicted by figure 59 to 67, do not follow any particular probability distribution and have a scatter over a range of values.

The relation between Froude number and discharge at ice jam is illustrated with the help of figure 77. The correlation coefficient is 0.61. This shows there is not very strong but acceptable level of relation between the two.

Figure 51 shows that the relation between the maximum stage and the stage at freeze-up rise up together at the start, but the later begins to recede even though the former increases.

Our attention were also drawn to see if available hydrometeorological data could be used in warning the oncoming of ice jam flooding. Figure 74 emphasizes there exists a direct relationship between the maximum stages in winter and the stages due to Freeze up. This shows that if this relation holds good for some of the river basins we could extend our observation elsewhere provided historical and morphological information of the basin is known in addition to stage relationships. Long time records of the river basin will, therefore pave a way for forecasting stages due to ice jam using probability approach.

The complete appendix I is devoted to the rating curves of rivers under investigation. The rating curves, except for southern Ontario, are drawn on the basis of data obtained by regional branches of WSC. Grand and Thames river conservation Authorities have furbished as with the data for some of southern Ontario locations. In all cases, available data does not take into consideration where there is an ice effect on the flow.

Presentation of time variation of discharge and water level in graphic form can be used to some degree of success in illustrating the probable interval at which antecedent ice jam events, among them freeze up and breakup, has taken place. In appendix II graphic presentation of the nature of time variation of discharge as well as water level both at the time of breakup and freeze up is presented to emphasize this conception. Detailed analysis of the time series is summarized in table 5 of Appendix IV. Among these numerous figures, figure 18, 25, 30, 31, 37 to 39, 41, 42, 52 and 56 give the probable date of freeze up and breakup without ambiguity. Distinct freeze up dates are depicted by figure 17, 24, 27, 28, 44, 45, 48 to 50, while breakup dates by figure 22, 29, 54 and 55. Figure 26, 35, 36, 46 and 51 are examples where ambiguity results as to the breakup dates but show distinct freeze up dates. One has to be constantly reminded that all these graphical interpretation has to be verified in most cases with the help of field observation. Some of the figures do not give the complete picture as to the likelihood of breakup and freeze up events as there is missing data. The most common culprit in such shortcoming is the failure of measuring gages because of blocked nozzles. The province of Québec and Yukon territory lack the time variant graphical presentation of freeze up and breakup water level and discharge. This is due to the special cost incurred in recovery of digital data from charts.

The absence of complete radiation data is surmounted by using temperature gradient instead. Cumulated over the winter they can be used as an indication of severity of the breakup and the resulting ice jam. If the rate of ATDD cumulation over a short period of time, just before breakup, is considerable the ice deterioration is minimal and the ice jam that takes place is notable for its outcome. Likewise ATDD accumulation that becomes considerable over a long period of time results with ice cover decay in place resulting with little or no consequences.

Prediction of ice jam occurrences solely rely on analysis of stochastic nature. The probability of certain events like flooding and extent of damages can be predicted with certain confidence interval. As to the whereabouts of occurrences there is no rule of thumb. The limiting value of AFDD ranges over the winter season for several river basins is illustrated by table. These values increase with latitude. The higher values being in Mackenzie river which is the most northerly river. The ATDD that causes ice deterioration is therefore proportional to the AFDD cumulated over the winter. Hence, the breakup events in northerly flowing rivers is more of mechanical than thermal in nature. The magnitude of freezing degree days and its rate of dissipation is very significant factor in predicting the severity of ice jams. Where freezing degree days were high at freeze up, with accelerated rate of ice growth, and coupled with rainfall of considerable intensity the ice jam incidents were found to result in considerable damages.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

Statistical method, rather than physical or mathematical modeling, are employed to characterize the random but frequent occurrences of ice jams in Canadian rivers. Several studies that describe the physical process of pre and post ice jam events were used in the extraction of place and time of ice jam occurrences. Relevant information were also retained for comparing field observations with statistical results.

Statistical analysis is performed to isolate and identify those geomorphologic and hydrometeorologic variables that could be used in characterizing and predicting ice jams in Canadian rivers. The results of this analysis recognize the main variables that play the leading roles in the formation and occurrences of ice jams. Furthermore, the results have inabled us to predict the frequency of ice jam occurences.

A variety of existing statistical techniques were implemented to isolate hydraulic and meteorological parameters that have strong influence on the genesis of ice jam formation. Several empirical relations among these parameters were found. The detailed discussion is provided in the previous chapter.

A limiting value of thawing degree days that results in favorable conditions for the formation of ice jams is established, based on available data. These range of values can be modified as further information get accumulated. Preferable ice jam orientation angles are determined for ice jam prone locations.

An upper envelope curve relating freeze up depth to the maximum probable winter depth is also established. This result can be used for the prediction of water level at breakup time. Extrapolation of these result to other reaches depends up on availability of data. At the moment, extraction of both freeze up and probable maximum winter depth are determined, if only the values obtained from charts are supplemented by field observations.

There is a pressing need for systematic collection and documentation of data which are pertinent to ice and ice jam related events. The guidelines recommended by NRC working group on ice jam (Prowse, 1985) is one small step ahead. A concerted effort by agencies responsible such as WSC and AES not only in following the guidelines but in collecting data is long overdue.

Improvement in discharge estimates at breakup and freeze up as well as development of techniques to establish freeze up and breakup dates that does not engage in field observation will become handy in future works. Availability of new measurement techniques under ice specially at breakup, will open new avenues in conducting detailed investigation.

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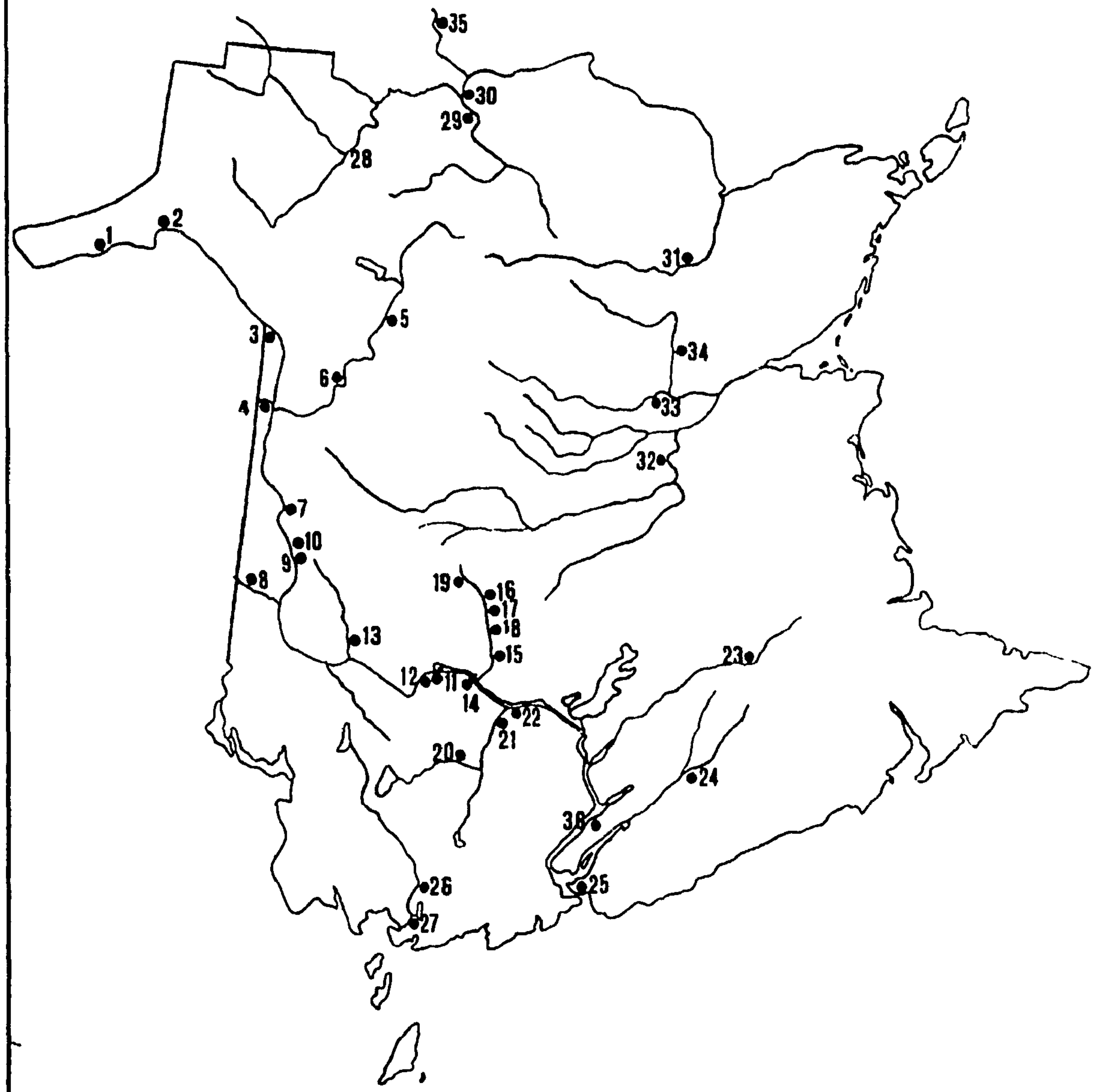
APPENDIX I - STUDY SITES



1. 01AD002
2. 01AD004
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10. 01AJ009
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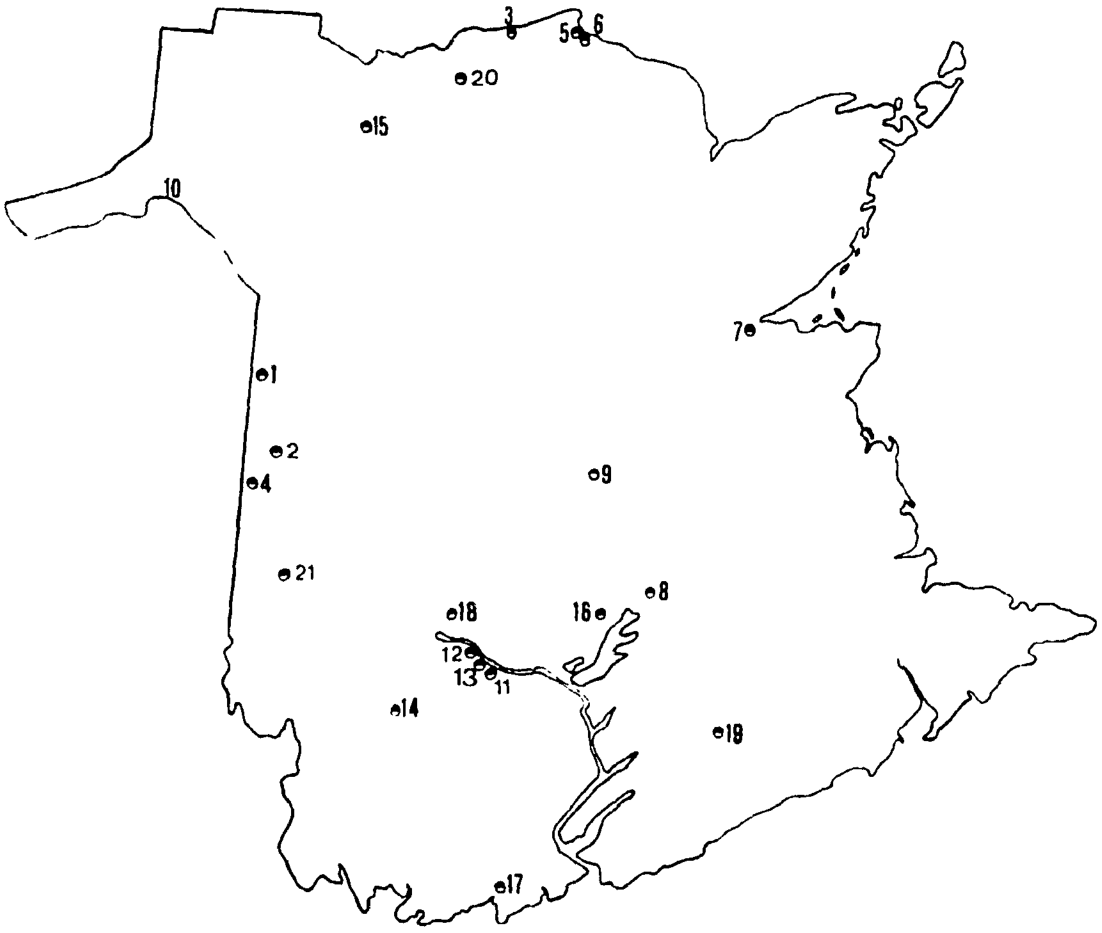
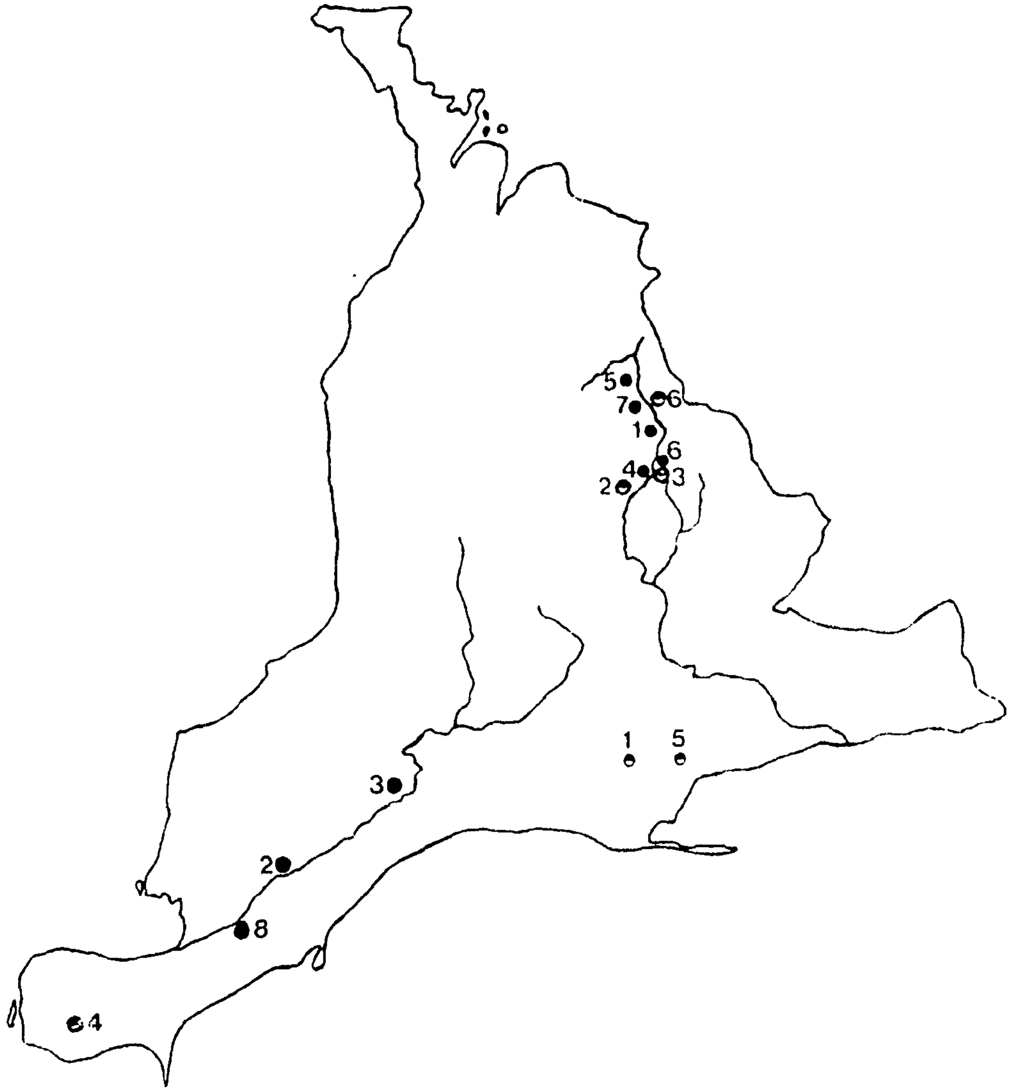
14. 01AK009
15. 01AL001
16. 01AL002
17. 01AL008
18. 01AL009
19. 01AL010
20. 01AM001
21. 01AM002
22. 01AO002
23. 01AP002
24. 01AP004
25. 01AP005
26. 01AQ002
27. 01AQ009
28. 01BC001
29. 01BE001
30. 01BJ007
31. 01BK003
32. 01BO001
33. 01BP001
34. 01BQ001
35. 011507
36. 01AP003

Figure 1. New Brunswick hydrometric stations used in the study



1. Aroostook
2. Beechwood
3. Campbellton
4. Centreville
5. Charlo A.
6. Charlo Falls
7. Chatham
8. Chipman
9. Doaktown
10. Edmunston
11. Fredericton A.
12. Fredericton CDA
13. Fredericton UNB
14. Harvey Station
15. Kedgwick
16. Minto
17. Pointe Lepreau
18. Royal Road
19. Sussex
20. Upsalquitch
21. Woodstock

Figure 2. New Brunswick meteorological stations used in the study



● Hydrometric stations

1. 02GA014
2. 02GE003
3. 02GE006
4. Fergus Shand dam
5. Legatt
6. Upper Belwood
7. Waldemar
8. Chatham

⊖ Meteorologic Stations

1. Delhi
2. Elora
3. Fergus Shand dam
4. Harrow CDA
5. Simcoe
6. Waldemar

Figure 3. Ontario hydrometric and meteorolologic stations used in the study

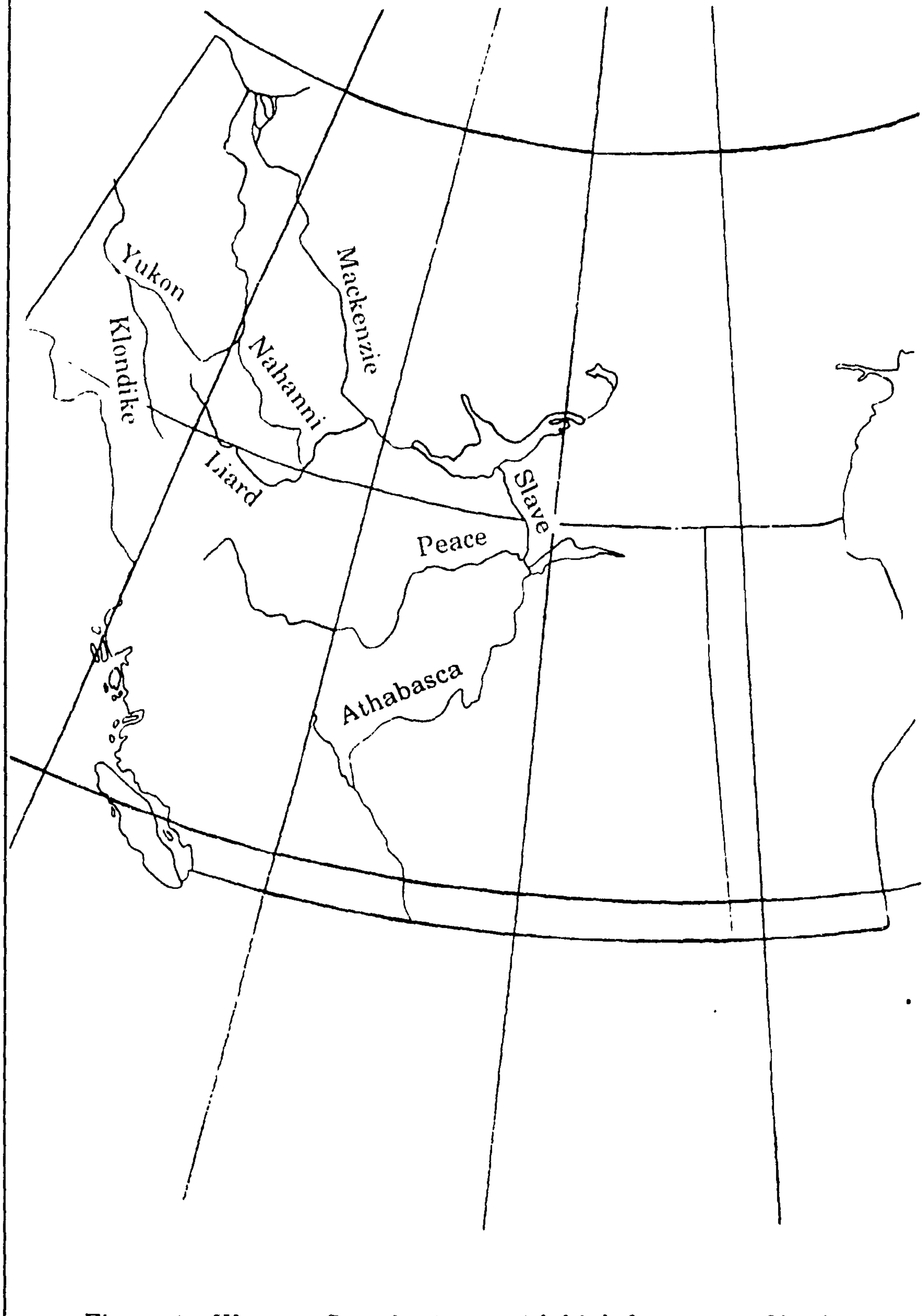


Figure 4. Western Canada rivers with high frequency of ice jams

Figure 5. Meteorological stations used for western Canada rivers

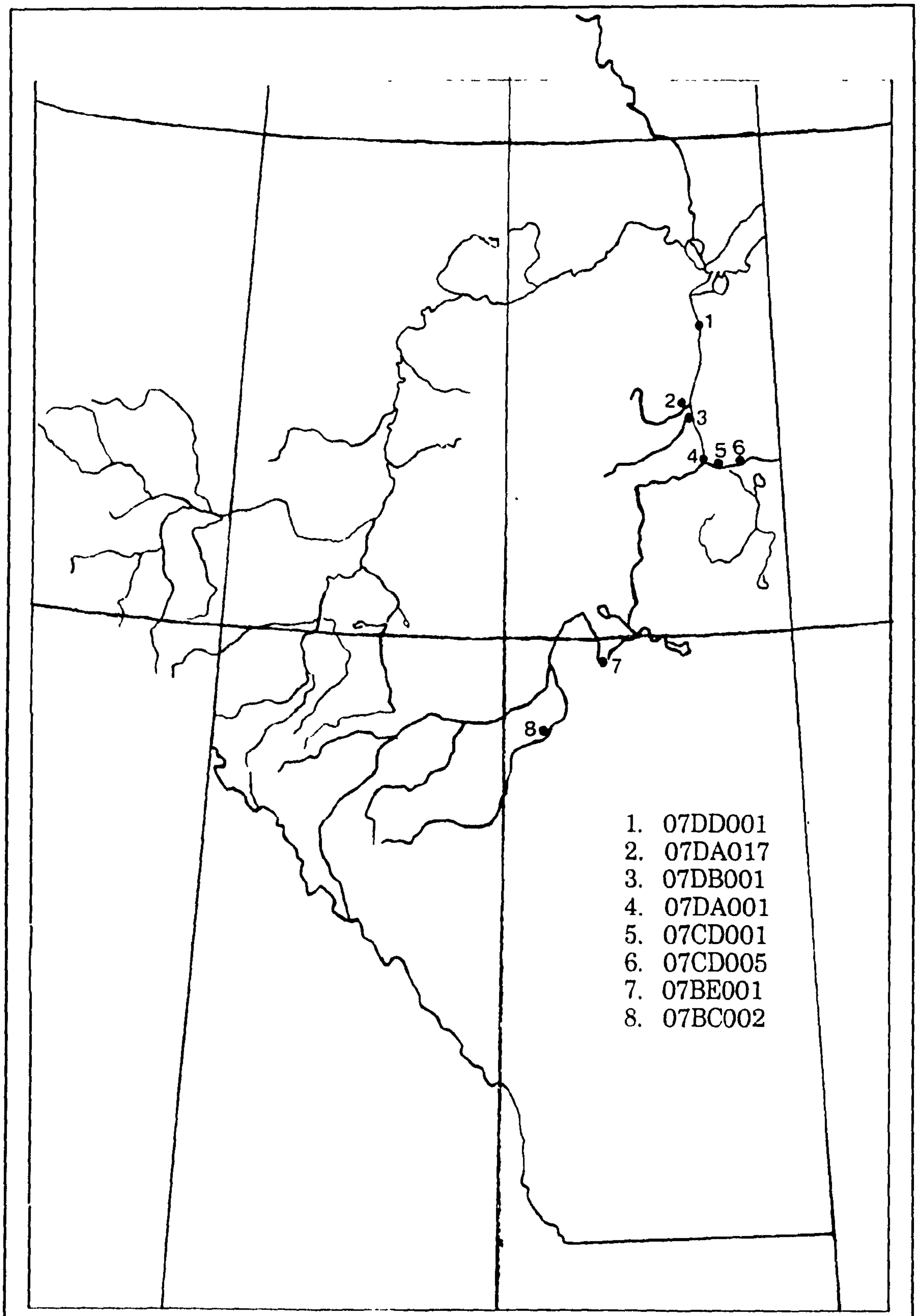


Figure 6. Alberta hydrometric stations used in the study

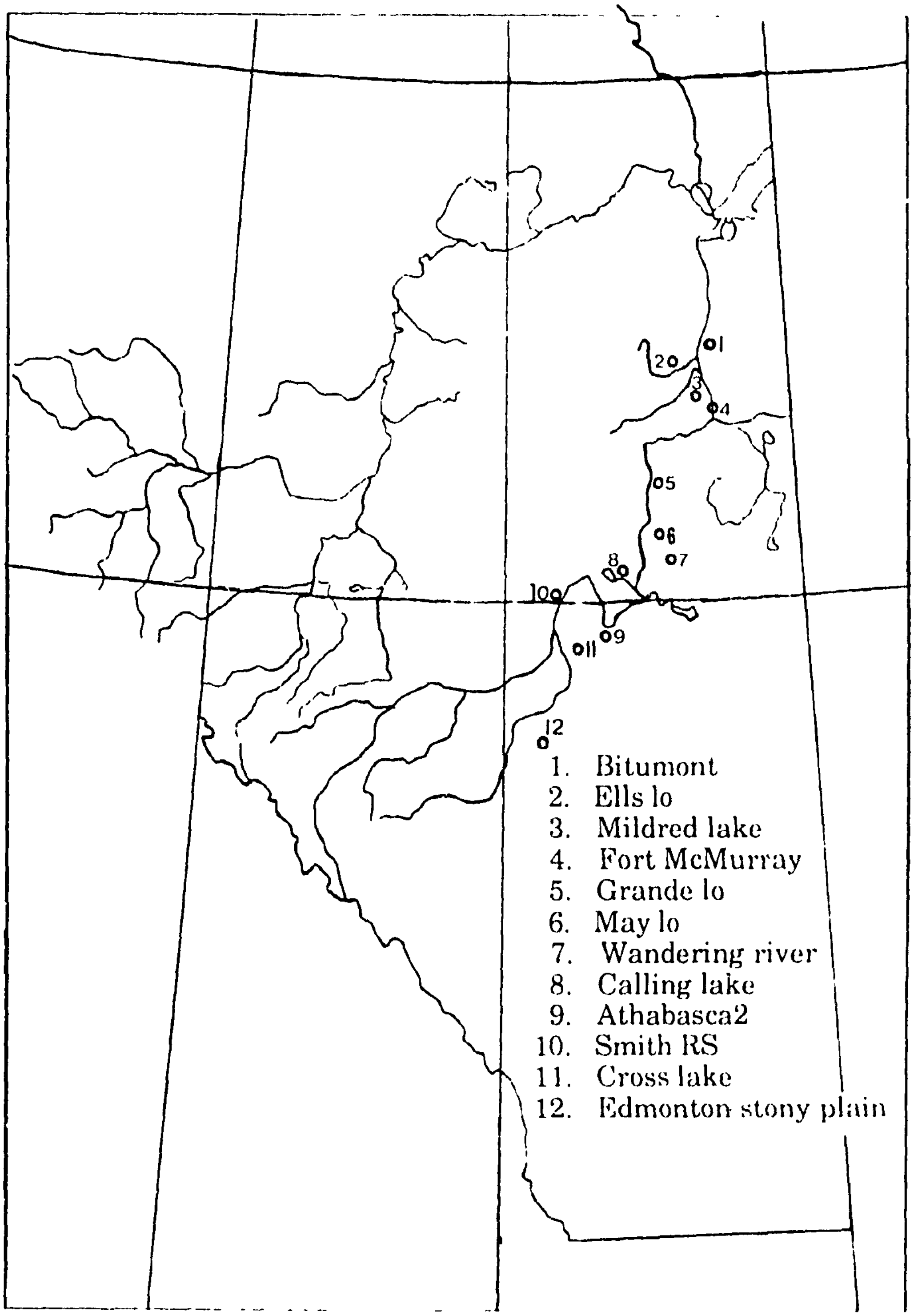


Figure 7. Alberta meteorological stations used in the study

APPENDIX II - RATING CURVES

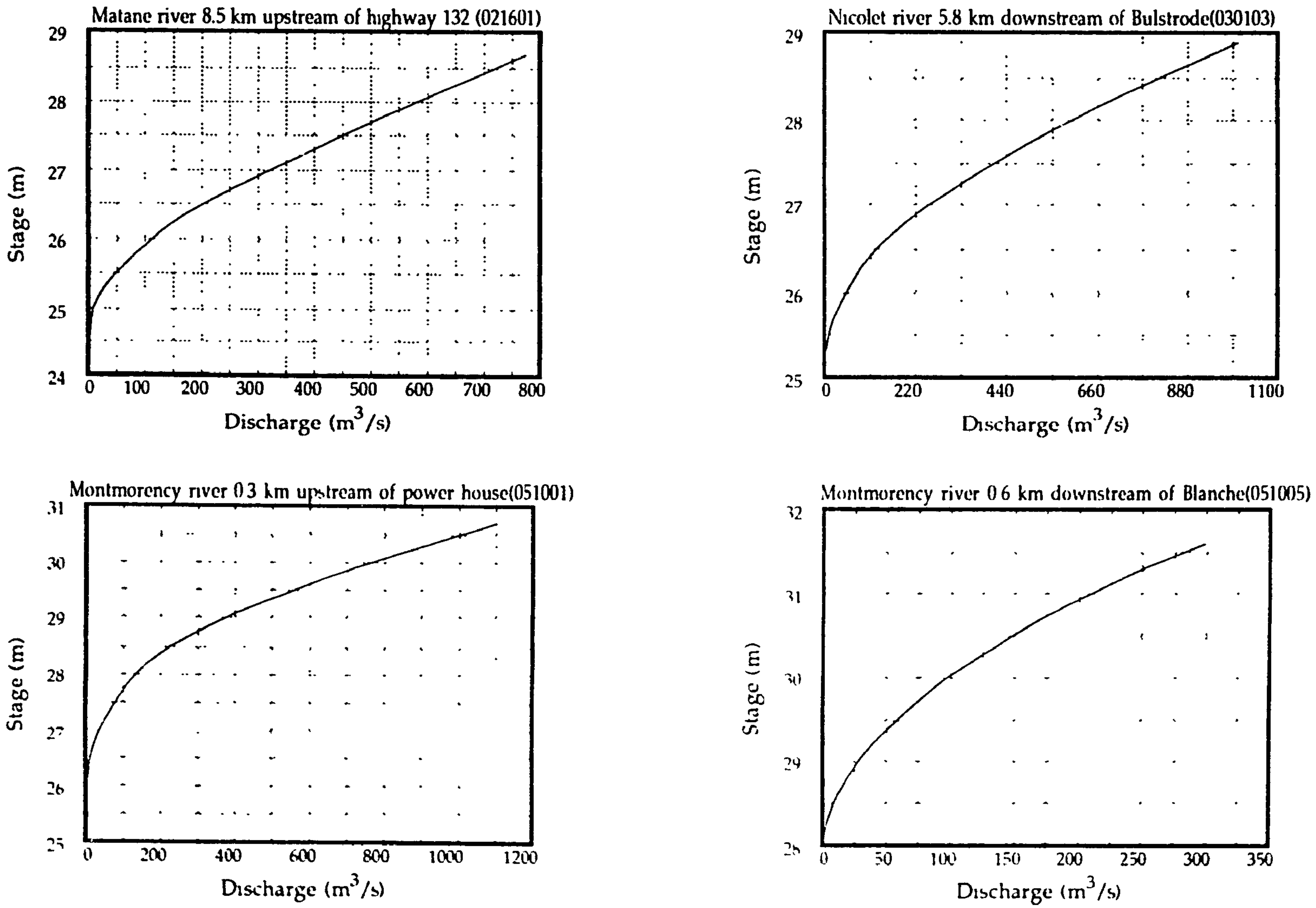


Figure 8. Rating curves for rivers and hydrometric stations in Québec

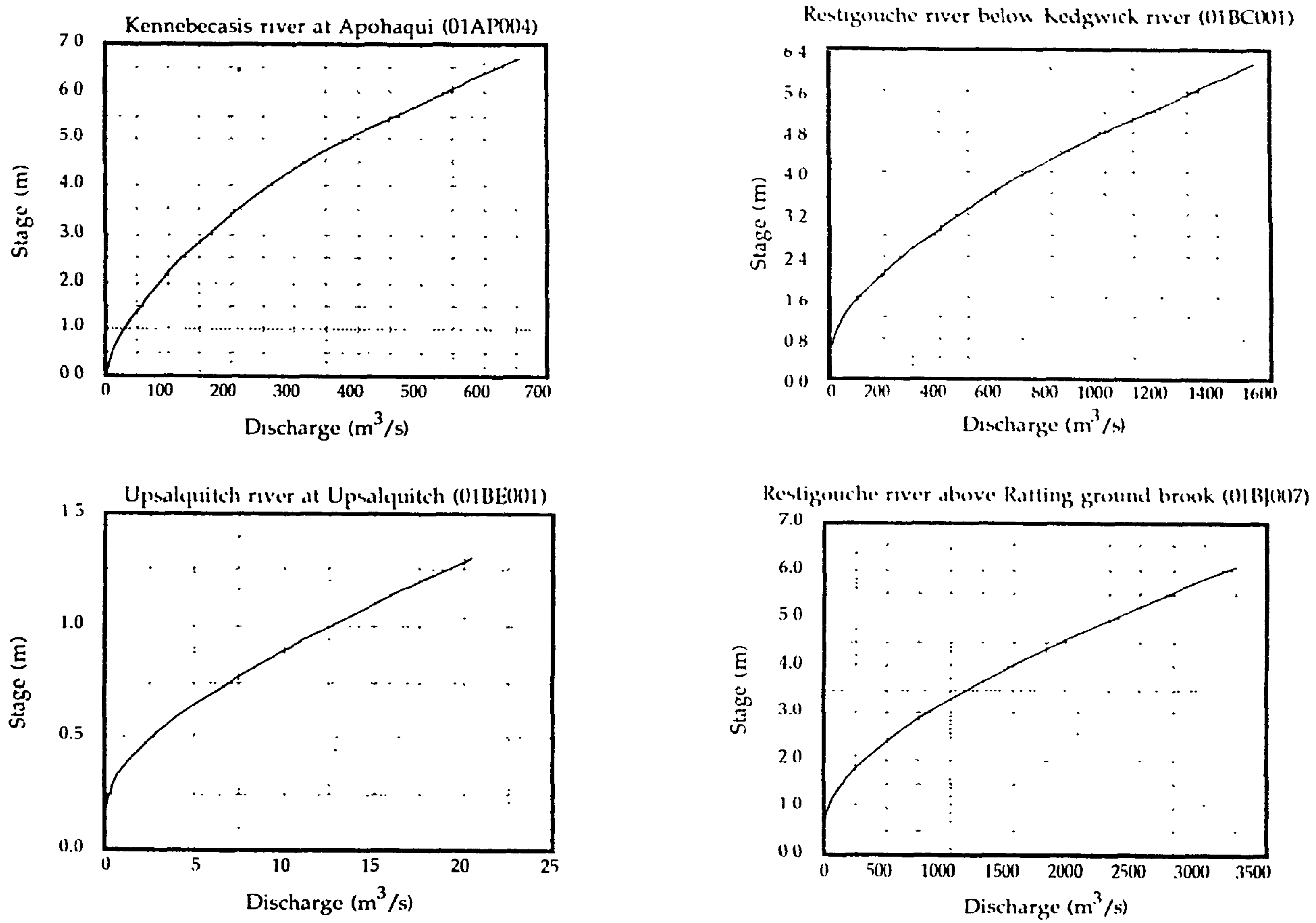


Figure 9. Rating curves for rivers and hydrometric stations in N. B.

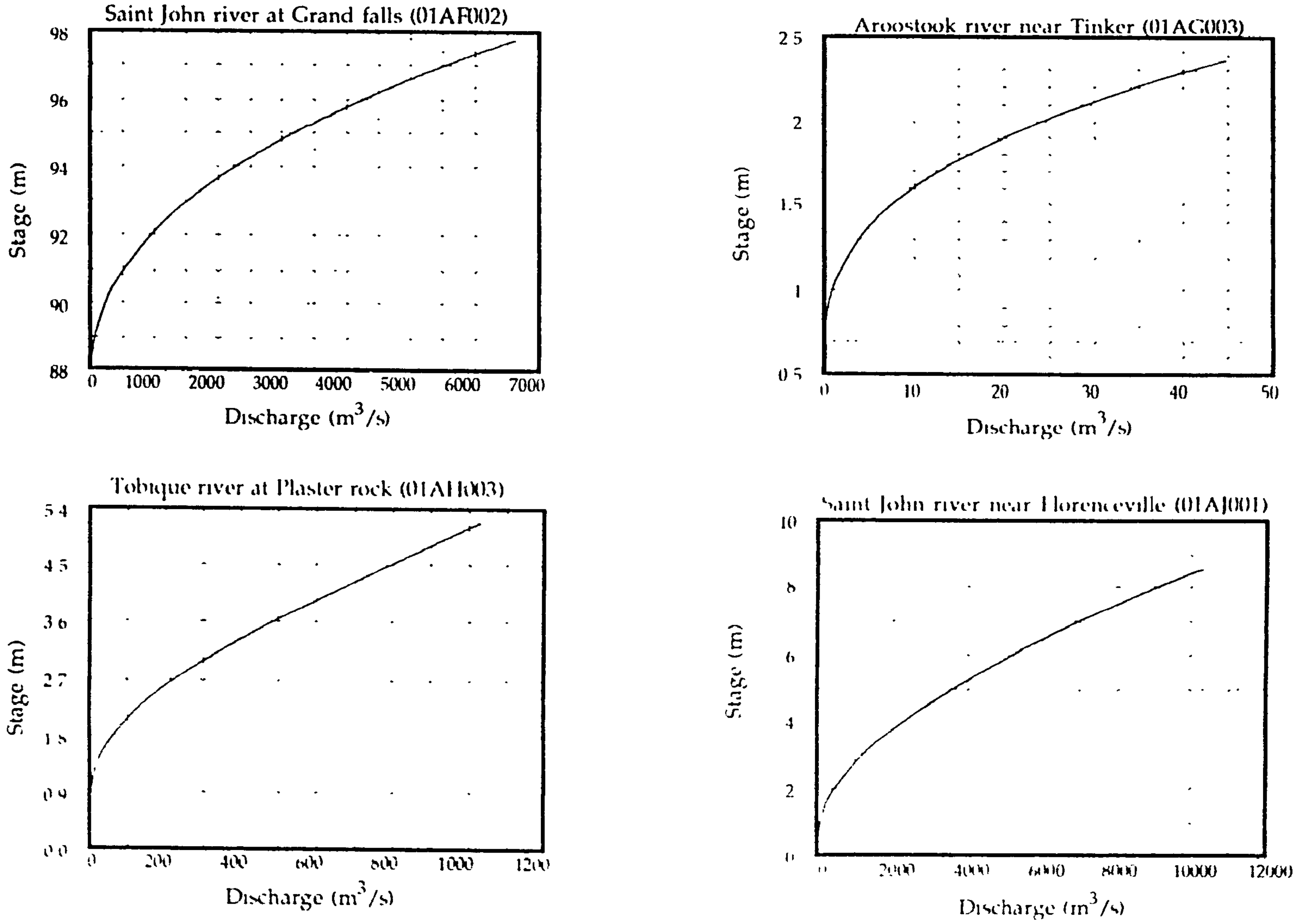


Figure 10. Rating curves for rivers and hydrometric stations in N. B.

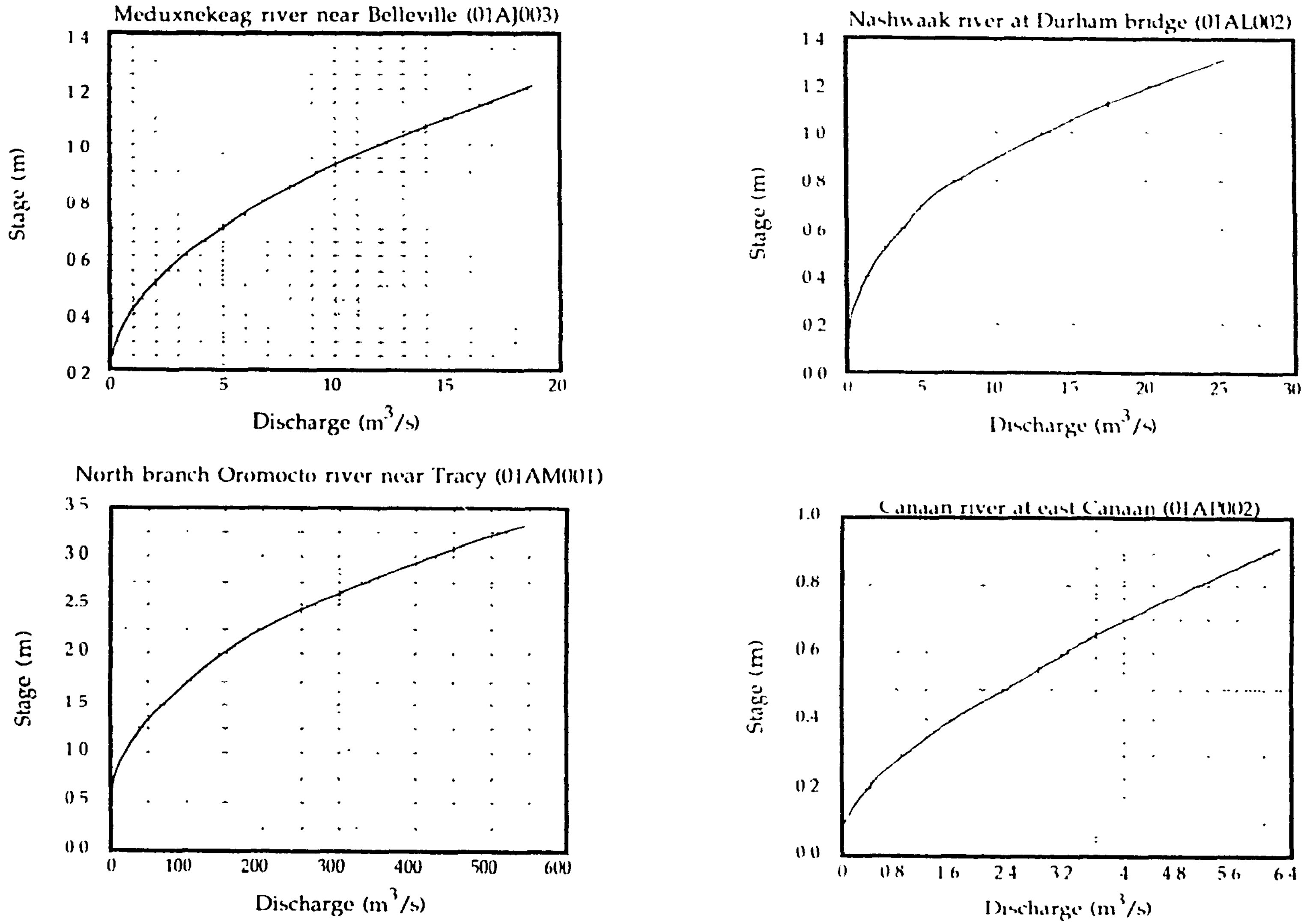


Figure 11. Rating curves for rivers and hydrometric stations in N. B.

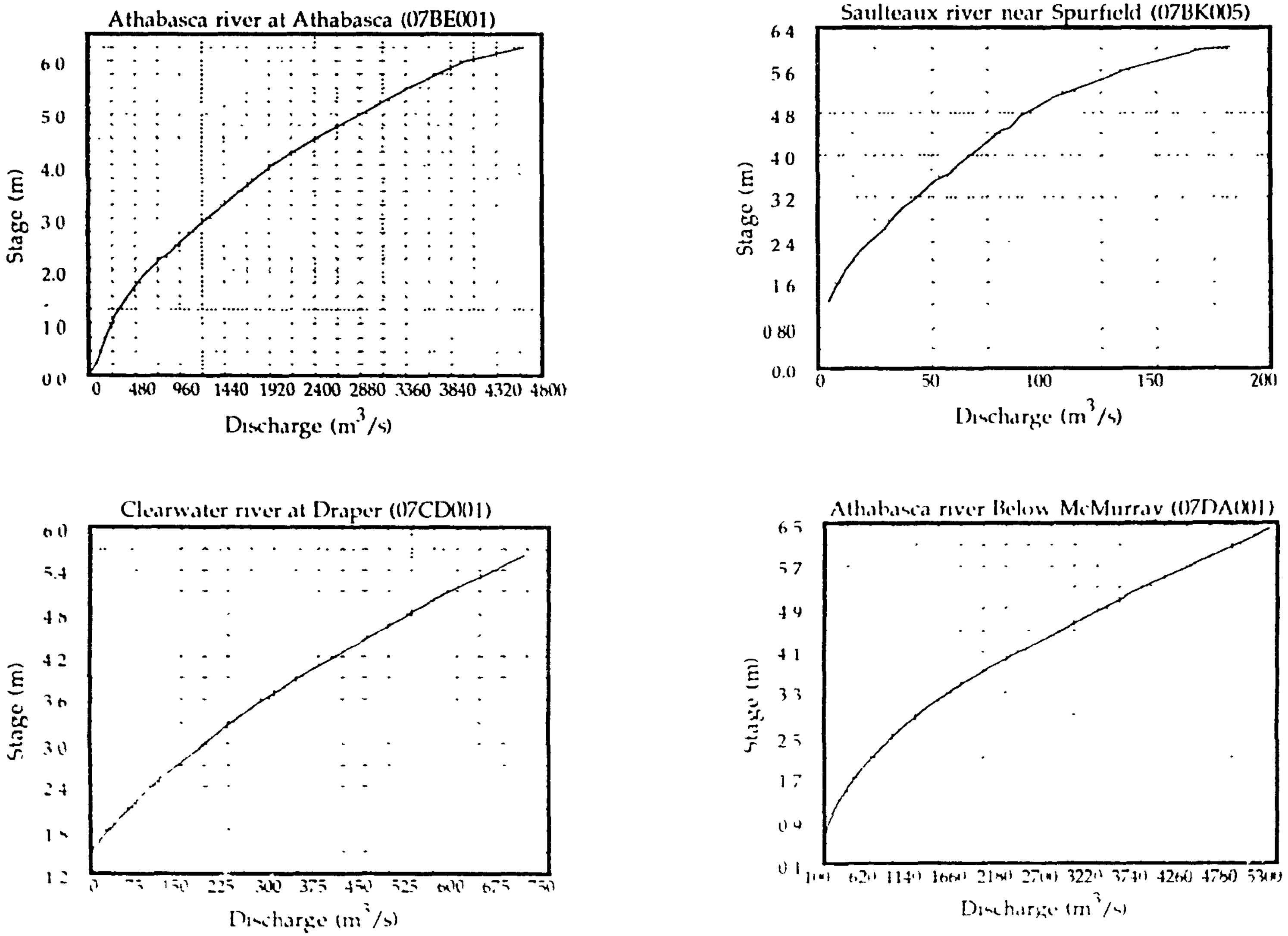


Figure 12. Rating curves for rivers and hydrometric stations in Alberta

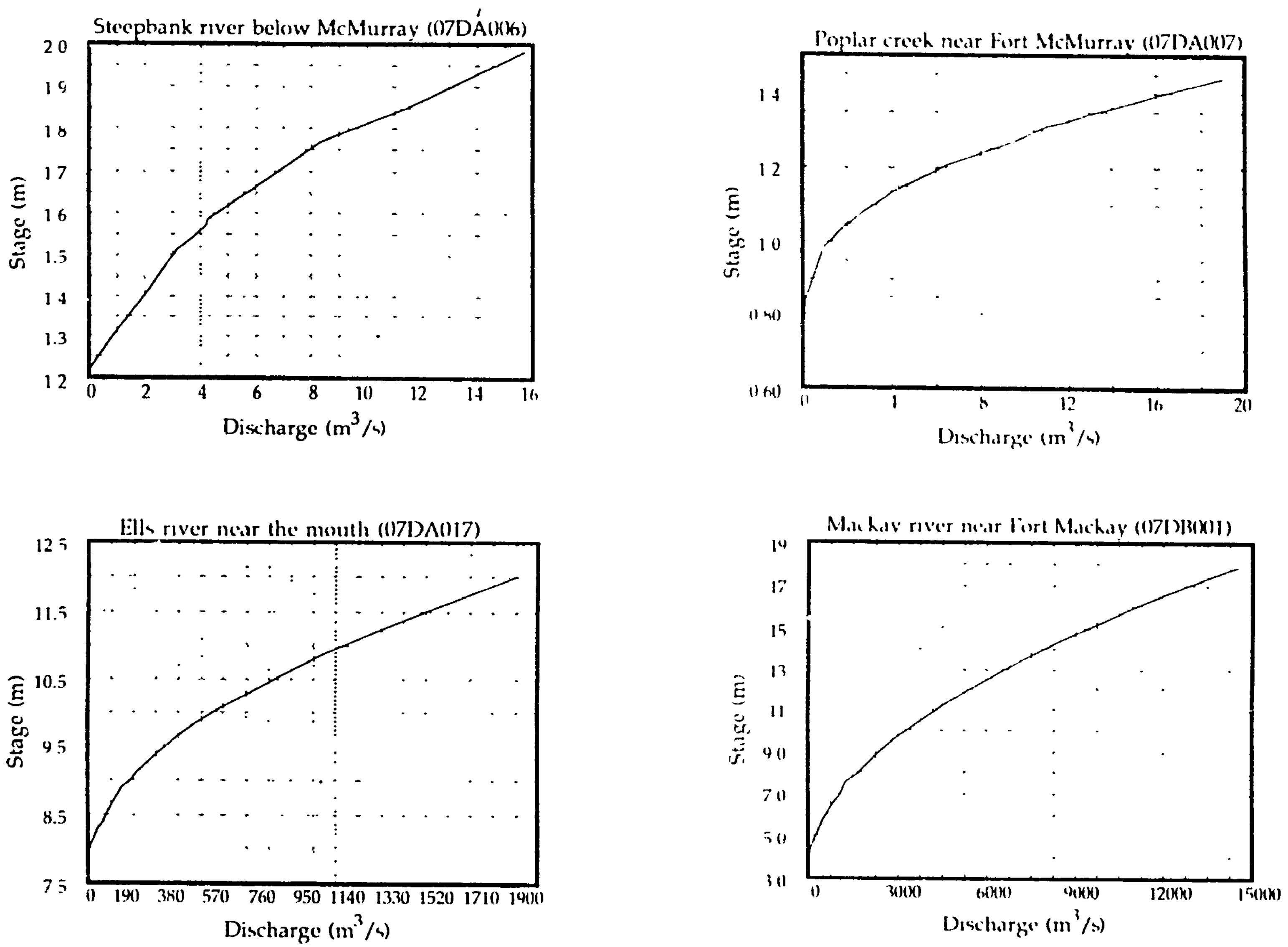


Figure 13. Rating curves for rivers and hydrometric stations in Alberta.

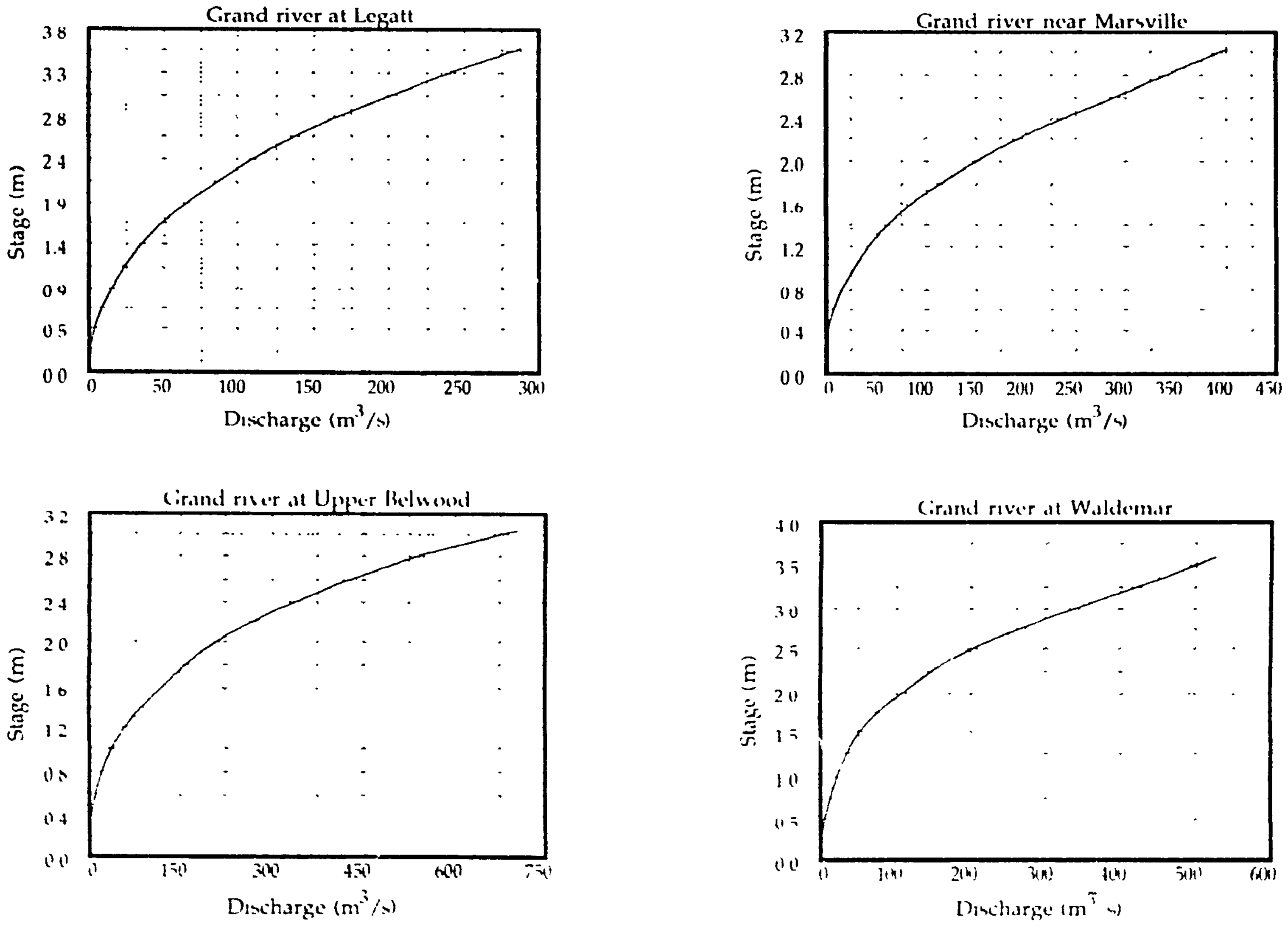


Figure 1.4. Rating curves for Grand river hydrometric stations in Southern Ontario.

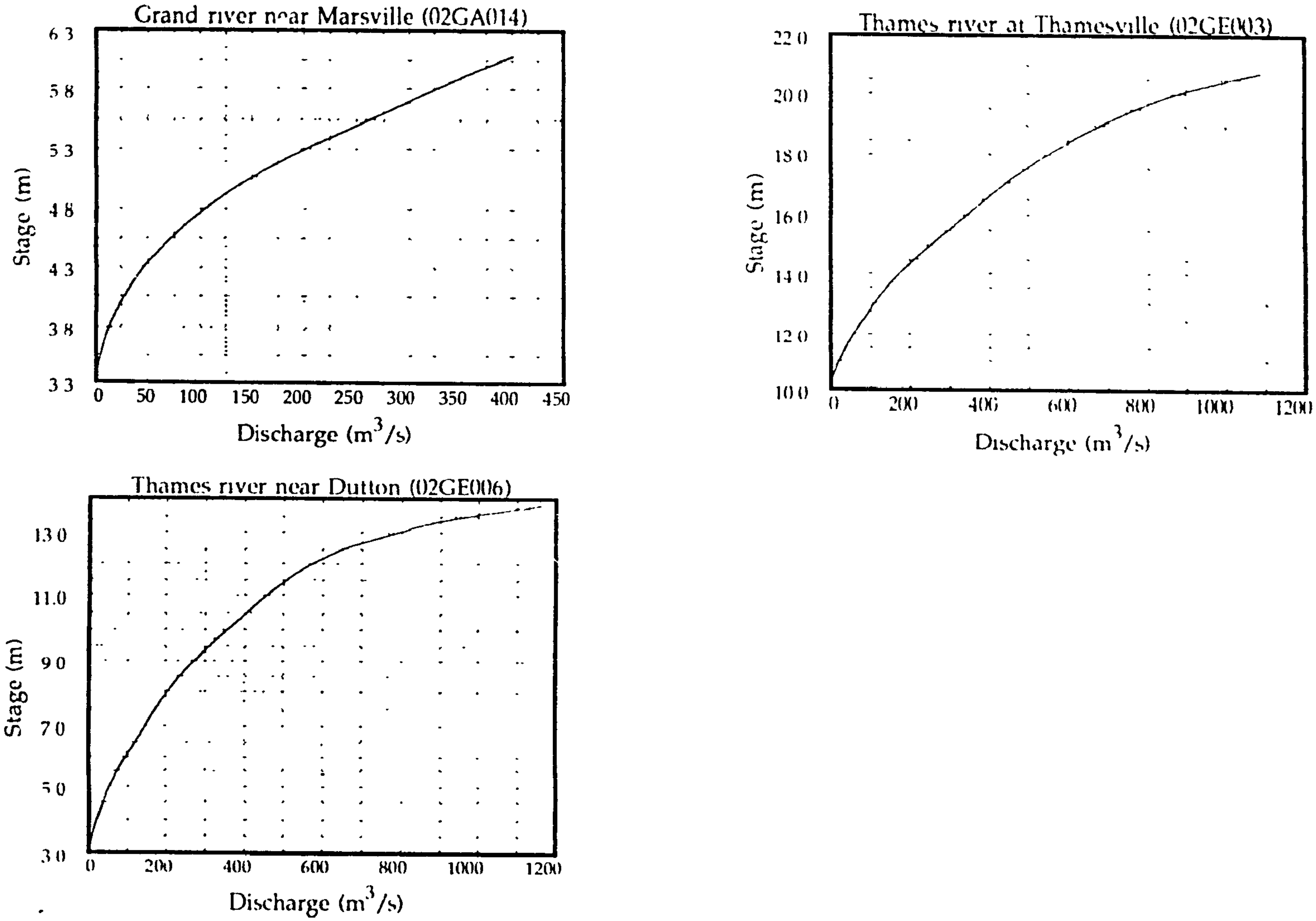


Figure 15. Rating curves for Grand river and Thames river hydrometric stations .

APPENDIX III

PRESENTATTION OF TIME SERIES DATA

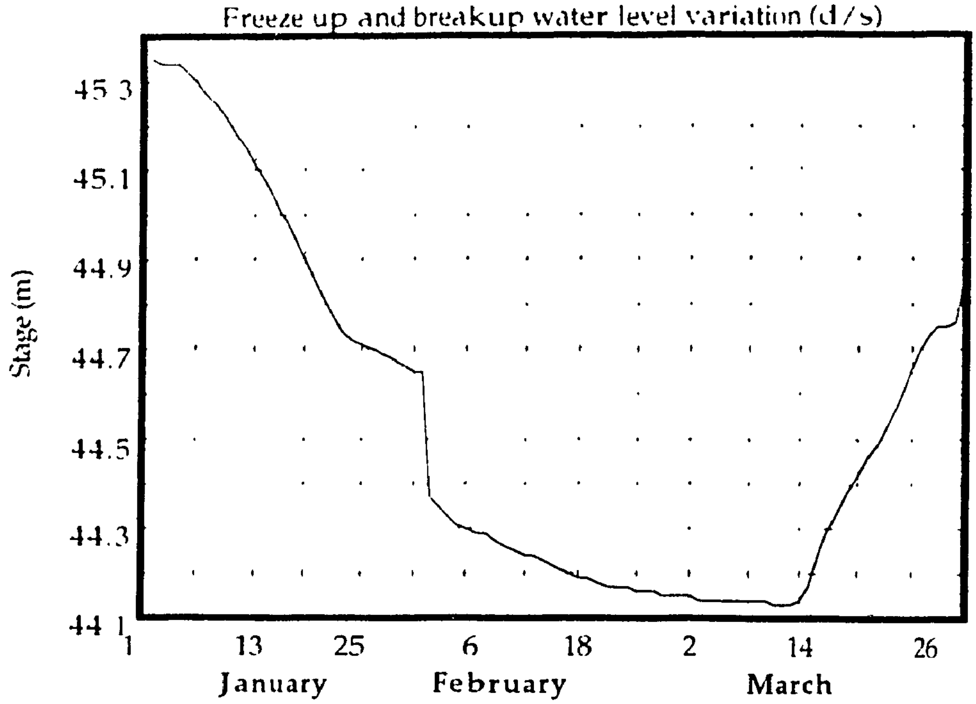


Figure 16. Freeze up and breakup daily water level variation at downstream hydrometric station for 30/3/82 ice jams on Grand river around Belwood crossing.

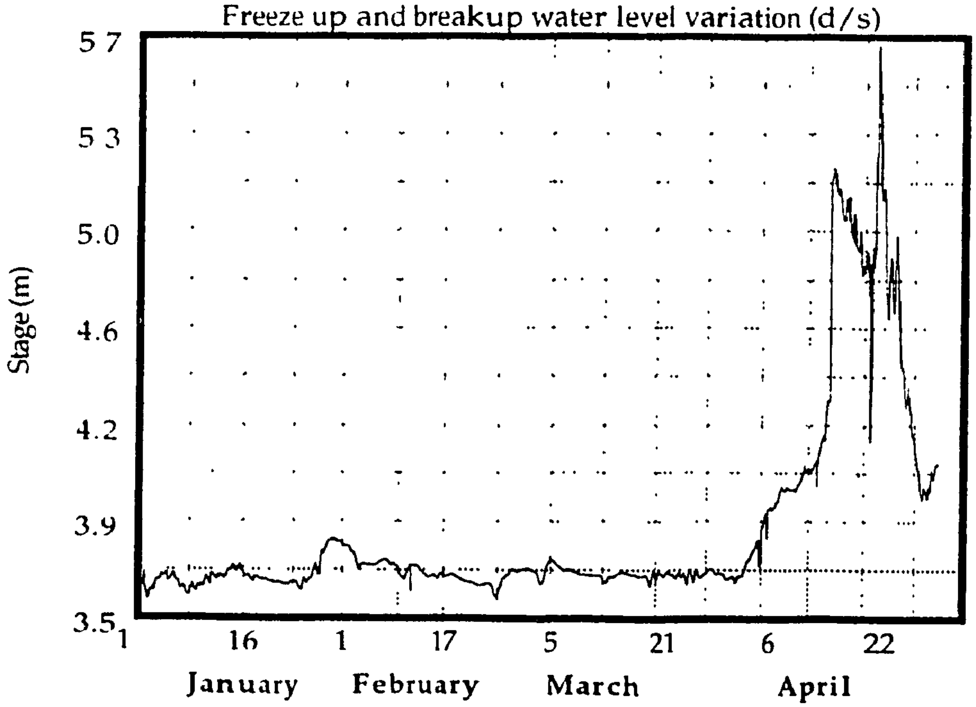


Figure 17. Freeze up and breakup water level variation at upstream hydrometric stations for 30/3/82 ice jams on Grand river at the vicinity of Marsville bridge and 2nd crossing.

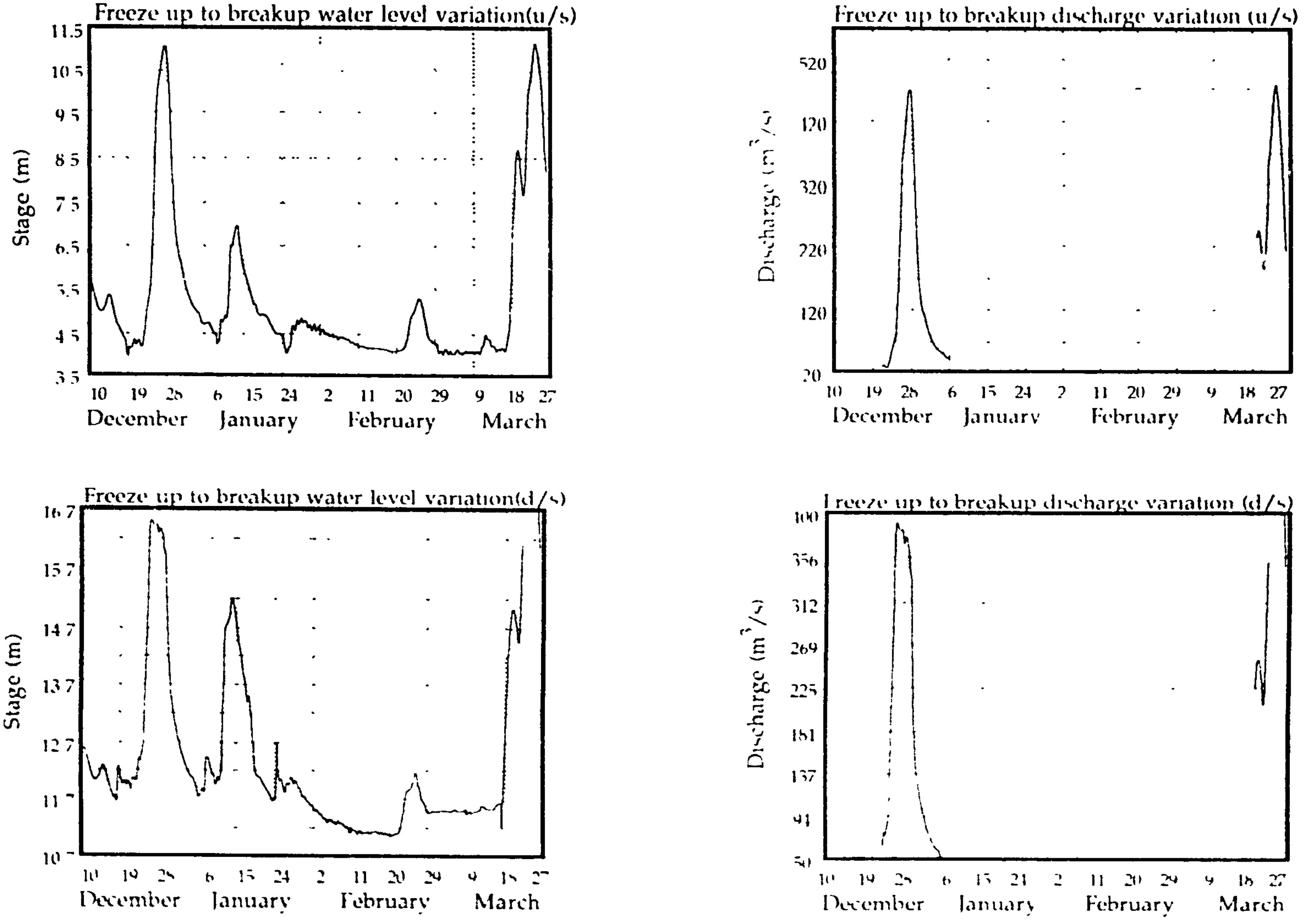
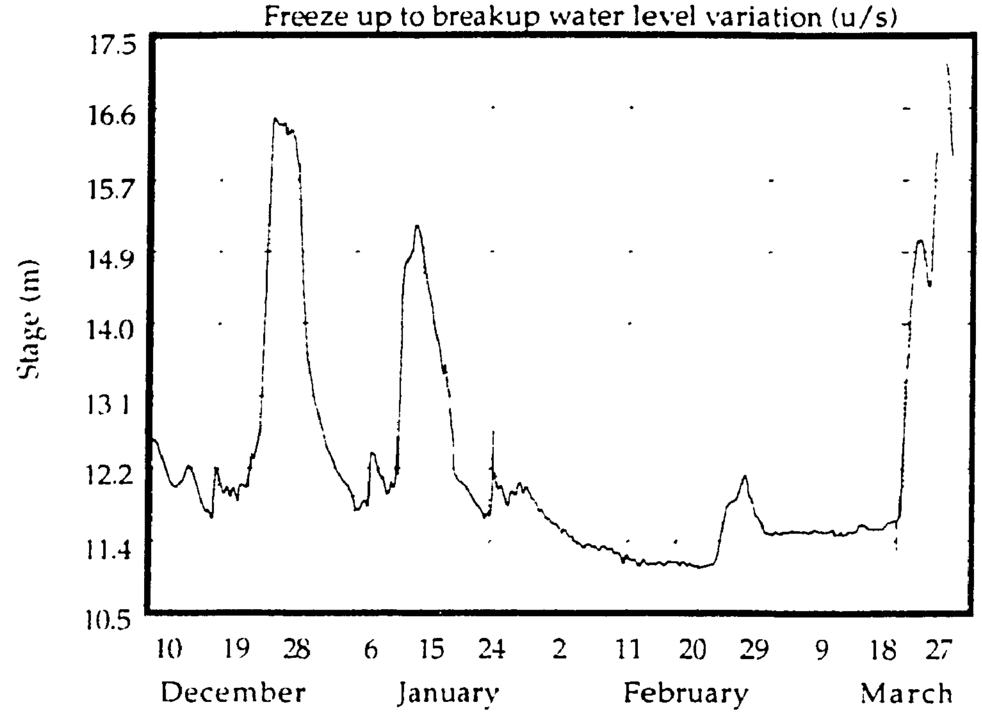


Figure 18. Freeze up water level and discharge variation at upstream and downstream hydrometric stations for 18/3/80 ice jams on Thames river upstream of Bothwell and near Fairfield museum.



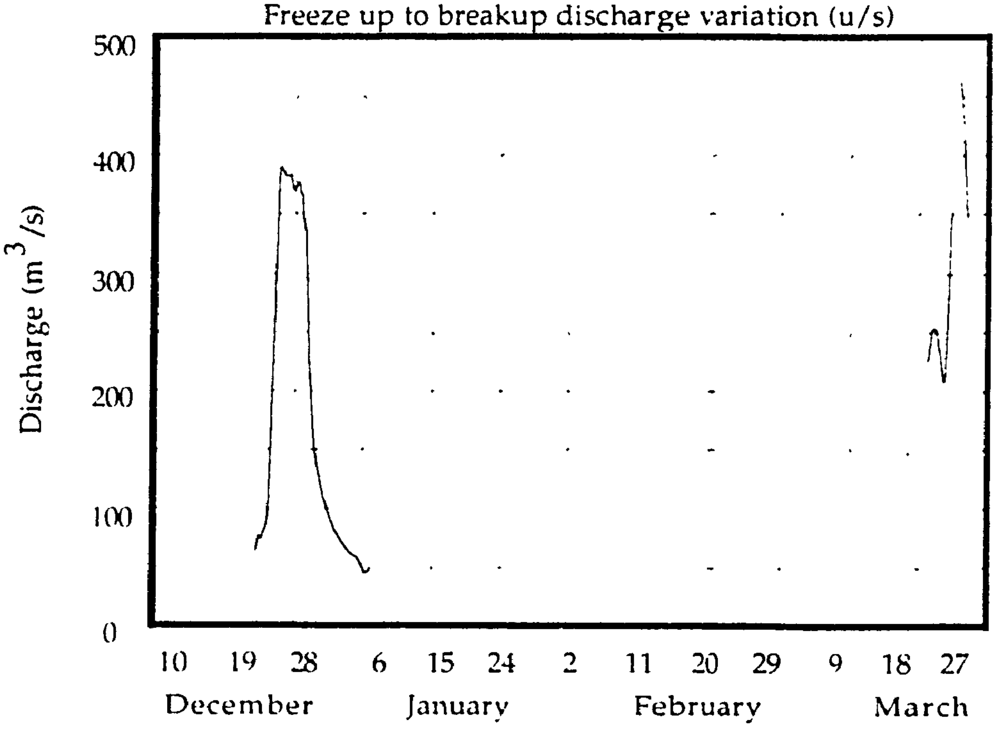
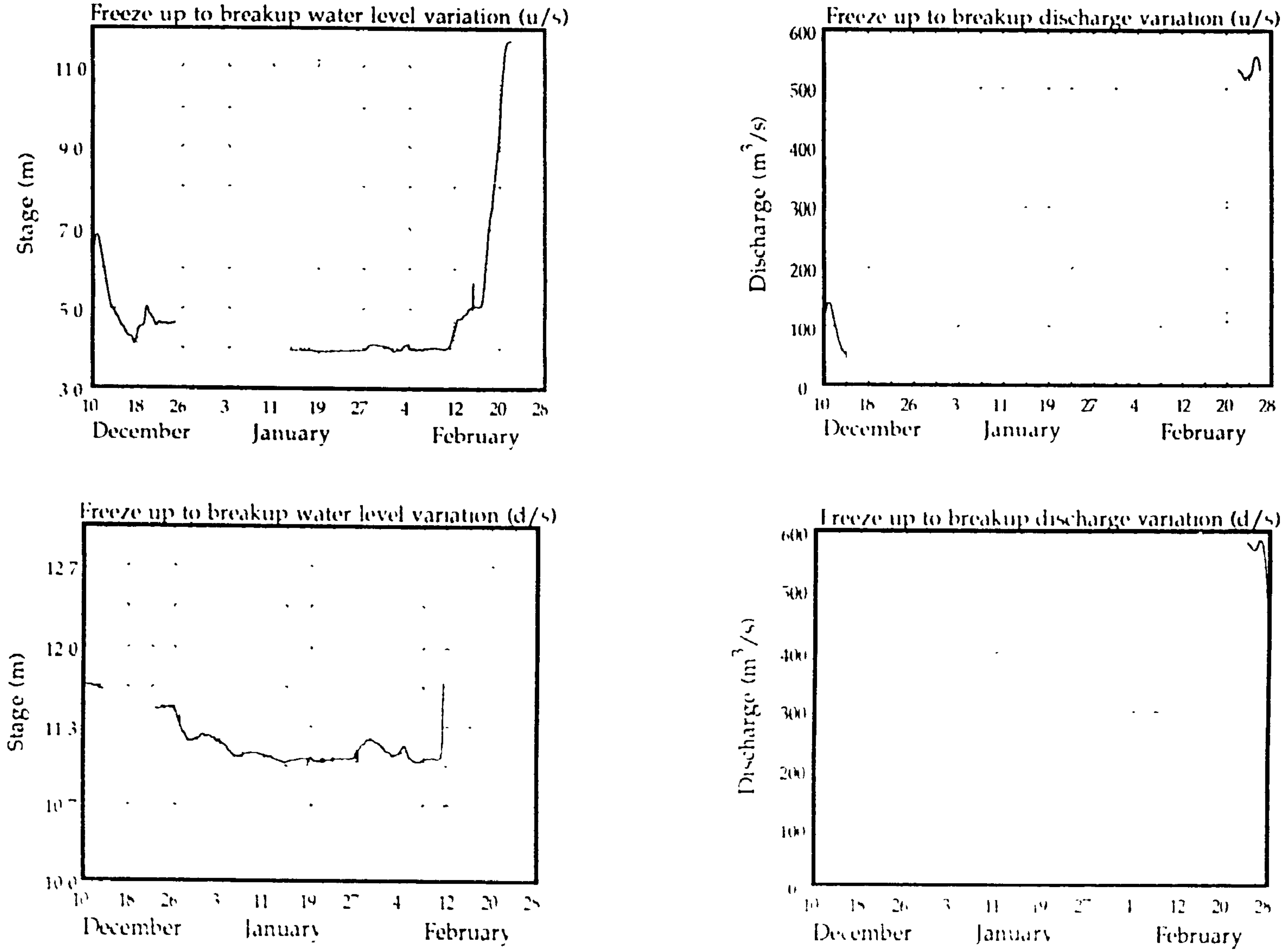


Figure 19. Freeze up and breakup water level and discharge variation at upstream hydrometric station for March 18 & 19/3/80 ice jams on Thames river at the vicinity of Kent bridge and Sherman Brown bridge.



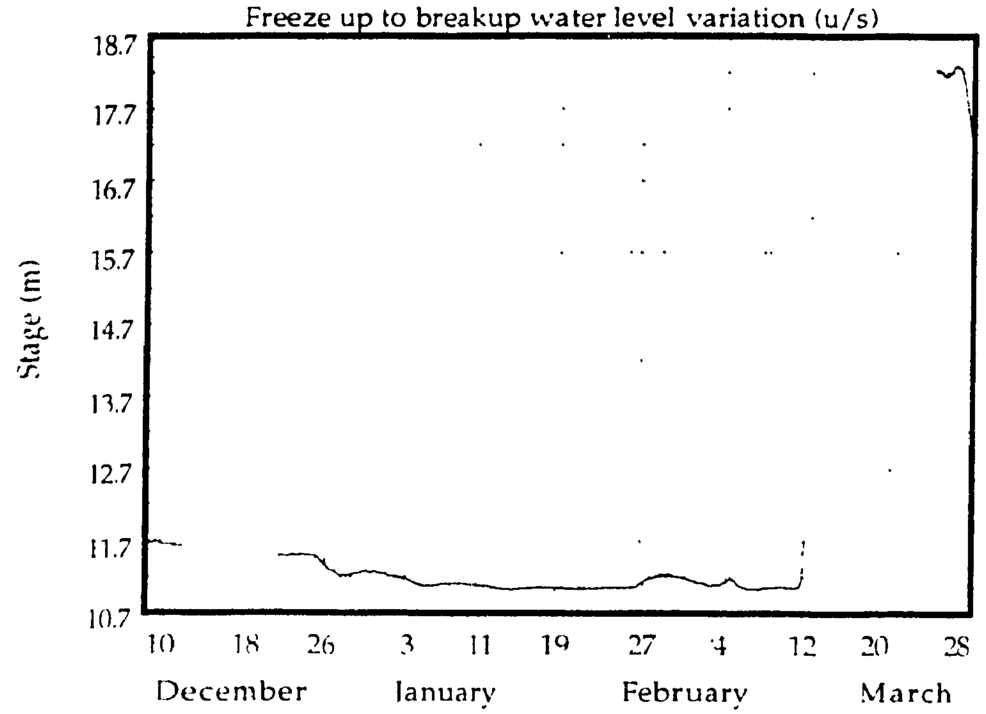
Freeze up to breakup water level variation (u/s)

Freeze up to breakup discharge variation (u/s)

Freeze up to breakup water level variation (d/s)

Freeze up to breakup discharge variation (d/s)

Figure 20. Freeze up water level and discharge variation at upstream and downstream hydrometric stations for 18/2/81 ice jam on Thames river near Fairfield museum.



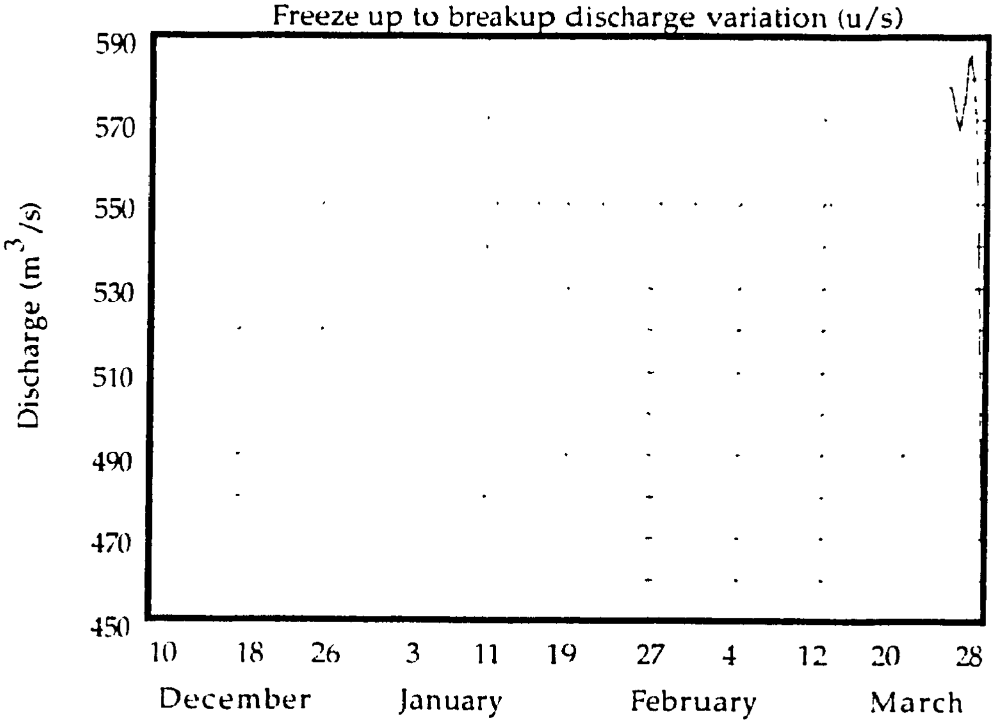


Figure 21. Freeze up and breakup water level and discharge variation at upstream hydrometric station for 19 & 20 /2/81 ice jams on Thames river at Kent bridge, near golf course and Louisville.

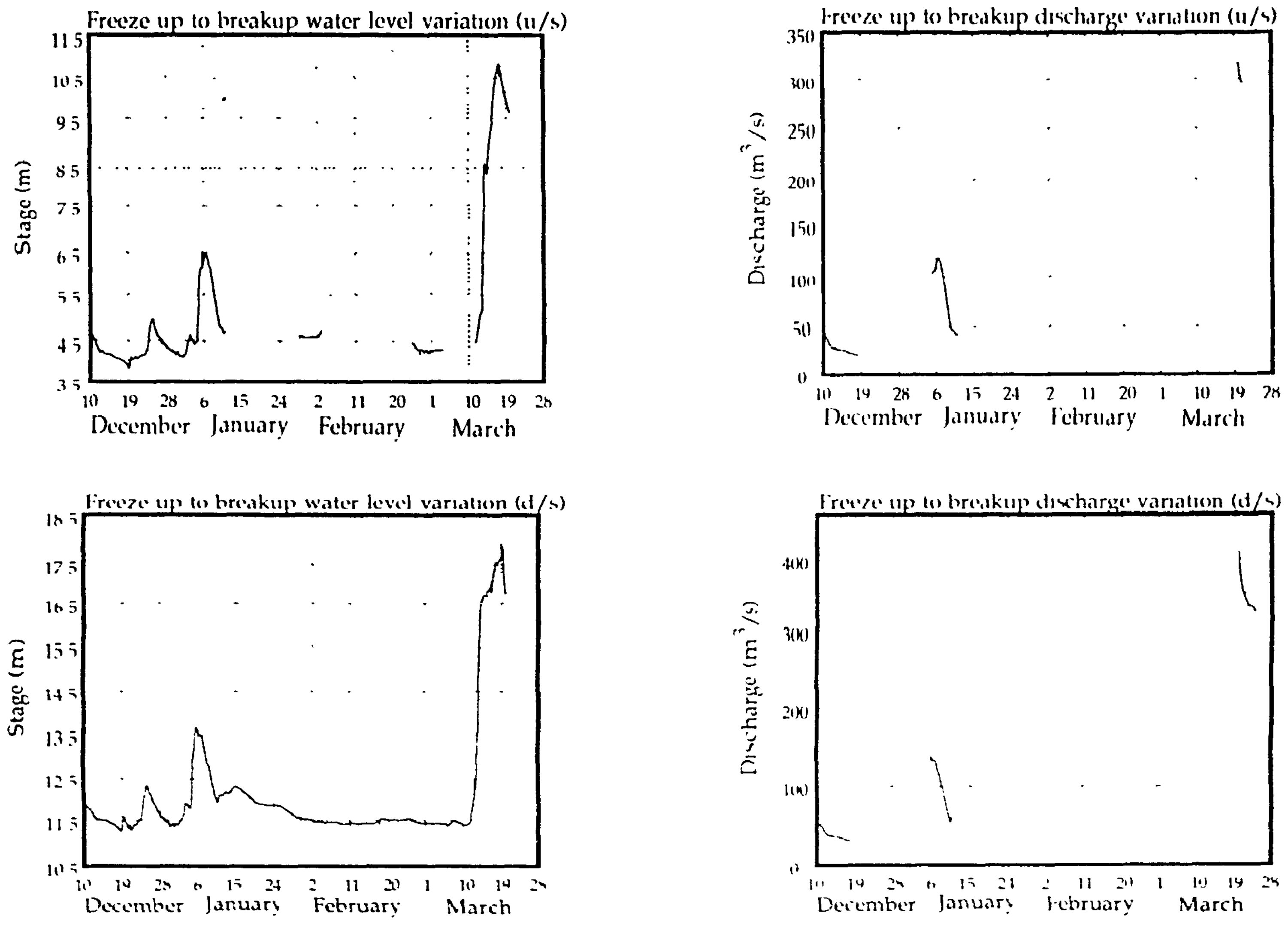
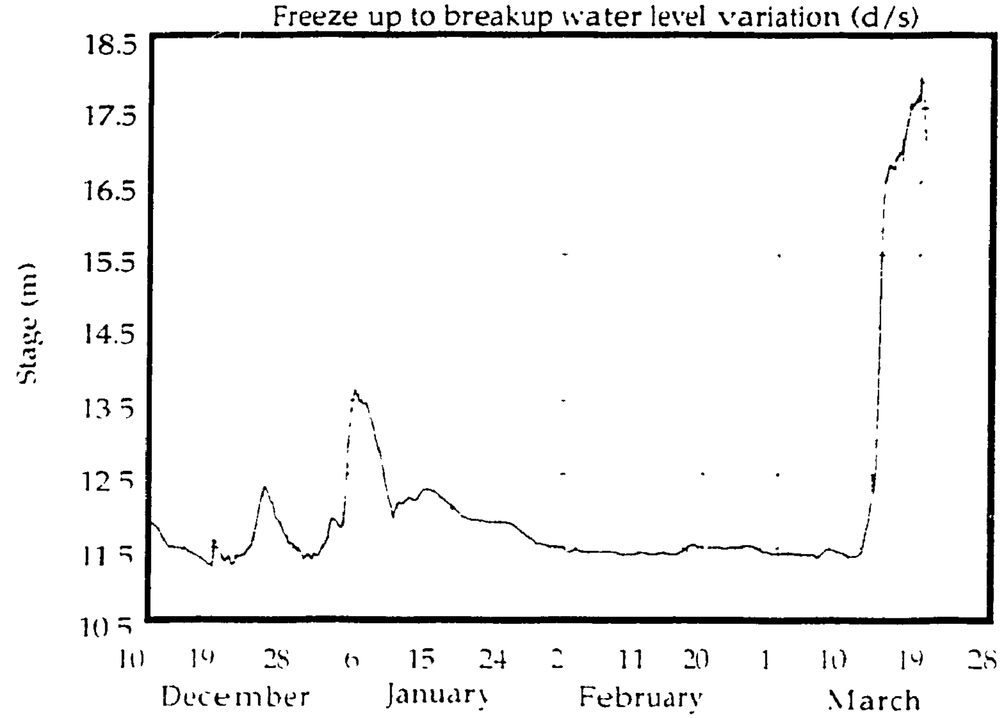


Figure 22. Freeze up and breakup water level and discharge variation at upstream and downstream hydrometric stations for 13 /3/82 ice jam on Thames river near Fairfield museum.



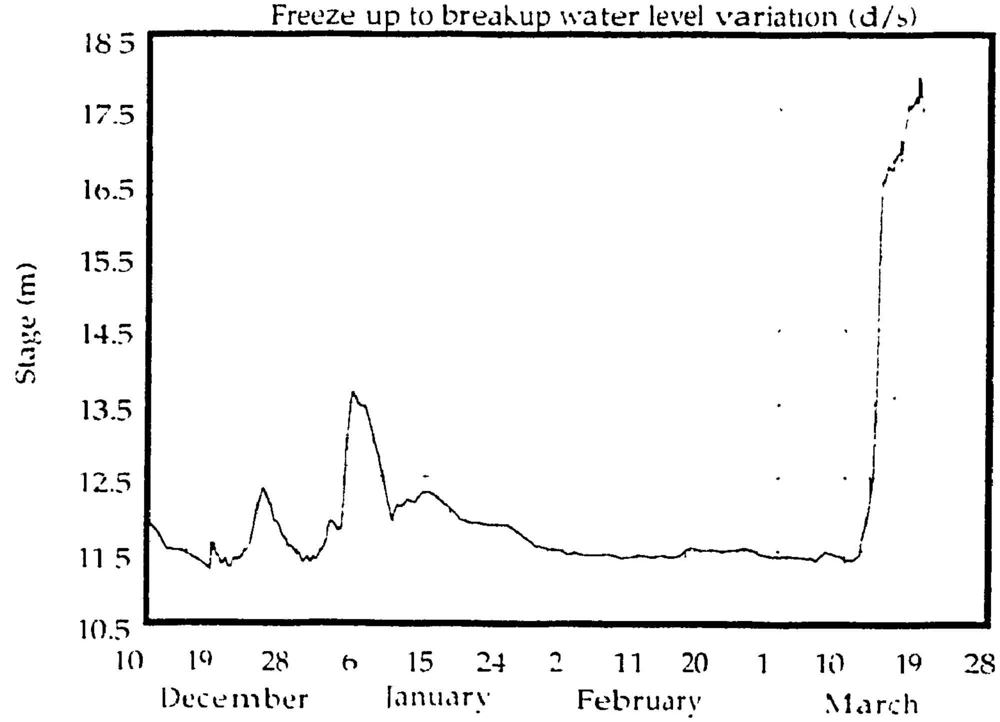


Figure 23. Freeze up and breakup water level and discharge variation at upstream hydrometric station for 16, 18 and 19/3/82 ice jams on Thames river near Louisville and at the vicinity of Kent bridge.

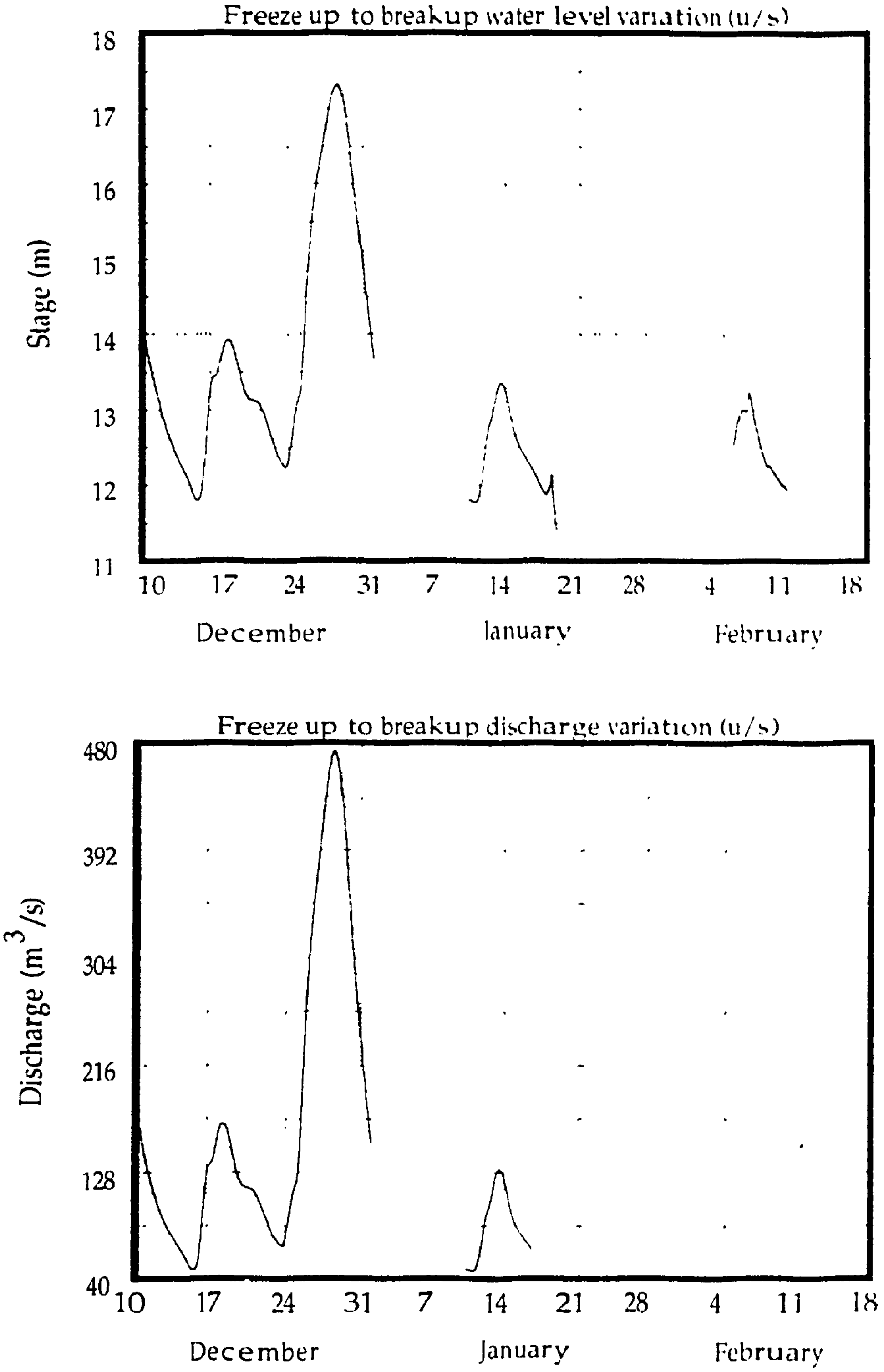


Figure 24. Freeze up and breakup water level and discharge variation at upstream hydrometric station for 5/2/83 ice jams on Thames river near the golf course and 6 km below Kent bridge.

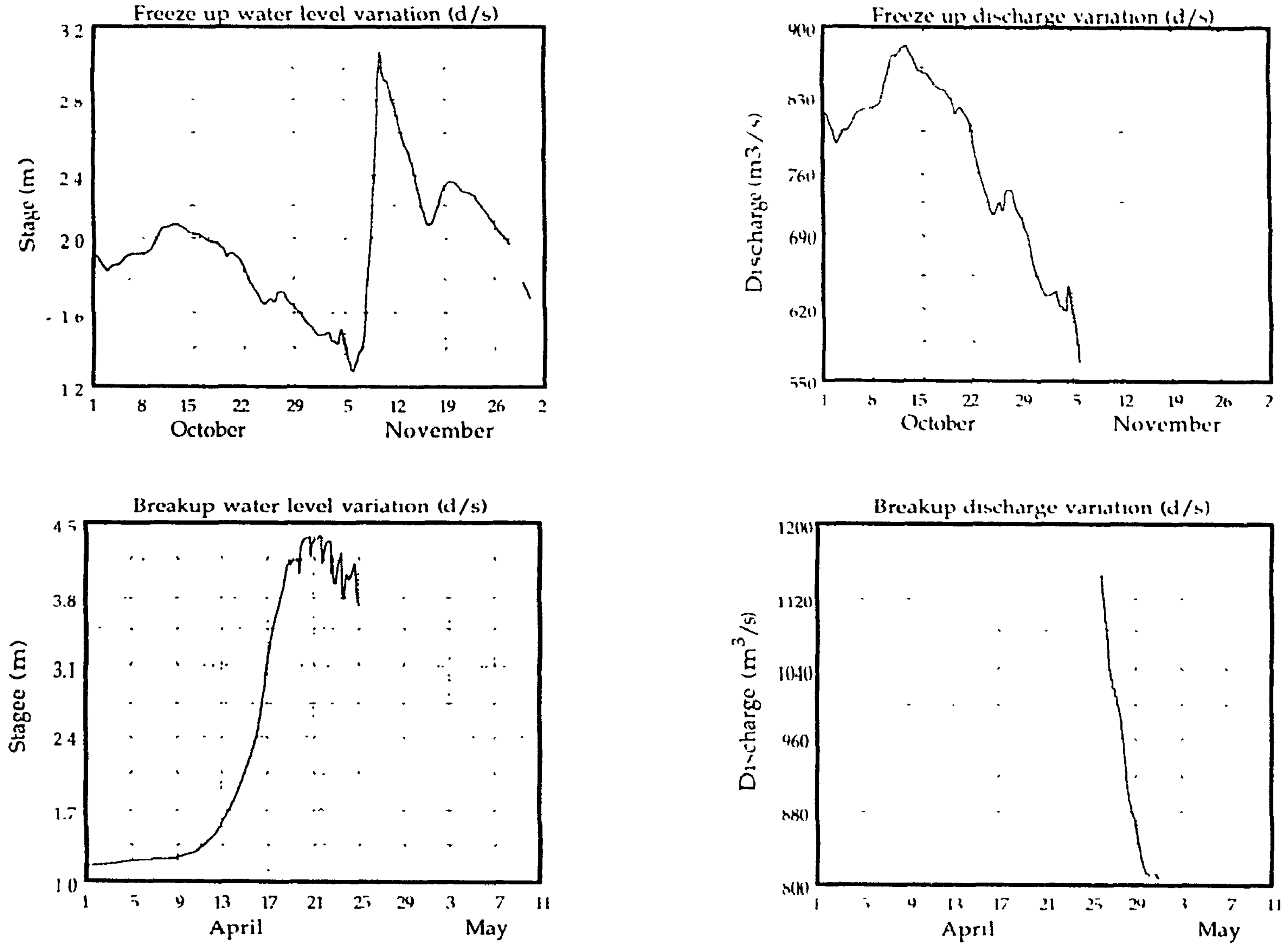


Figure 25. Freeze up and breakup water level and discharge variation at upstream and downstream hydrometric stations for 14 and 16/4/77 ice jams on Athabasca river at Poplar island, Inglis island and downstream of Ellis river.

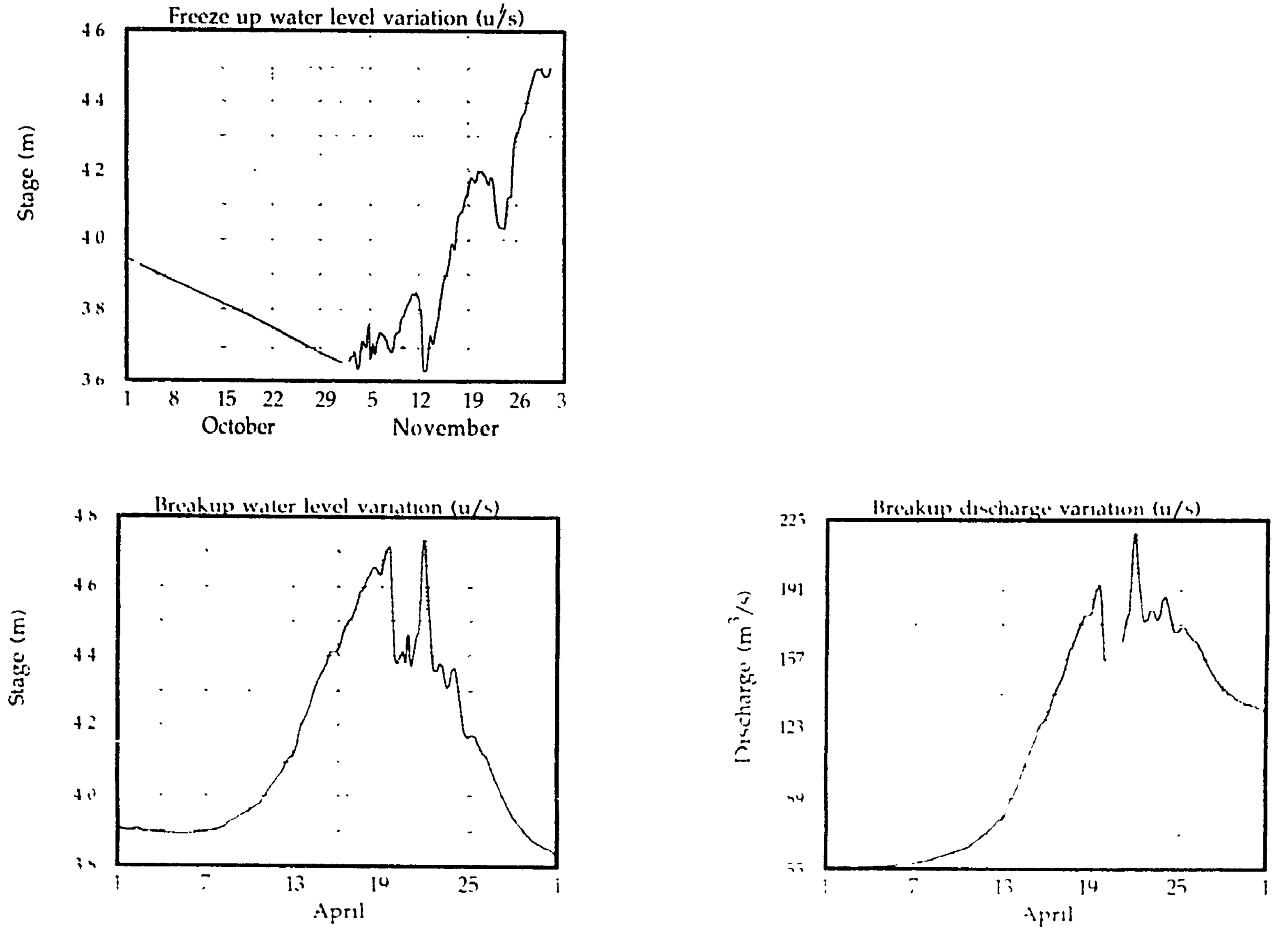


Figure 26. Freeze up and breakup water level and discharge variation at upstream hydrometric stations for 15/4/77 ice jams on Athabasca river at the mouth and downstream of Clearwater river.

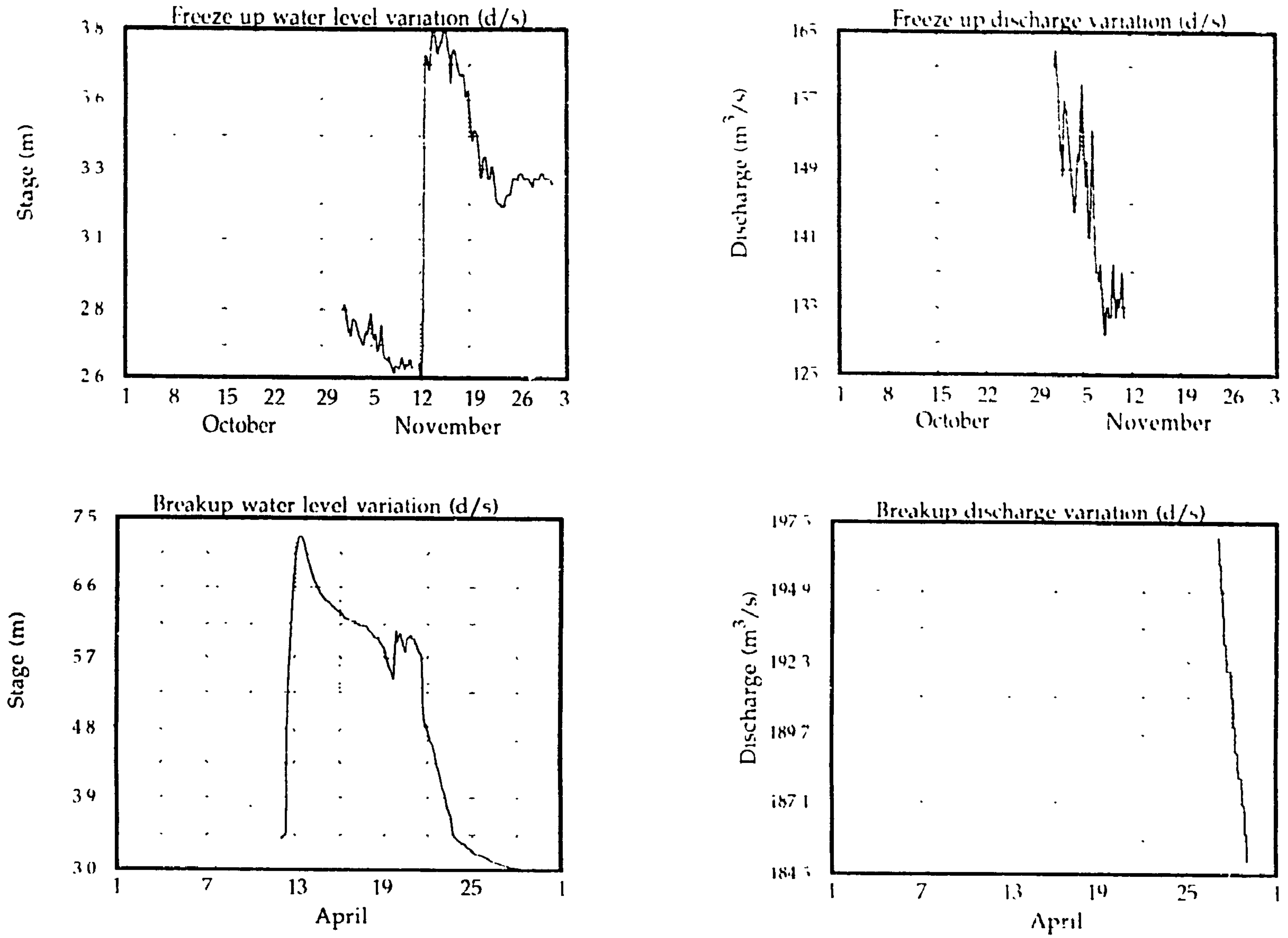


Figure 27. Freeze up and breakup water level and discharge variation at downstream hydrometric stations for 15/4/77 ice jams on Athabasca river at the mouth and downstream of Clearwater river.

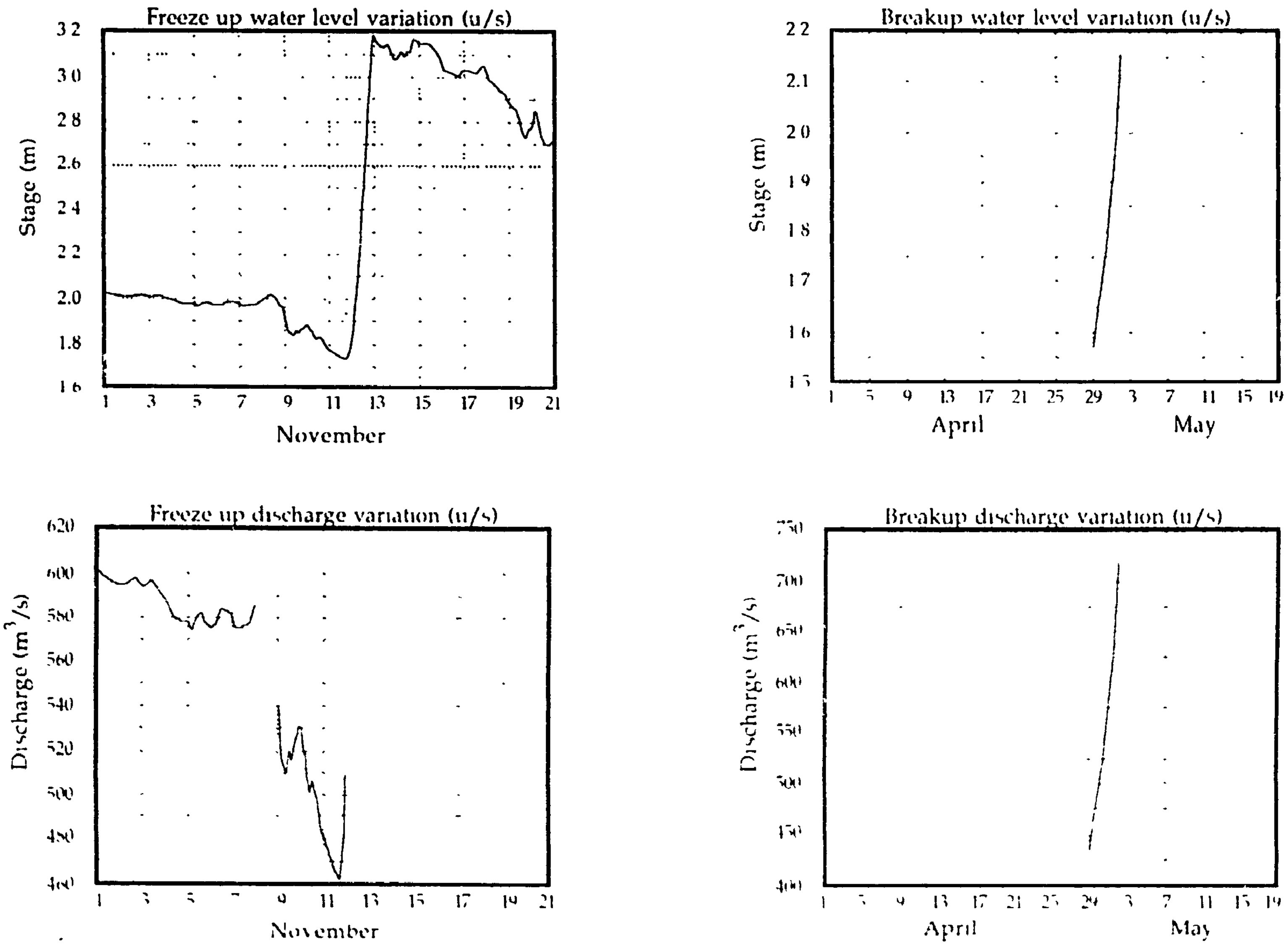


Figure 28. Freeze up and breakup water level and discharge variation at upstream hydrometric stations for 15 & 19/4/78 ice jams on Athabasca river downstream of long rapids, at Cascade rapids, upstream of Crooked rapids and MacEwan bridge.

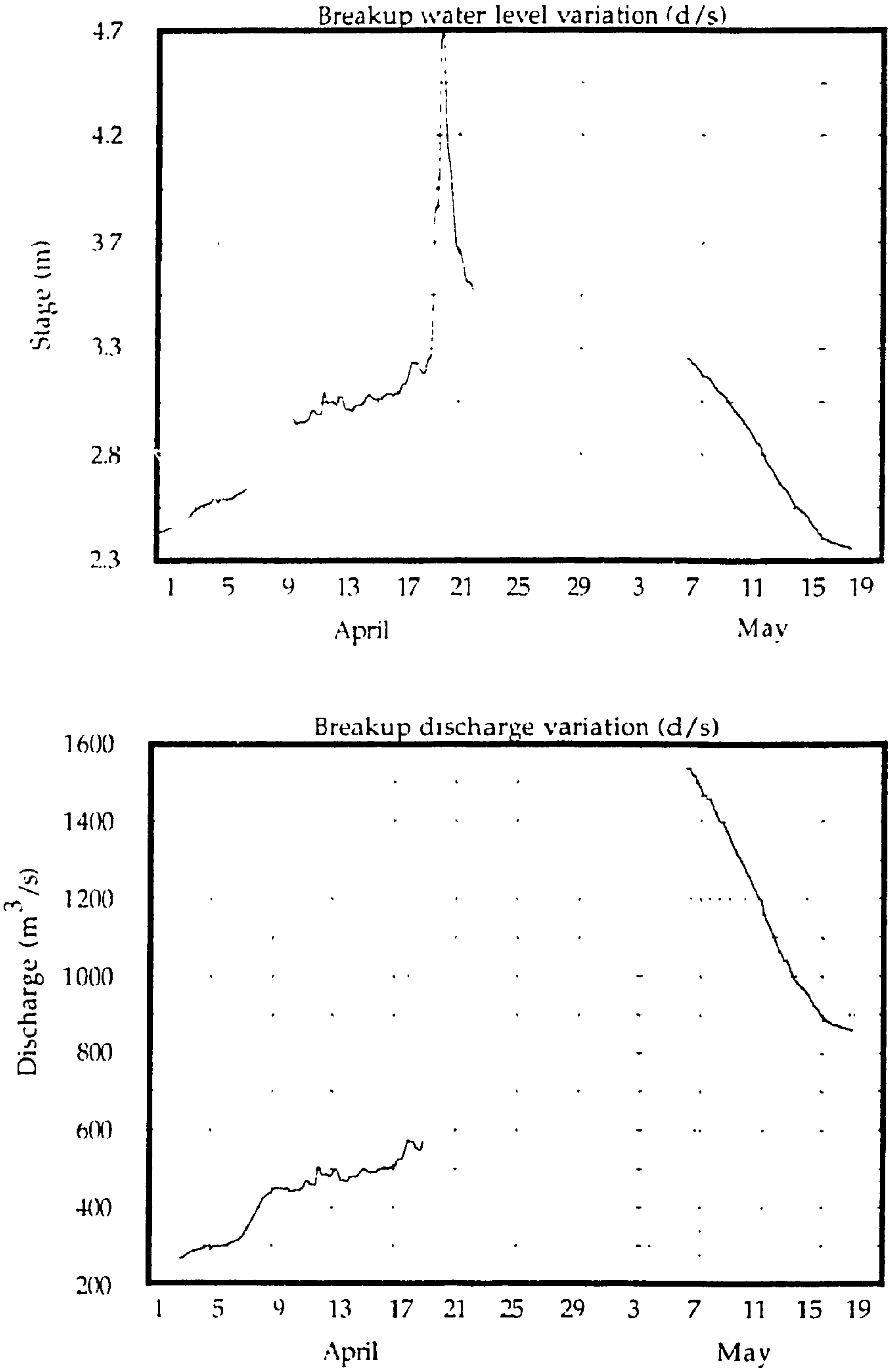


Figure 29. Freeze up and breakup water level and discharge variation at downstream hydrometric stations for 15 & 19/4/78 ice jams on Athabasca river downstream of long rapids, at Cascade rapids, upstream of Crooked rapids and MacEwan bridge.

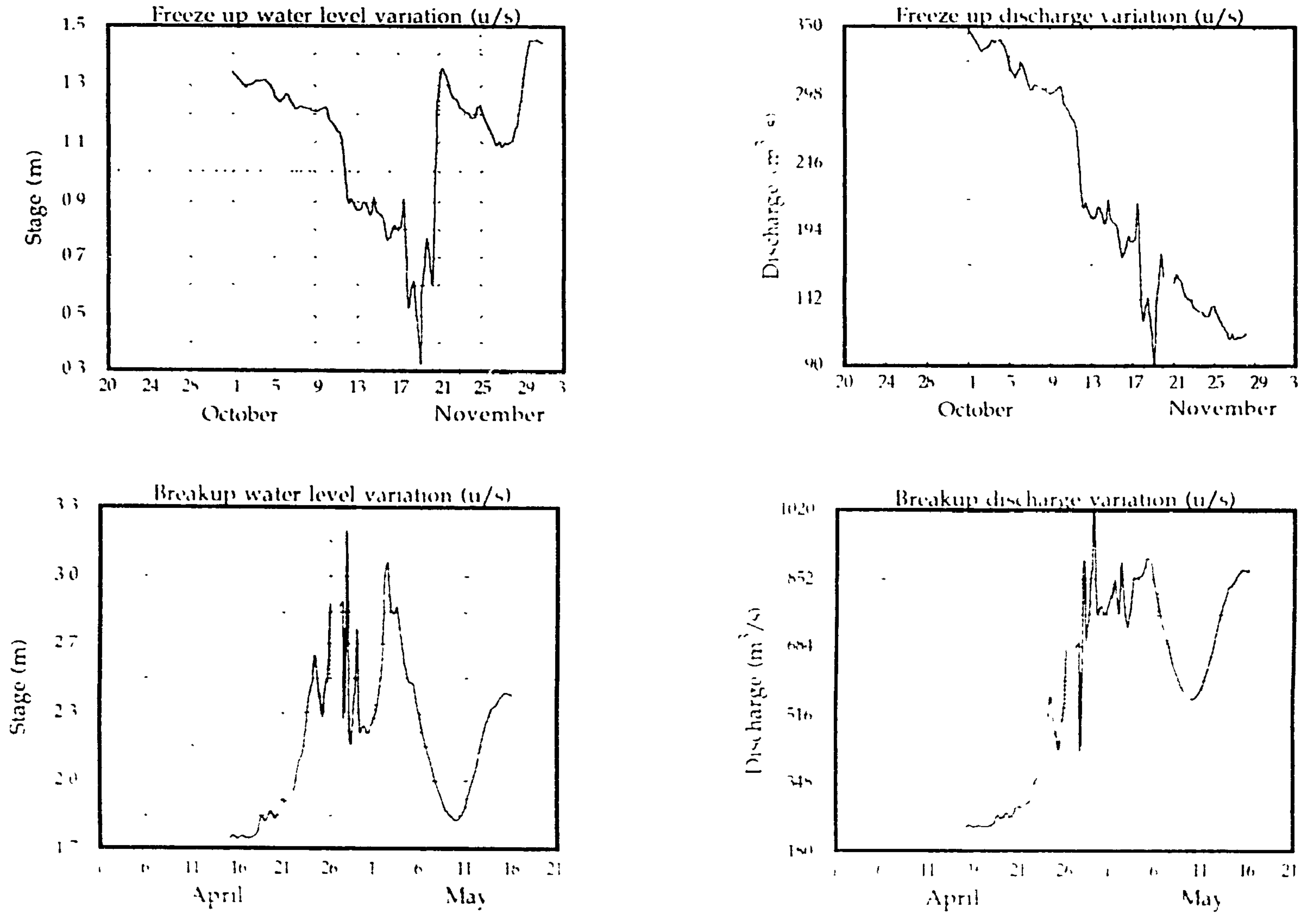


Figure 30. Freeze up and breakup water level and discharge variation at upstream hydrometric stations for 26 & 28/4/79 ice jams on Athabasca river upstream of Mountain rapids, downstream of Grande and Cascade rapids. (48 to 50)

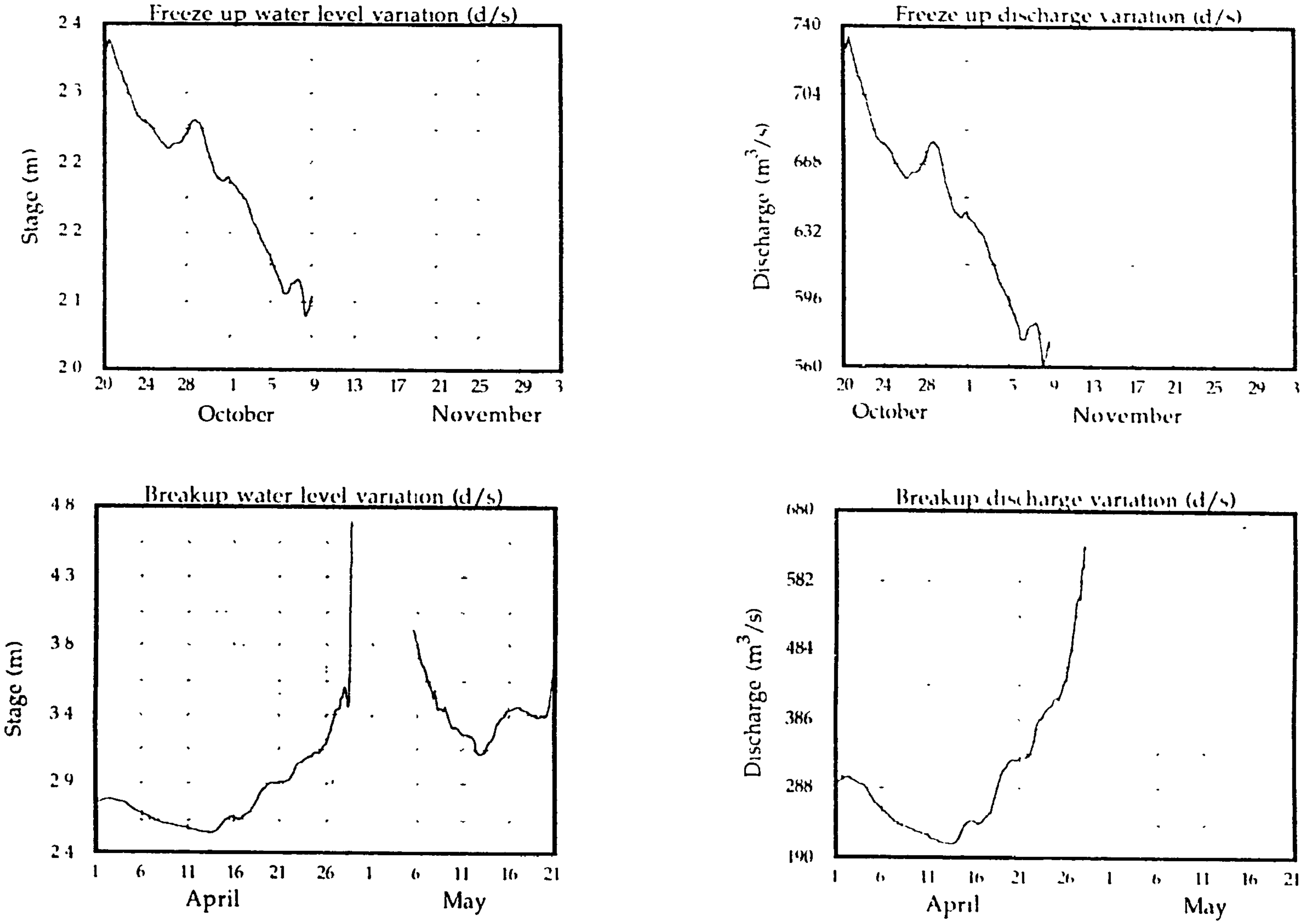


Figure 31. Freeze up and breakup water level and discharge variation at downstream hydrometric stations for 26 & 28/4/79 ice jams on Athabasca river upstream of Mountain rapids, downstream of Grande and Cascade rapids. (48 to 50)

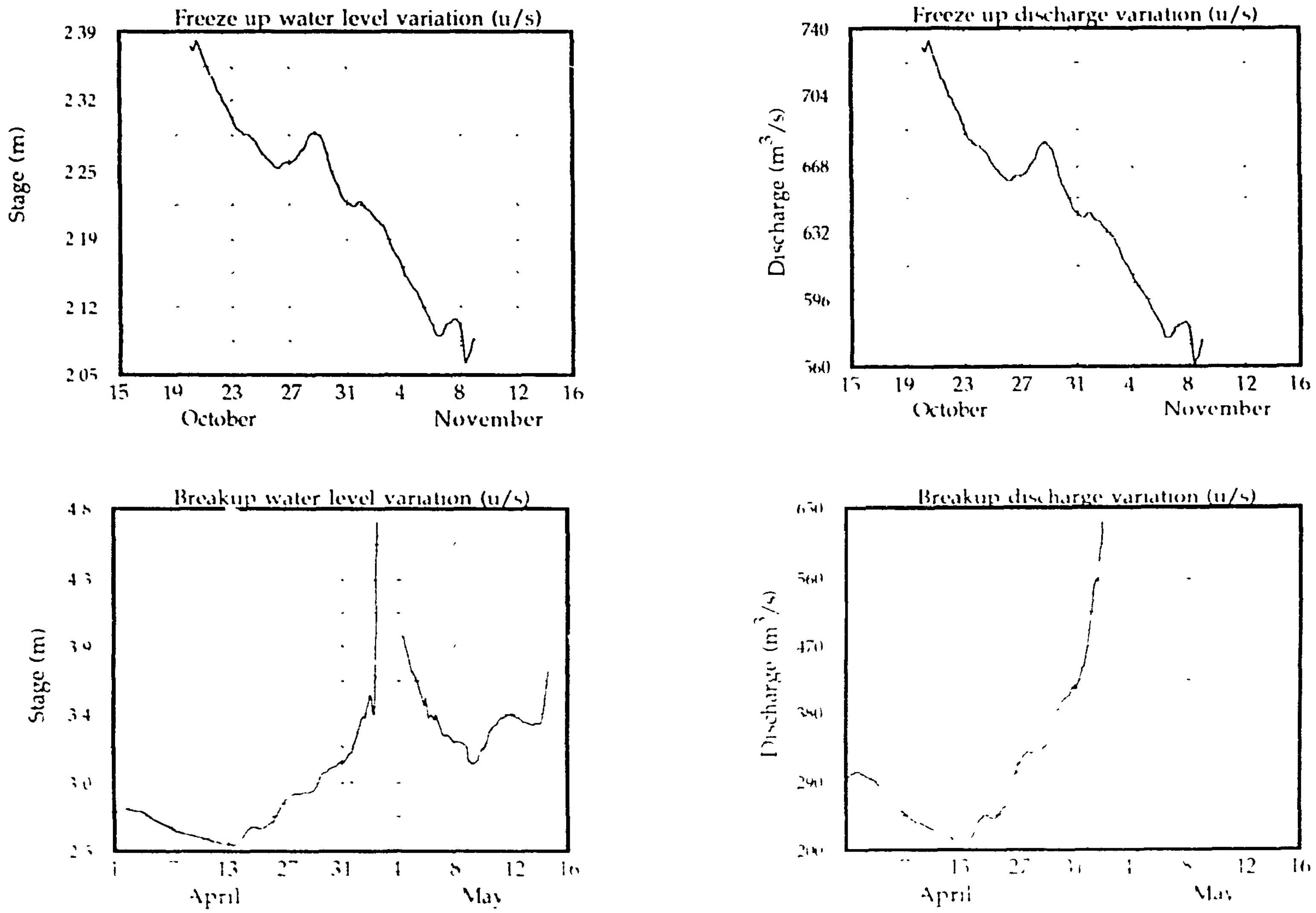


Figure 32. Freeze up and breakup water level and discharge variation at upstream hydrometric stations for 29/4/79 ice jam on Athabasca river 16 and 28 km downstream of McEwan bridge.

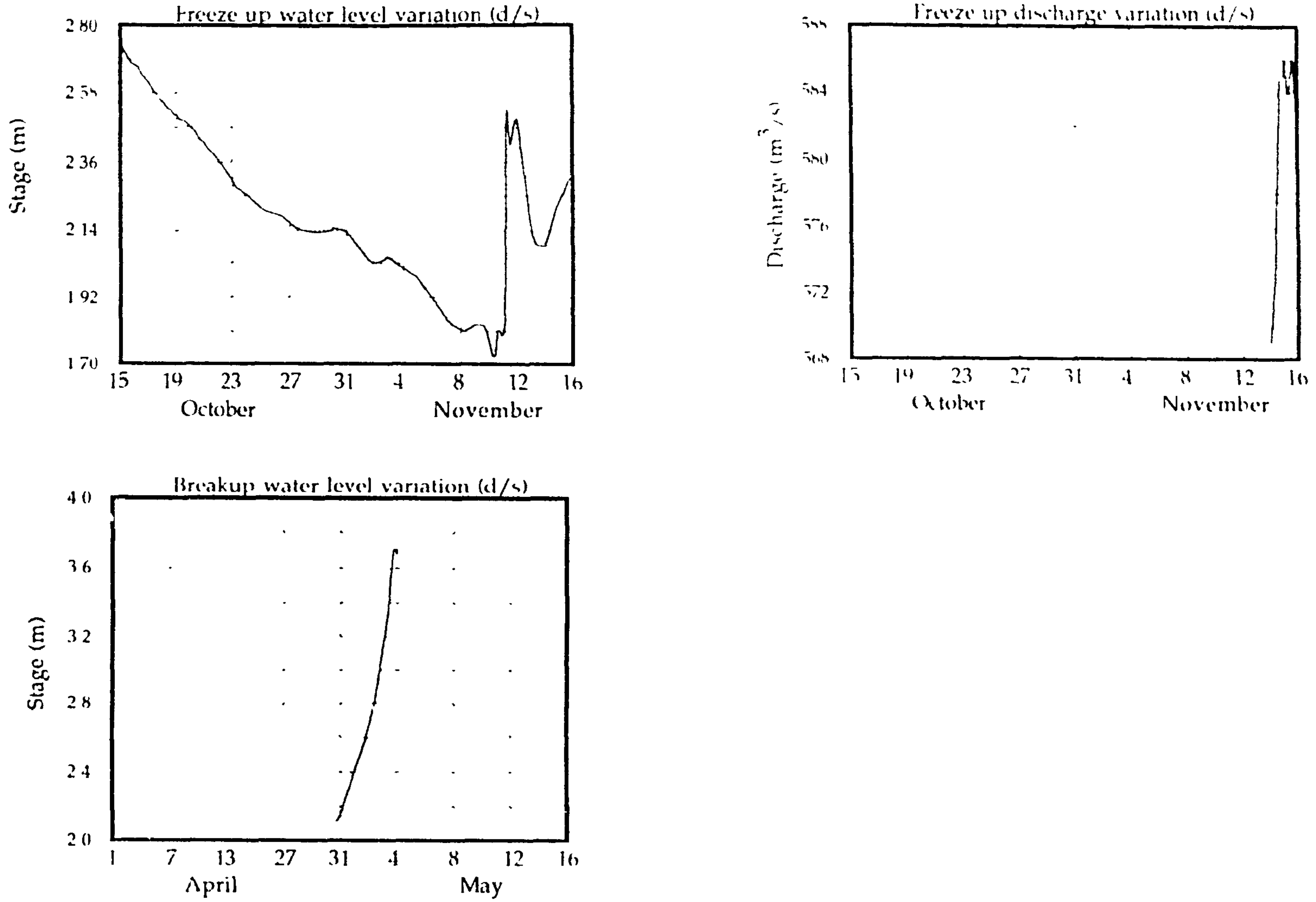
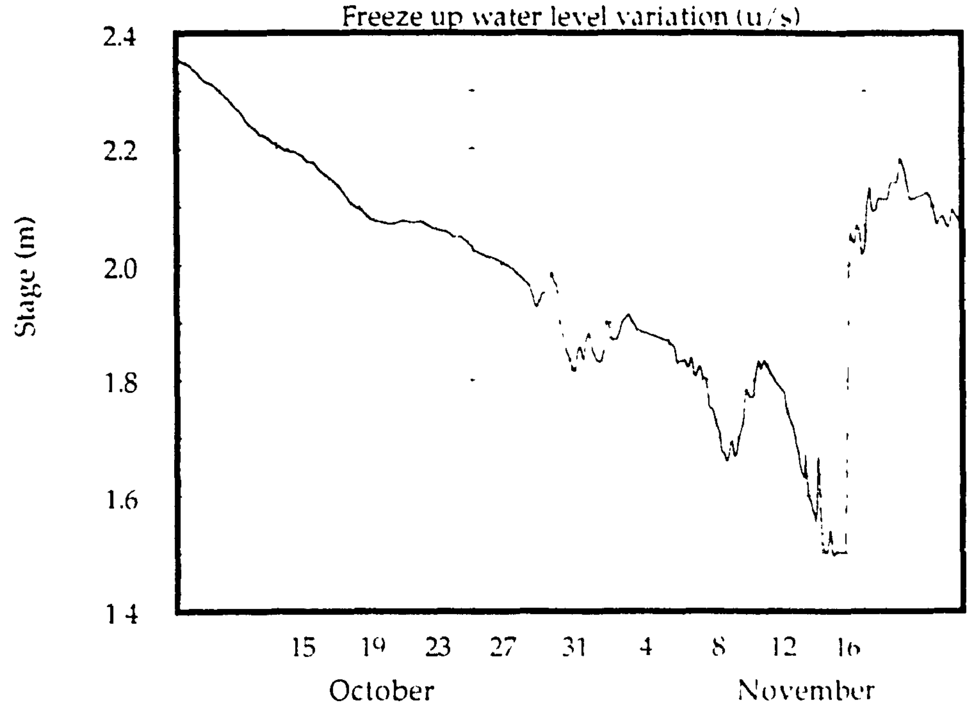


Figure 33. Freeze up and breakup water level and discharge variation at downstream hydrometric stations for 29/4/79 ice jam on Athabasca river 16 and 28 km downstream of McEwan bridge.



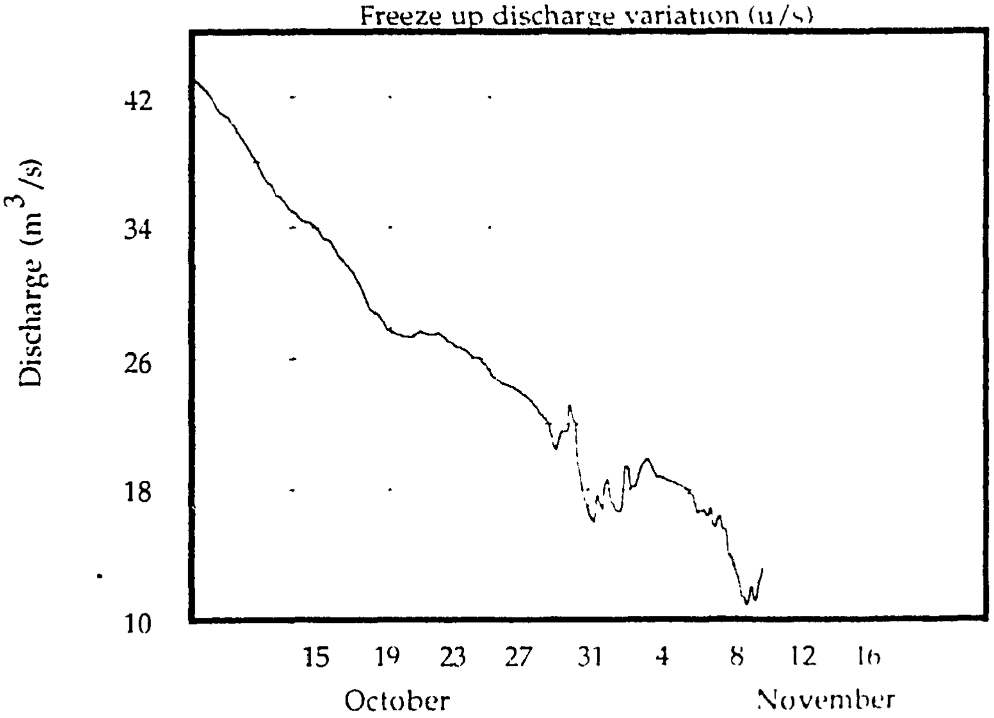


Figure 34. Freeze up water level and discharge variation at upstream hydrometric station for 30/4/79 ice jam on Athabasca river at Mackay river confluence.

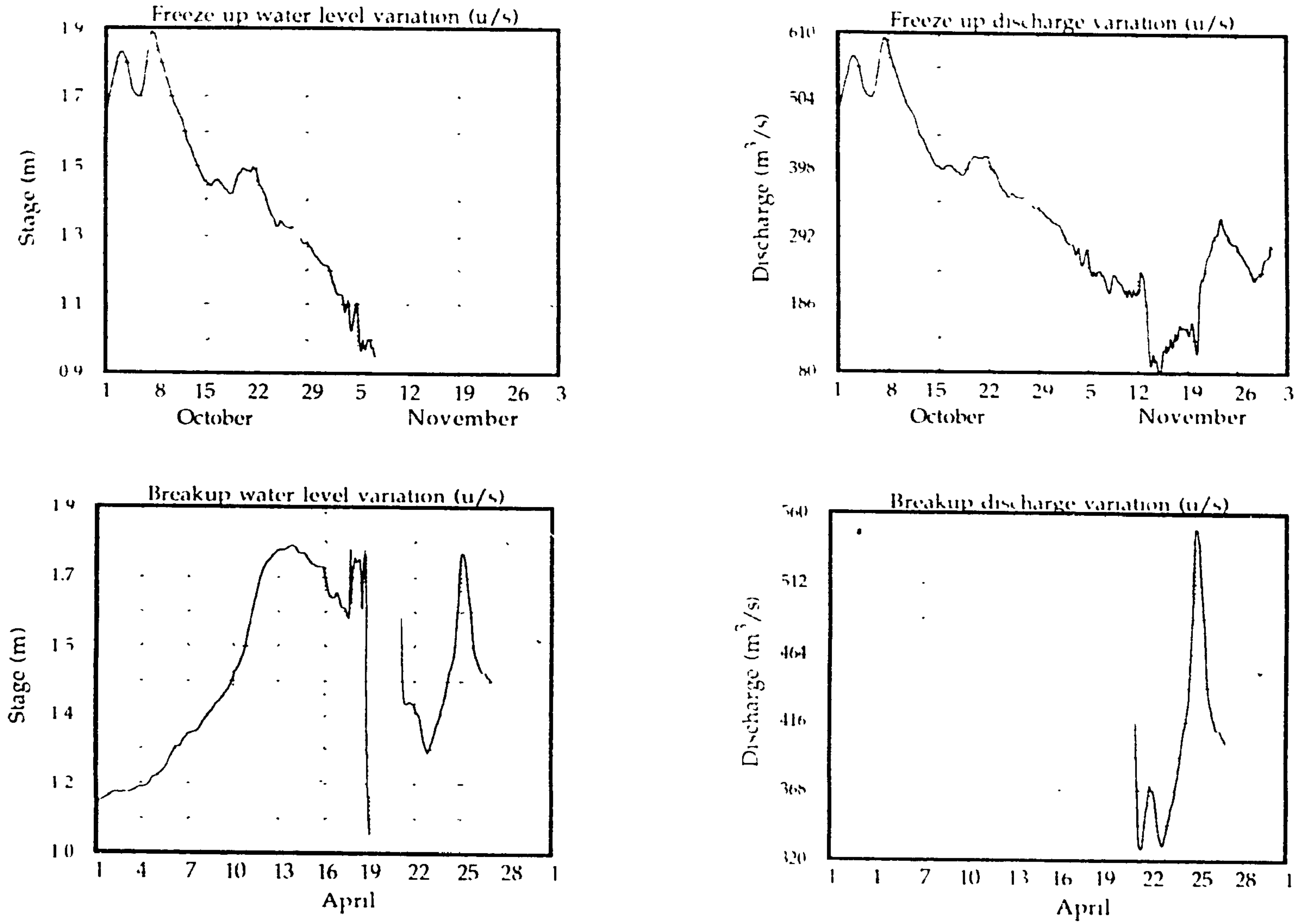


Figure 35. Freeze up and breakup water level and discharge variation at upstream hydrometric stations for 18 & 19/4/83 ice jams on Athabasca river downstream of Crooked rapids and upstream of Upper wells.

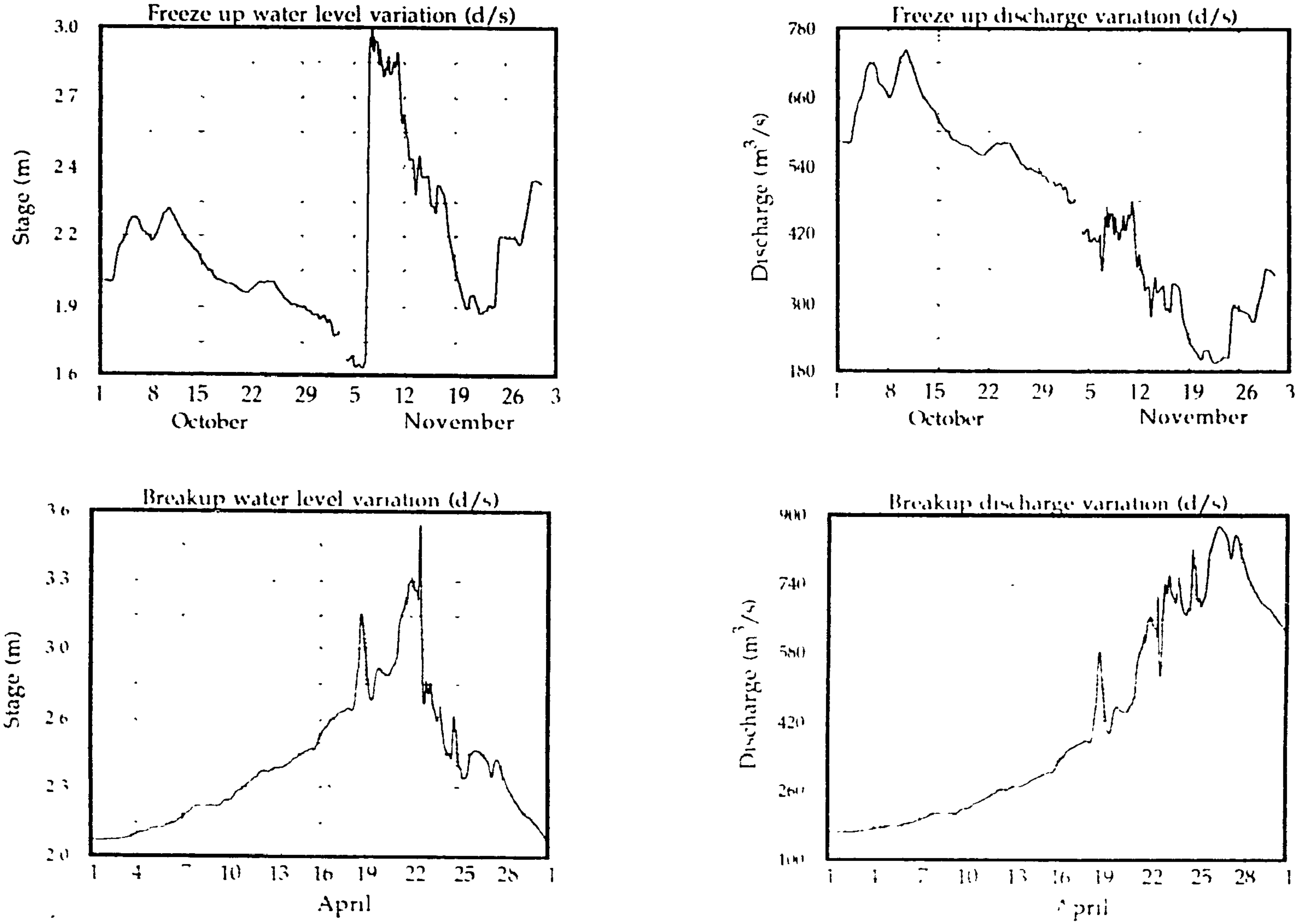


Figure 36. Freeze up and breakup water level and discharge variation at downstream hydrometric stations for 18 & 19/4/83 ice jams on Athabasca river downstream of Crooked rapids and upstream of Upper wells.

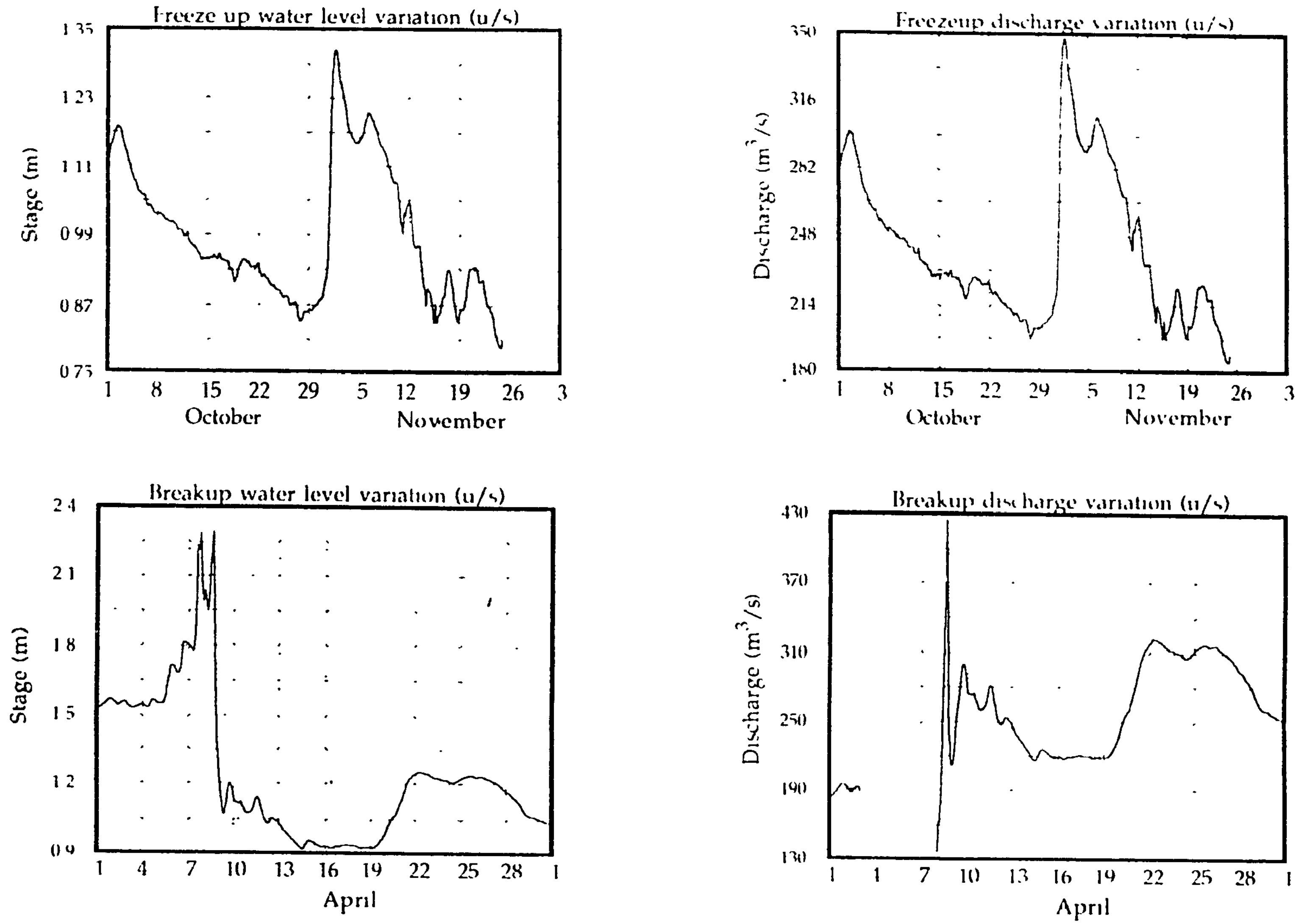


Figure 37. Freeze up and breakup water level and discharge variation at upstream hydrometric stations for 9 & 10/4/84 ice jams on Athabasca river at Rourke creek, Moberly rapids, downstream of Long rapids, House river mouth, and downstream of House river mouth.

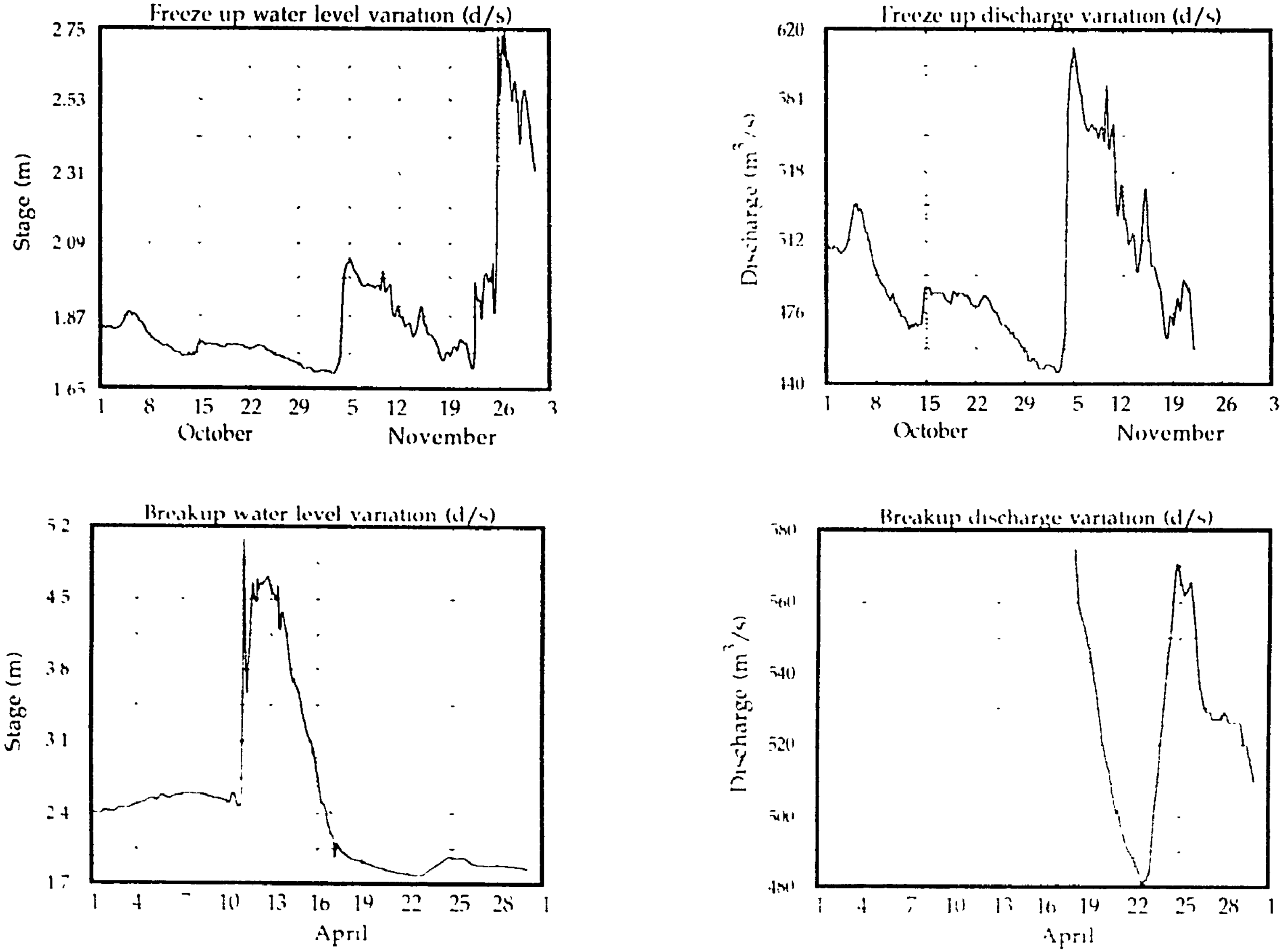


Figure 38. Freeze up and breakup water level and discharge variation at downstream hydrometric stations for 9 & 10/4/84 ice jams on Athabasca river at Rourke creek, Moberly rapids, downstream of Long rapids, House river mouth, and downstream of House river mouth.

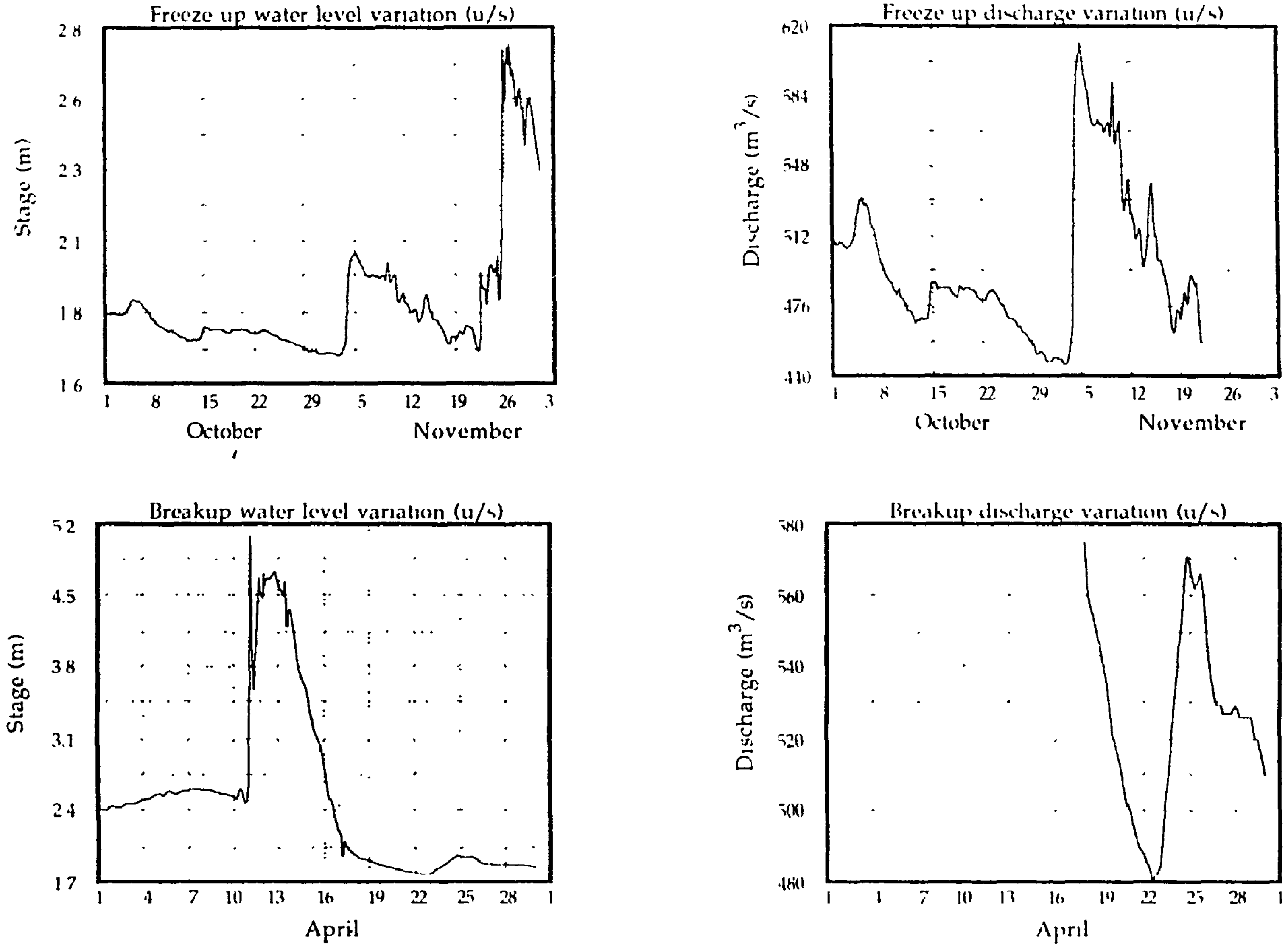


Figure 39. Freeze up and breakup water level and discharge variation at upstream hydrometric stations for 10/4/84 ice jams on Athabasca river downstream of gauge.

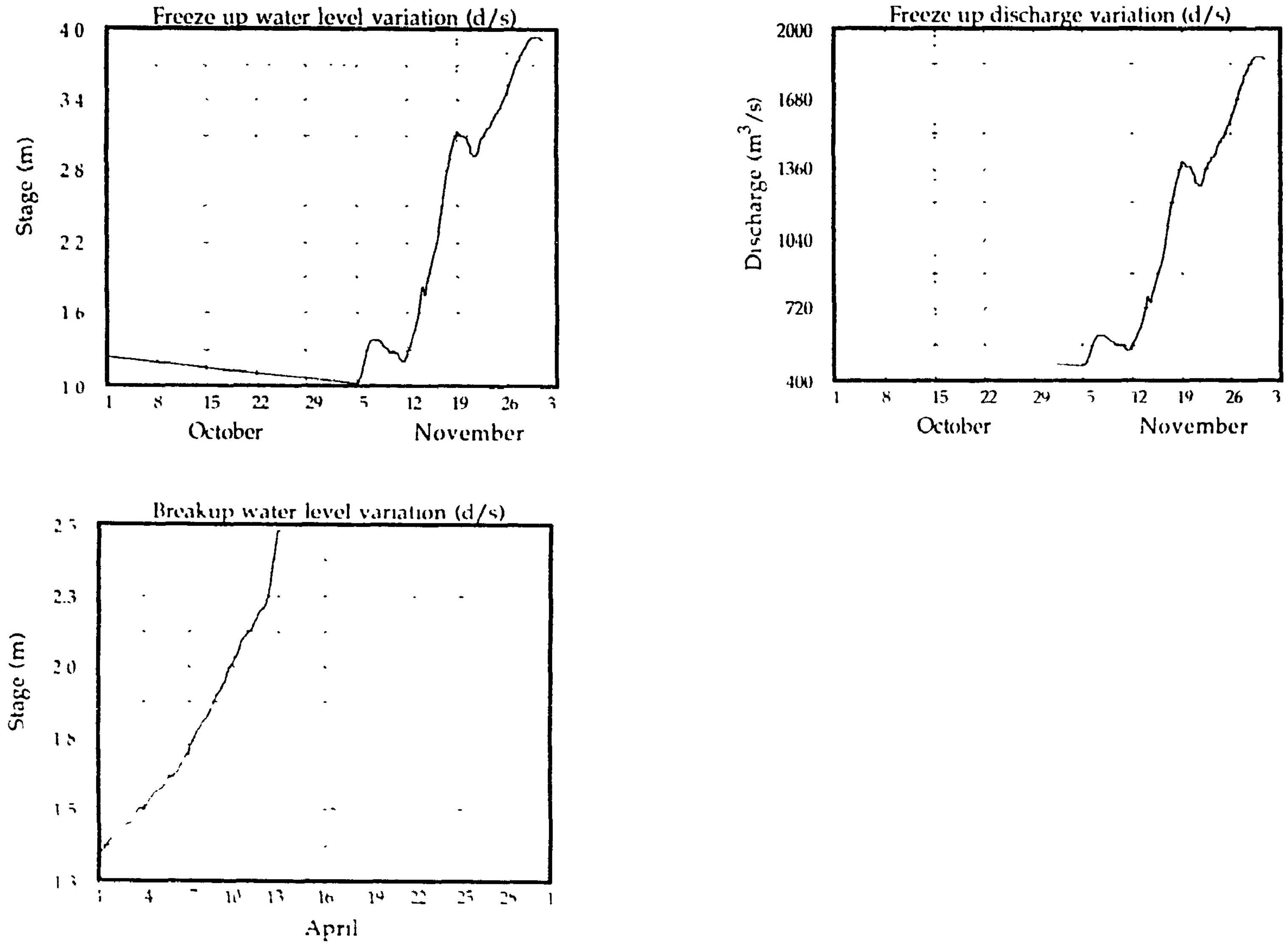


Figure 40. Freeze up and breakup water level and discharge variation at downstream hydrometric stations for 10/4/84 ice jams on Athabasca river downstream of gauge.

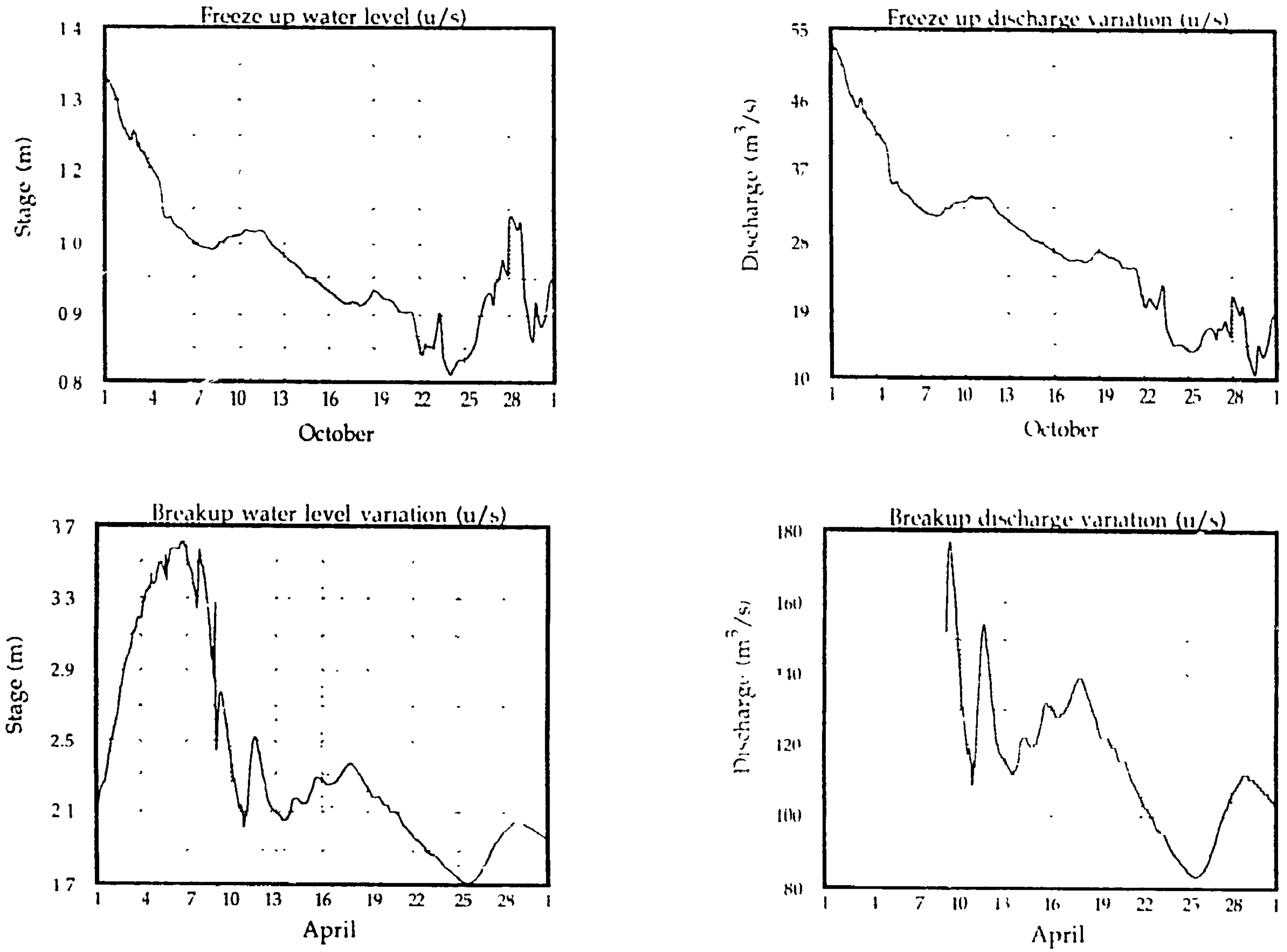


Figure 41. Freeze up and breakup water level and discharge variation at downstream hydrometric stations for 10/4/84 ice jam on Athabasca river at Pembina river confluence.

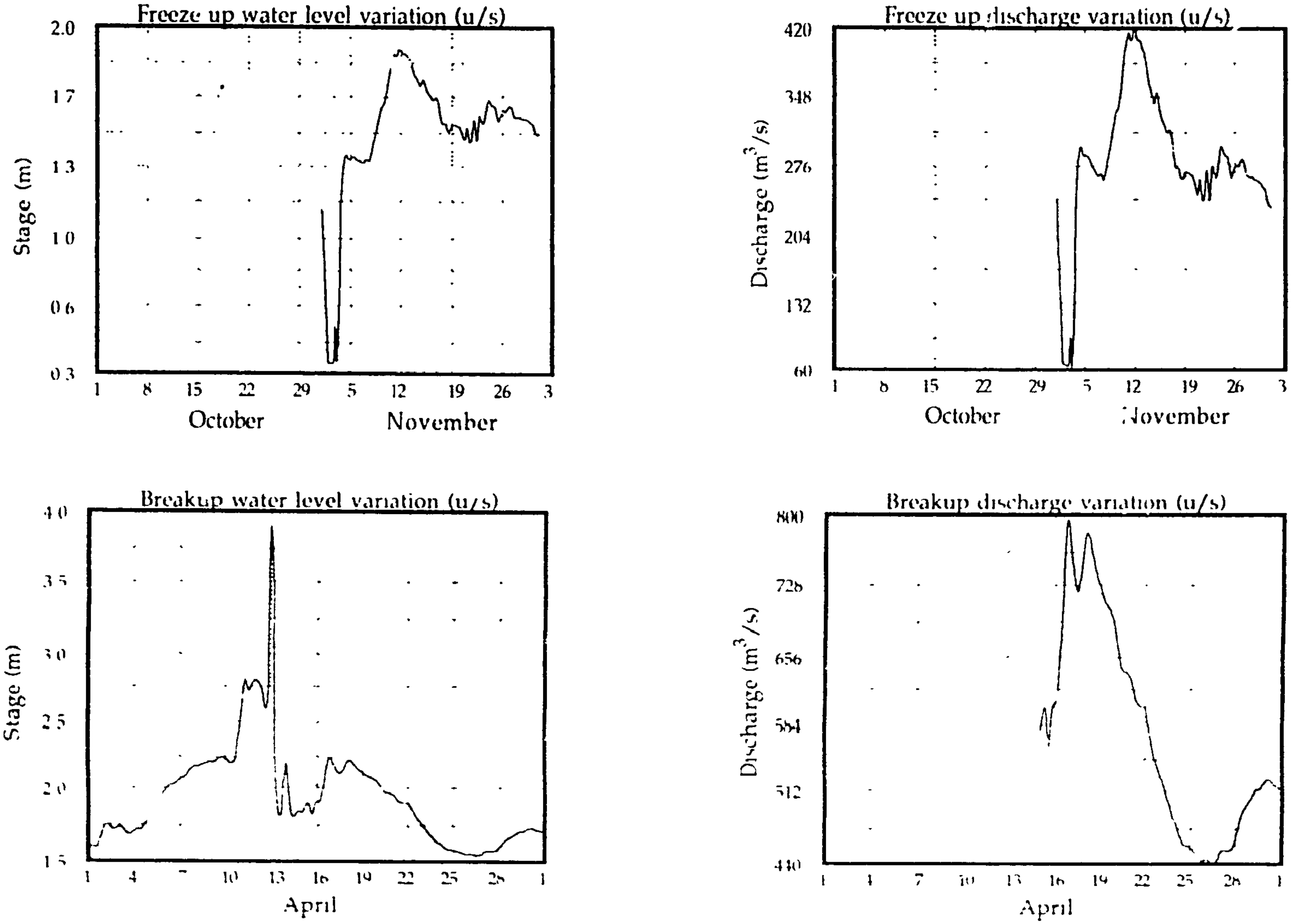


Figure 42. Freeze up and breakup water level and discharge variation at upstream hydrometric stations for 13, 14 & 17/4/85 ice jams on Athabasca river at Algar river mouth, Stony rapids, upstream of Cascade, Stony rapids, Joli fou, and downstream of town of Athabasca.

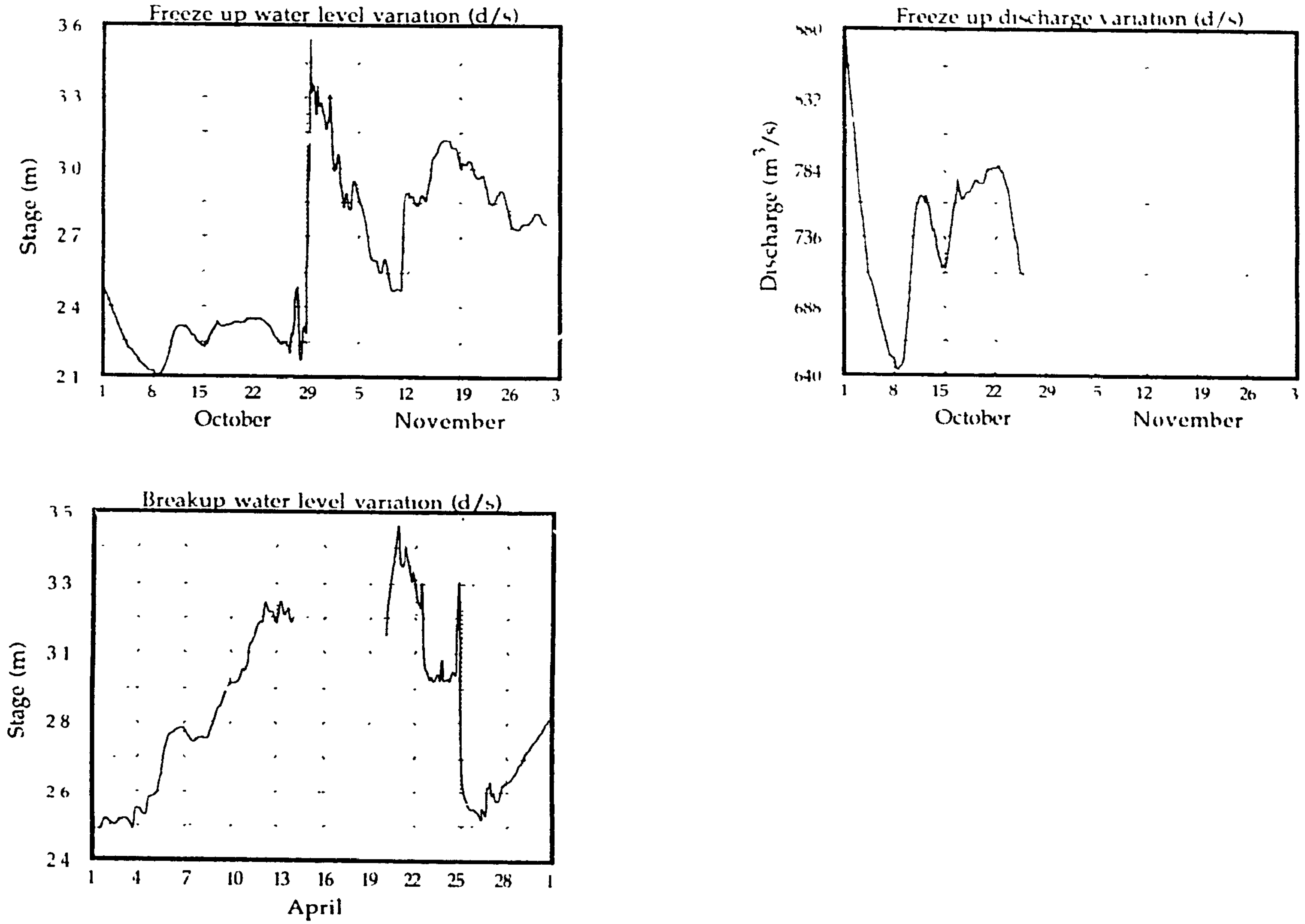


Figure 43. Freeze up and breakup water level and discharge variation at downstream hydrometric stations for 13, 14 & 17/4/85 ice jams on Athabasca river at Aigar river mouth, Stony rapids, upstream of Cascade, Stony rapids, Joli fou, and downstream of town of Athabasca.

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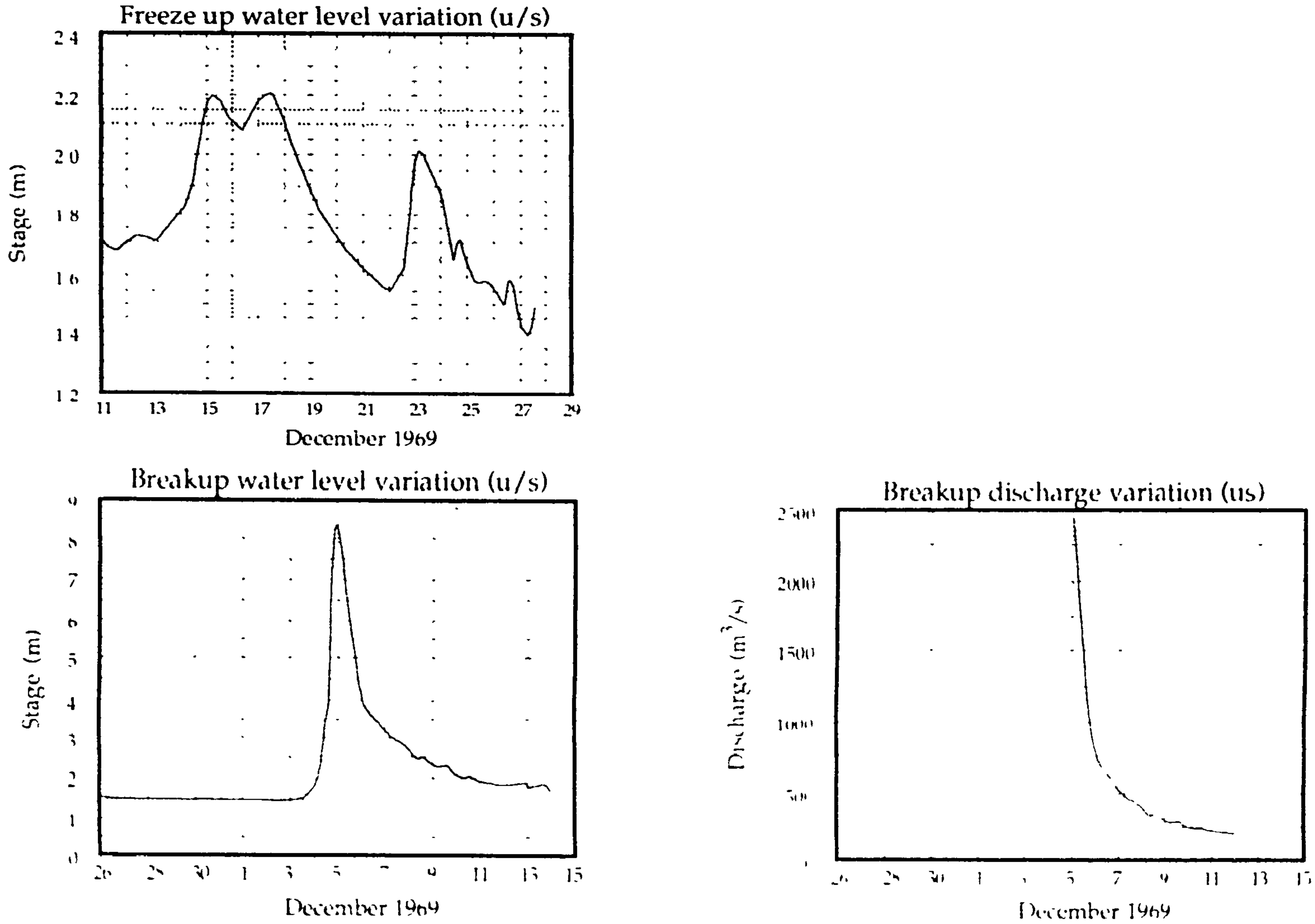


Figure 44. Freeze up and breakup water level and discharge variation at upstream hydrometric station for 2/2/70 ice jam on Miramichi river at Morrisey bridge in New castle.

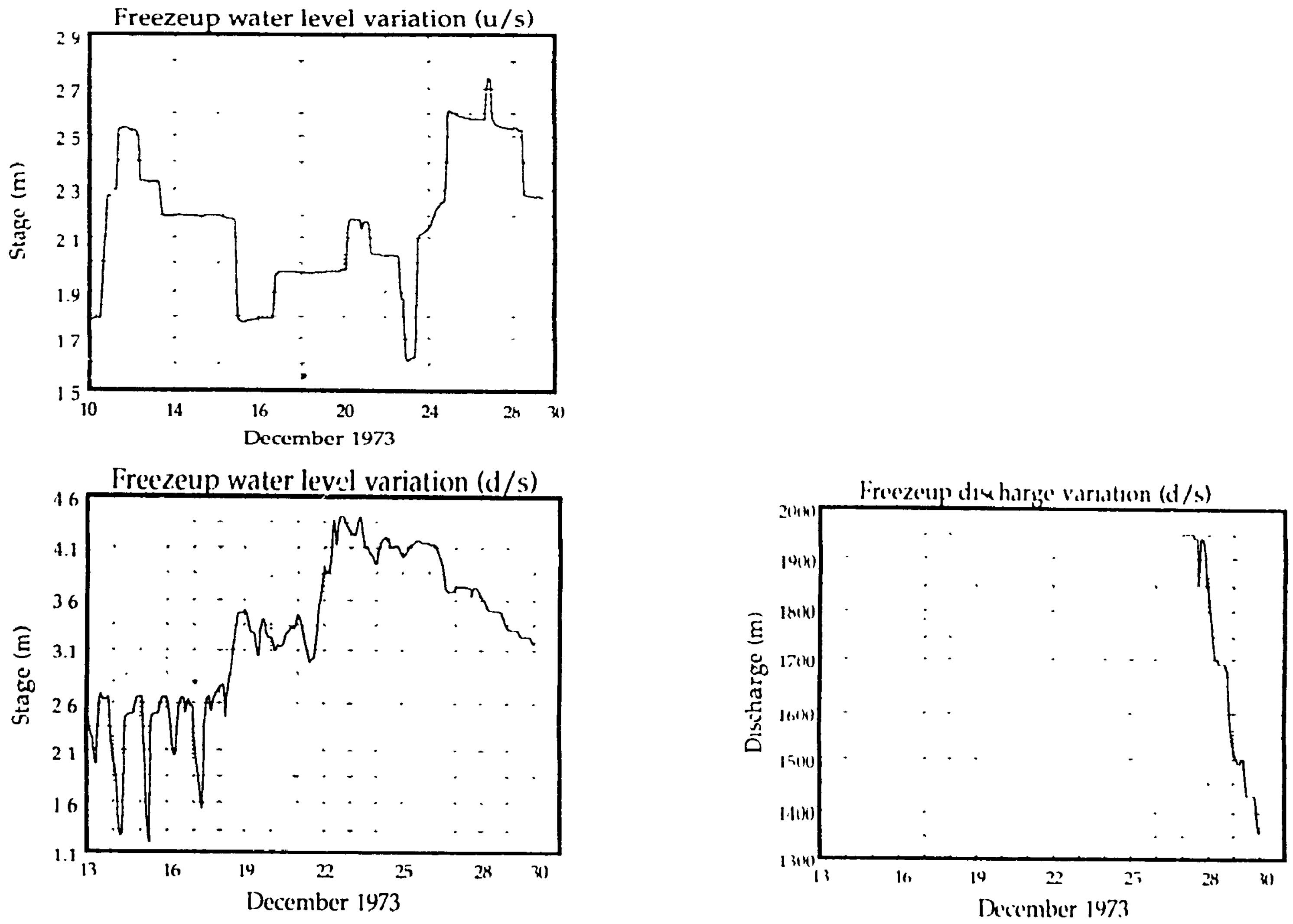


Figure 45. Freeze up water level and discharge variation at upstream and downstream hydrometric stations for 20/12/73 ice jam on Saint John river 3 miles south of Perth-Andover.

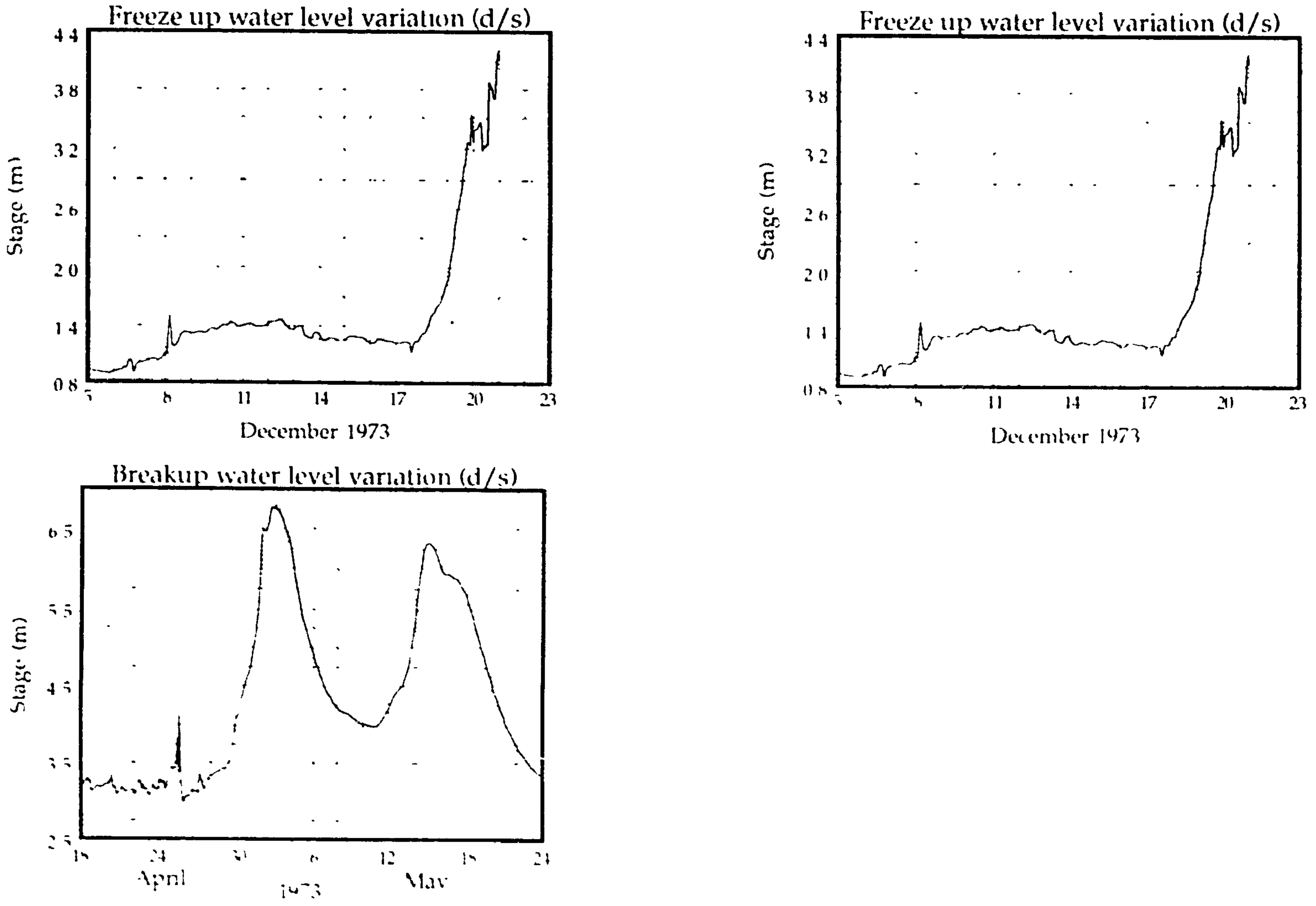


Figure 46. Freeze up and breakup water level and discharge variation at downstream hydrometric station for 29/4 74 ice jam on St. John river at Fort Kent

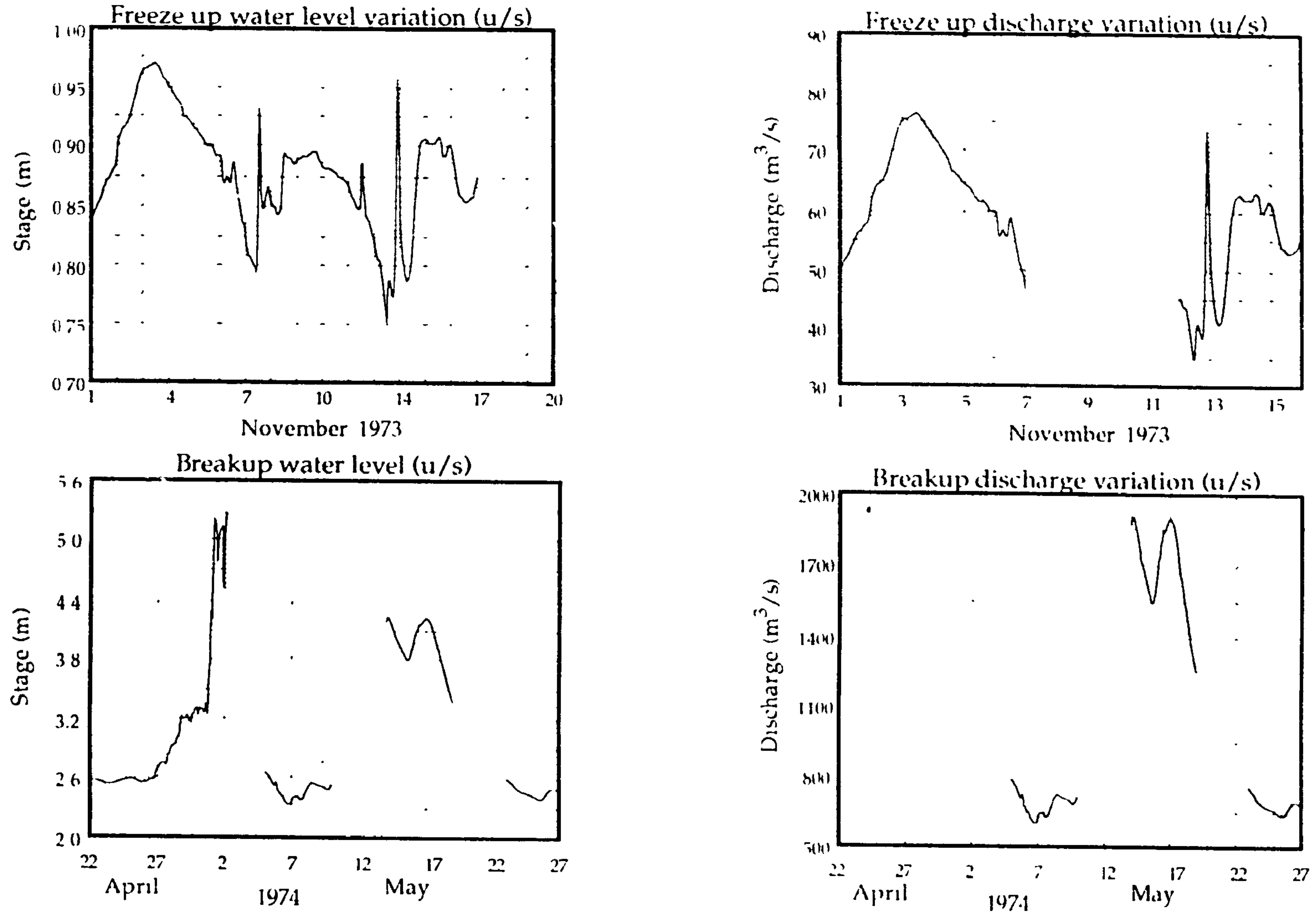


Figure 47. Freeze up and breakup water level and discharge variation at upstream hydrometric station for 29/4/74 ice jam on Restigouche river at old interprovincial bridge near Campbellton.

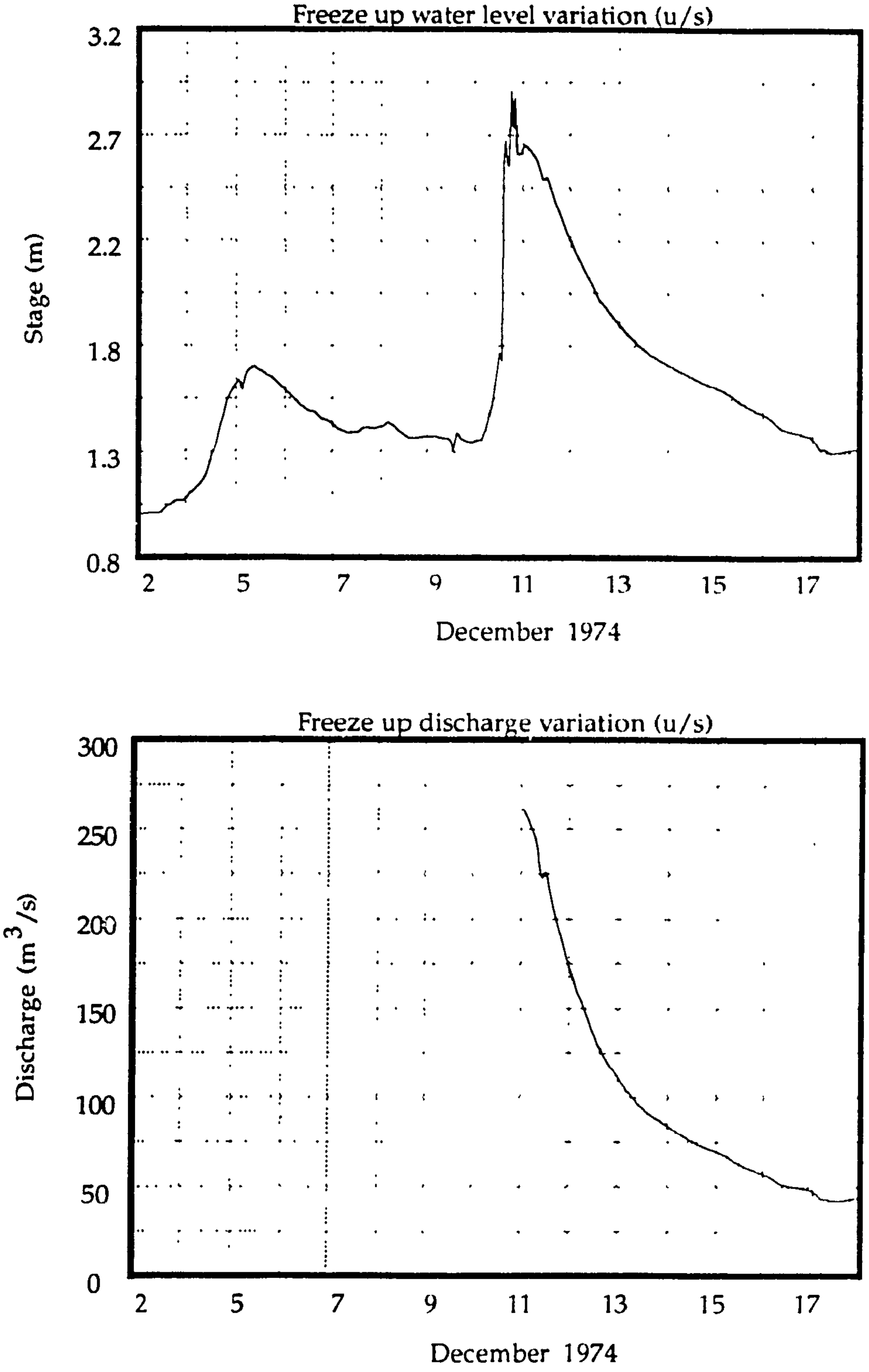


Figure 48. Freeze up water level and discharge variation at upstream hydrometric station for 9/12/74 ice jam on Nashwaak river at Nashwaak village.

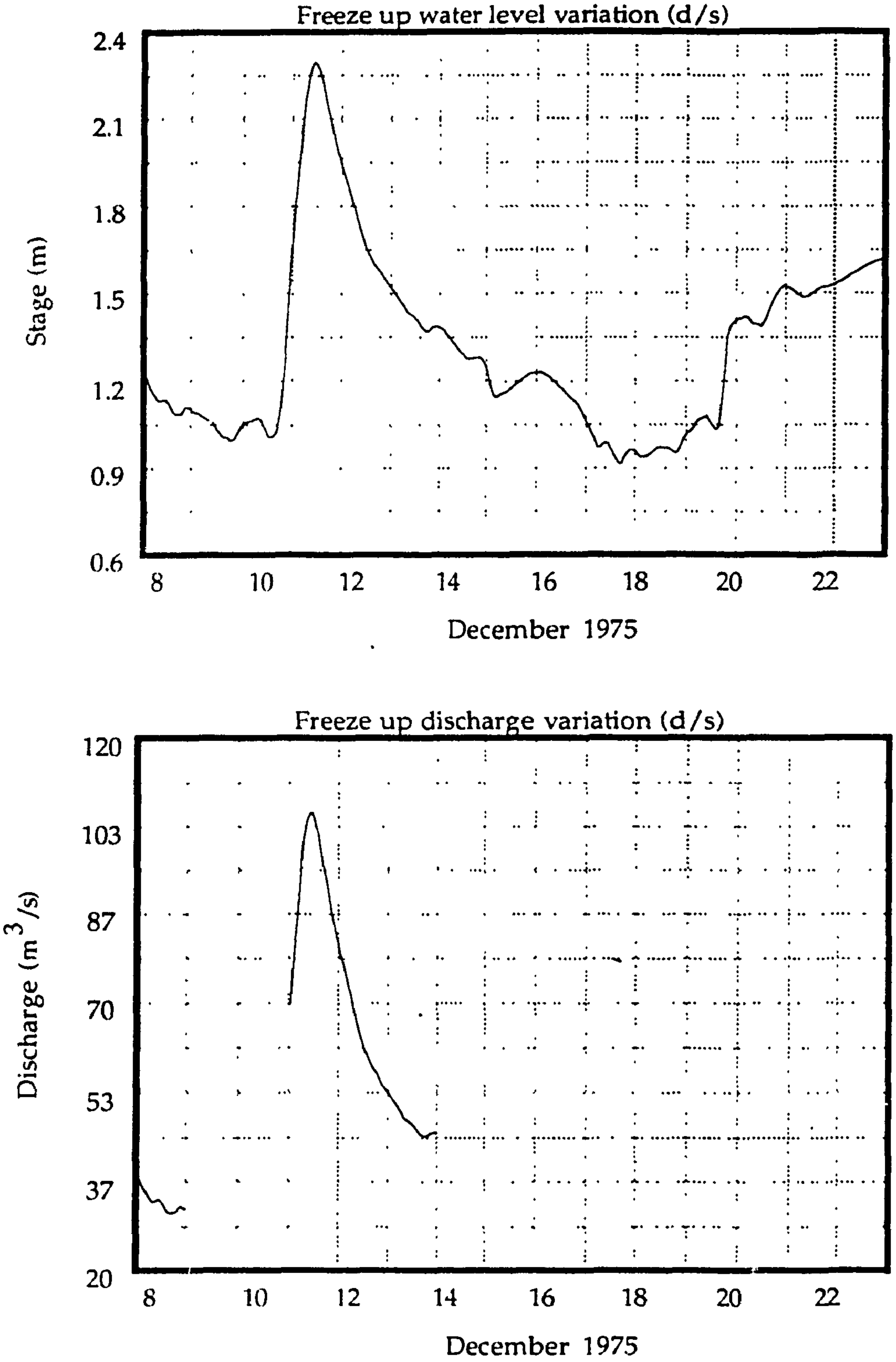


Figure 49. Freeze up water level and discharge variation at downstream hydrometric station for 27/1/76 ice jam on Kennebecasis river at Sussex corner bridge.

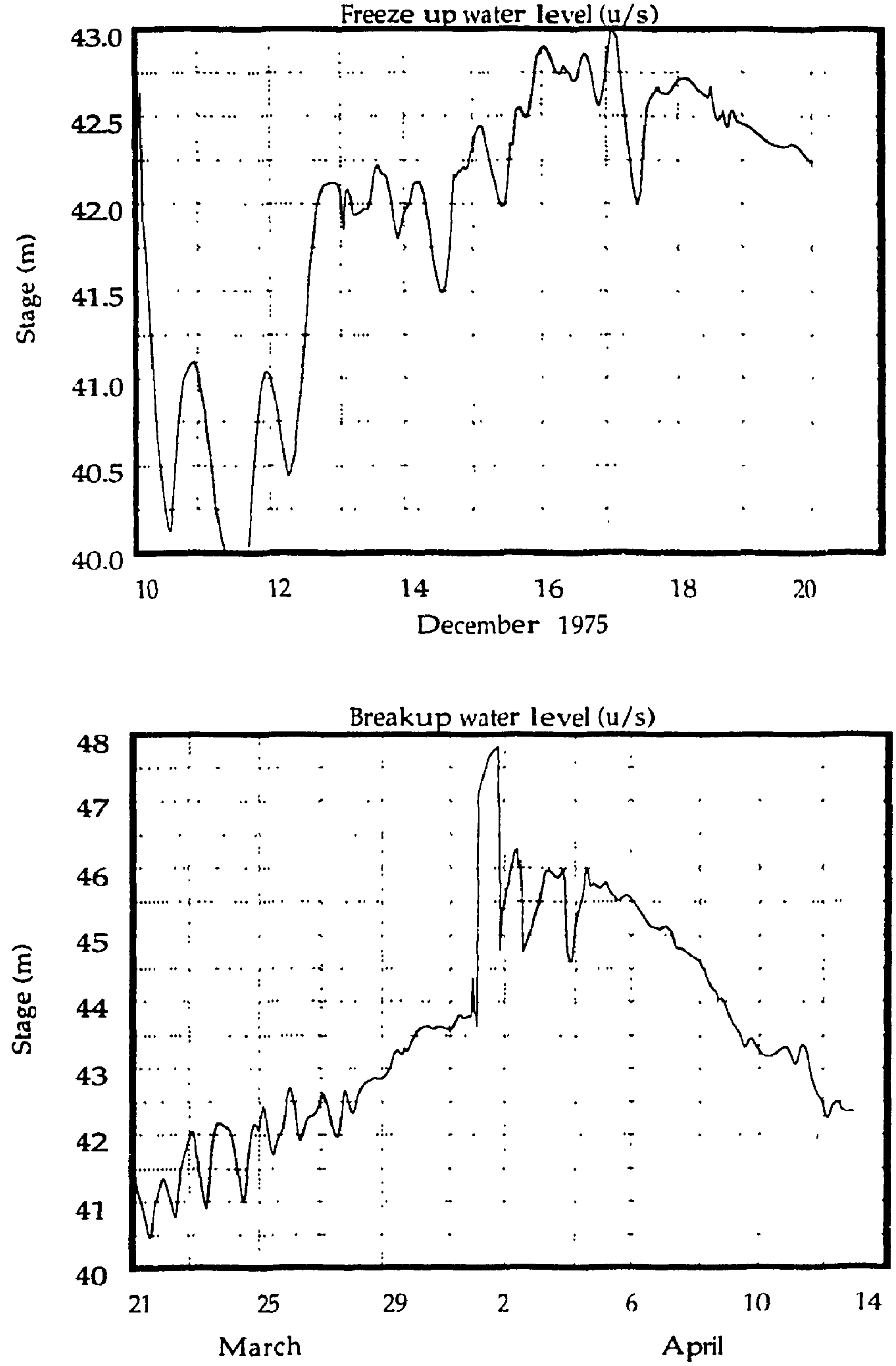


Figure 50. Freeze up and breakup water level variation at upstream hydrometric station for 31/3/76 ice jam on St. John river at Perth-Andover, Anne-de-Madawska, Grafton bridge north of Woodstock and Hartland to upstream of Hugh John Flemming bridge.

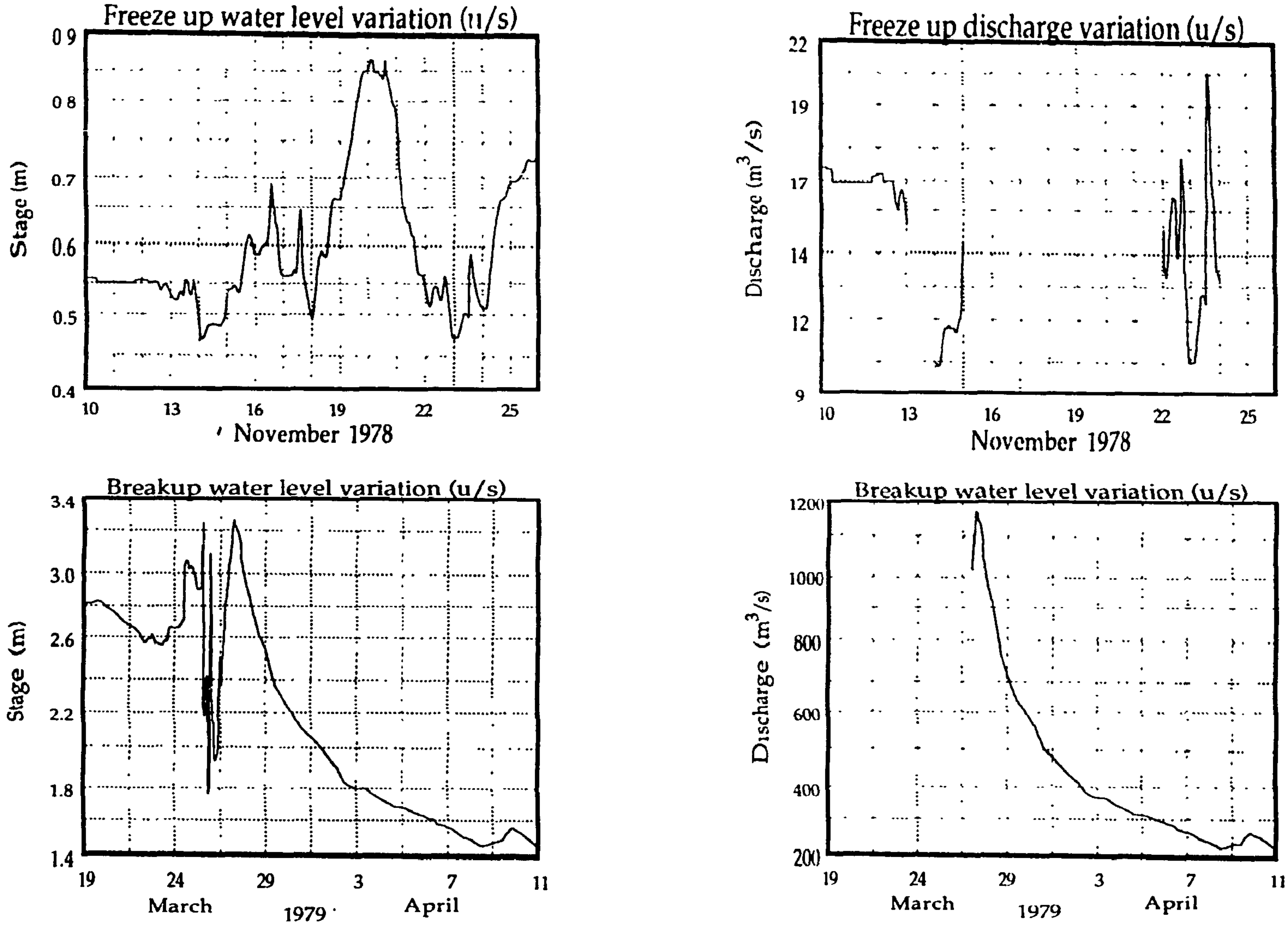
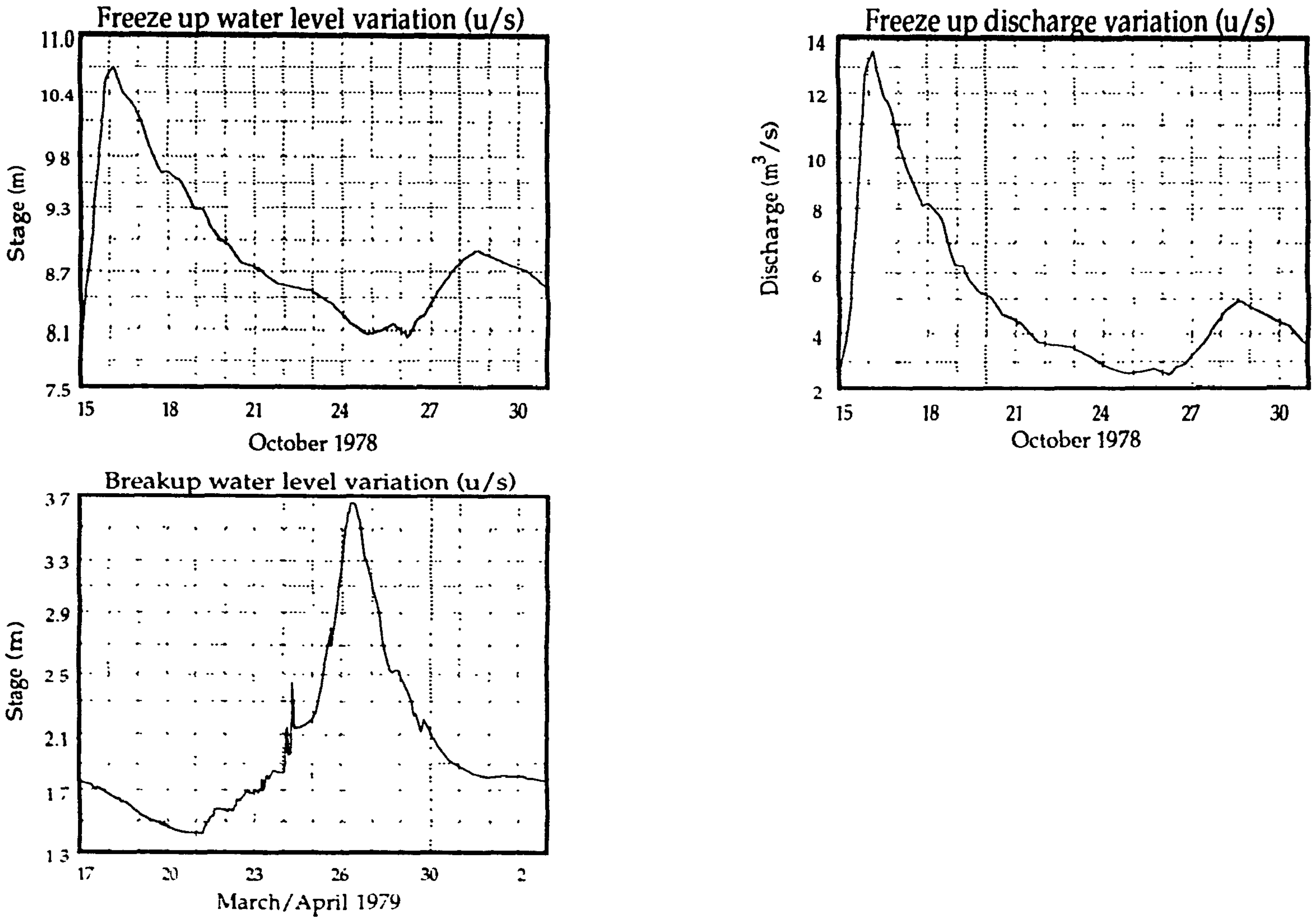


Figure 51. Freeze up and breakup water level and discharge variation at upstream hydrometric station for 26/3/79 ice jam on Restigouche river at Flat lands.


Freeze up water level variation (u/s)

Freeze up discharge variation (u/s)

Breakup water level variation (u/s)

Figure 52. Freeze up and breakup water level and discharge variation at upstream hydrometric station for 27/3/79 ice jam on Meduxnekeag river at Woodstock.

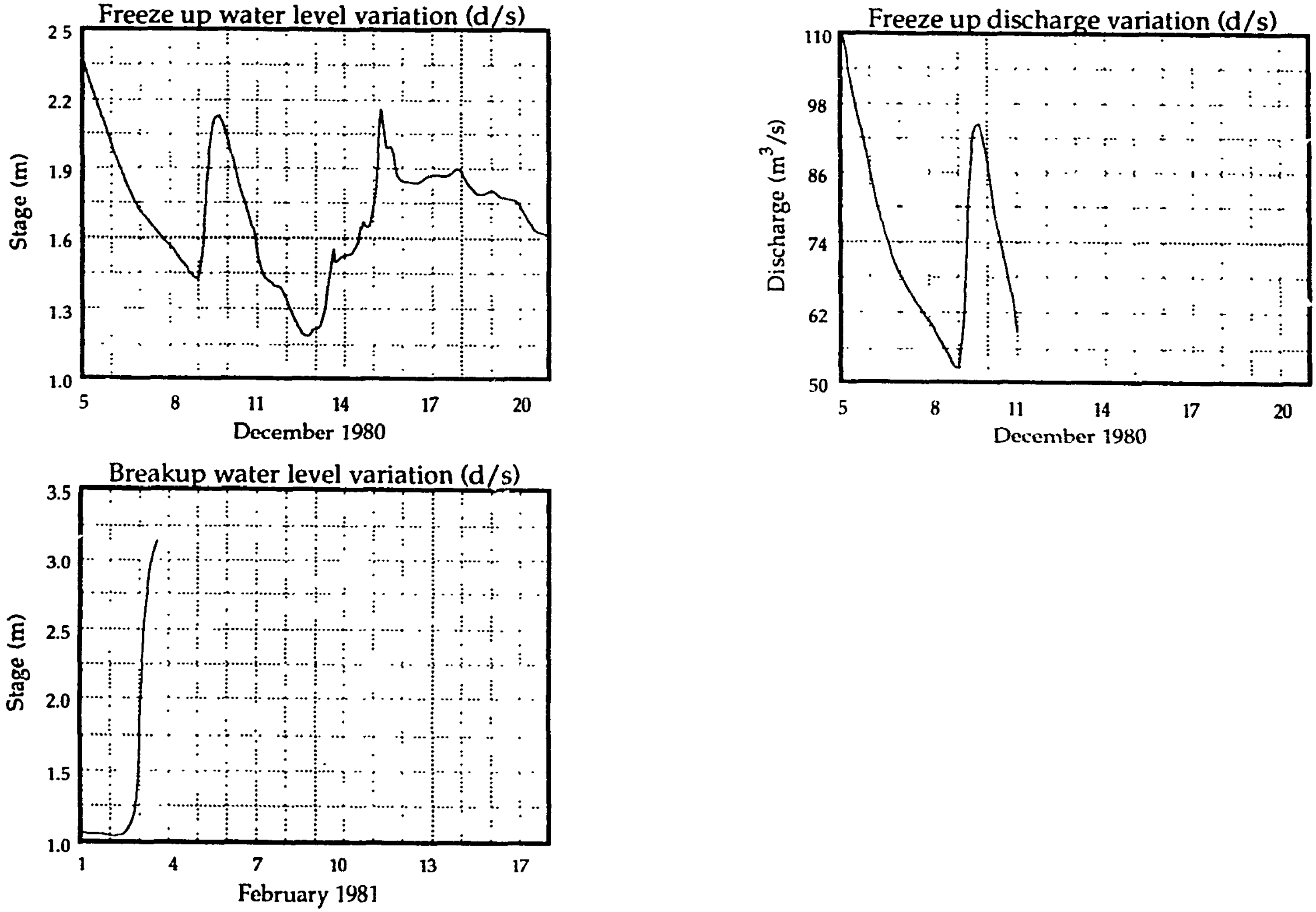


Figure 53. Freeze up and breakup water level and discharge variation at downstream hydrometric station for 11/2/81 ice jam on Kennebecasis river near Roachville area at Sussex.

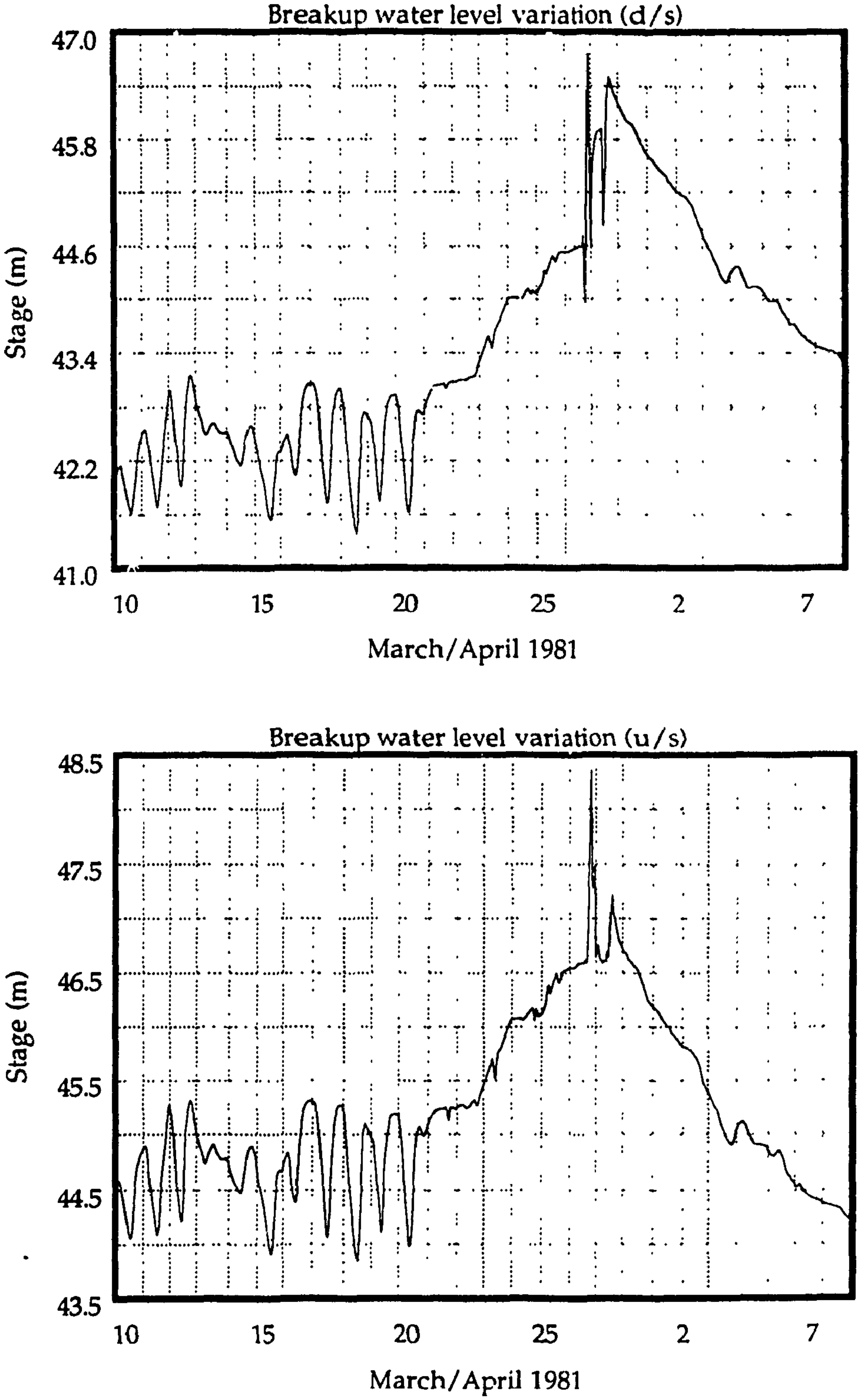


Figure 54. Breakup water level variation at upstream and downstream hydrometric stations for 24/2/81 ice jam on St. John river at and above Hugh John Flemming bridge and lower end of Sproll island.

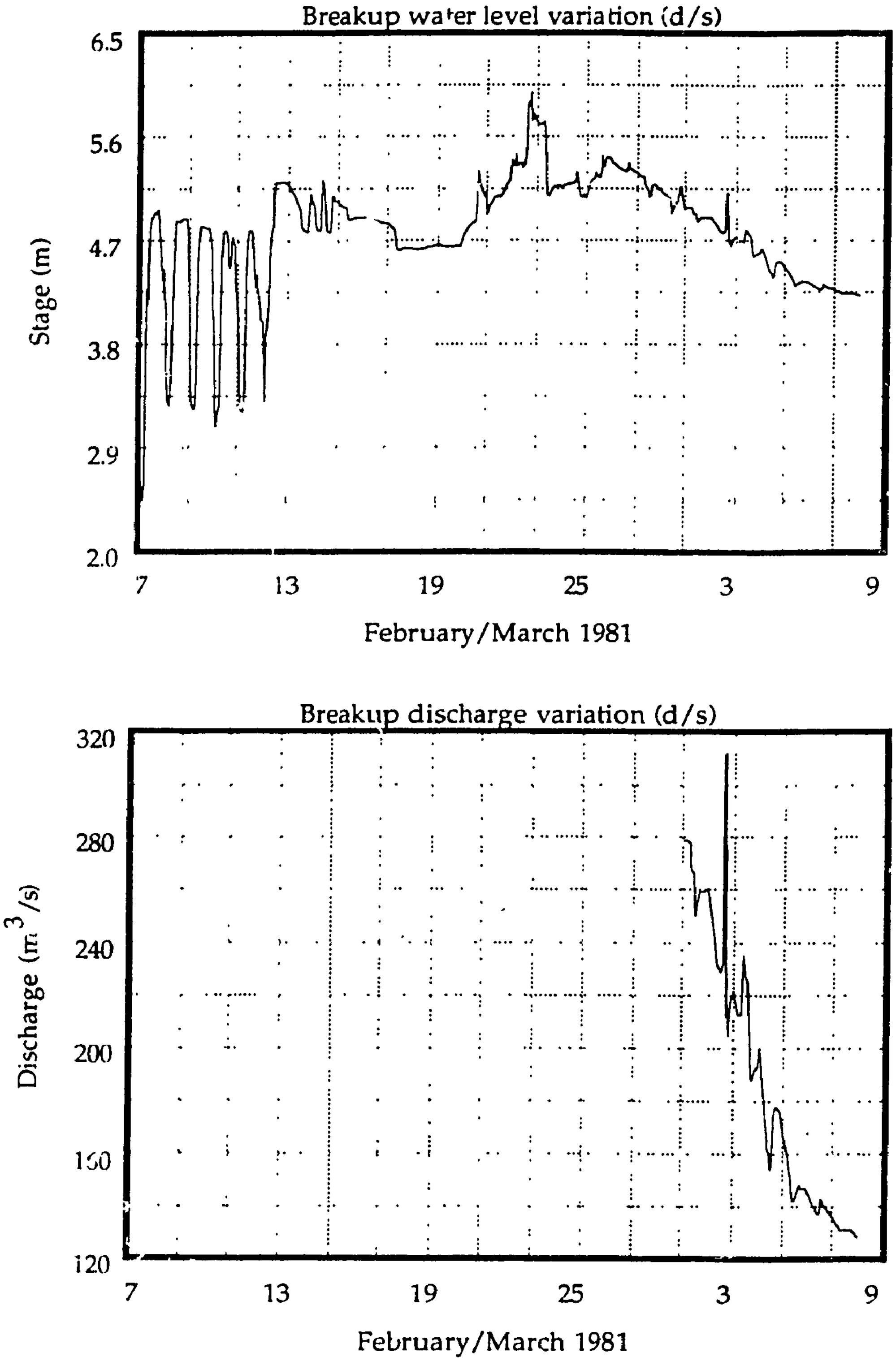


Figure 55. Breakup water level and discharge variation at downstream hydrometric station for 11/4/83 ice jam on Meduxnekeag river at Woodstock.

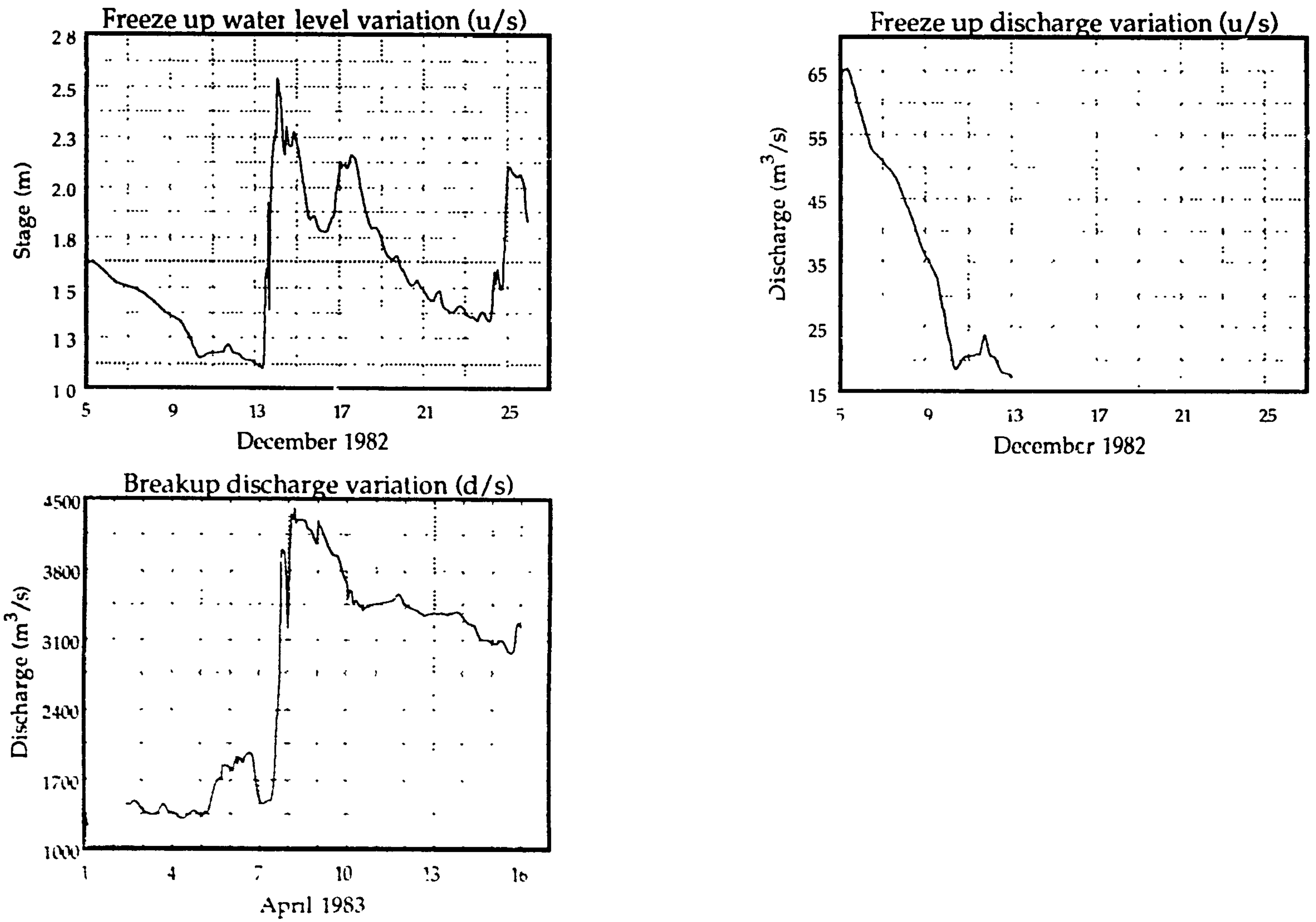


Figure 56. Freeze up and breakup water level and discharge variation at downstream hydrometric station for 11/4/83 ice jam on Meduxnekeag river at Woodstock.

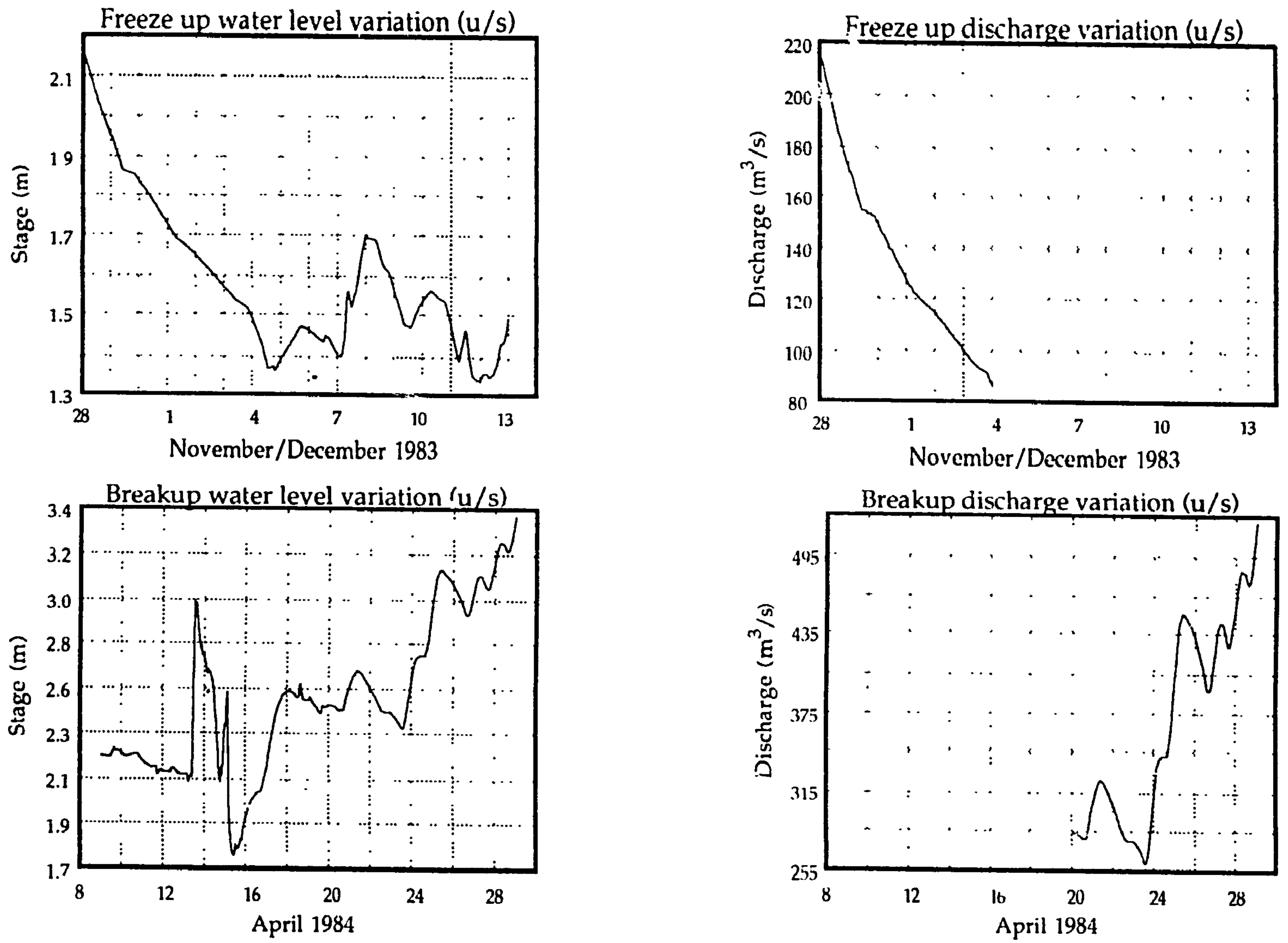


Figure 57. Freeze up and breakup water level and discharge variation at upstream hydrometric stations for 18/4/84 Restigouche river at confluence of upsalquitch river.

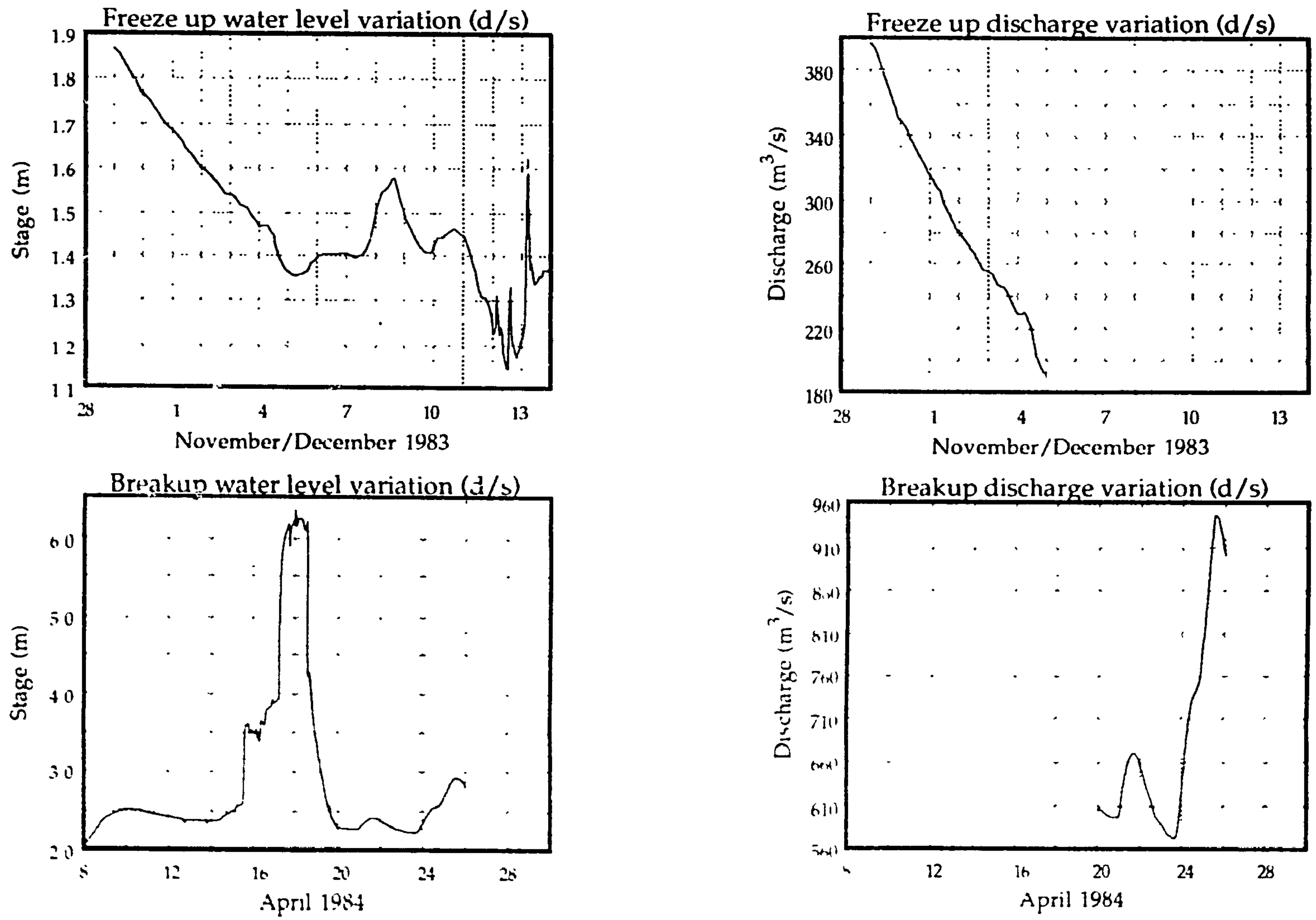


Figure 58. Freeze up and breakup water level and discharge variation at downstream hydrometric stations for 18/4/84 Restigouche river at confluence of upsalquitch river.

APPENDIX IV

RESULTS OF STATISTICAL ANALYSIS

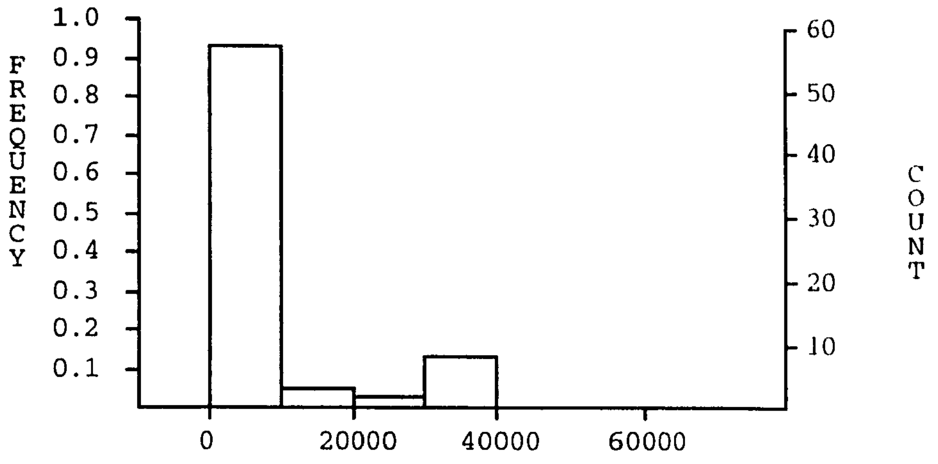


Figure 59. Basin areas for upstream hydrometric stations (N. B.)

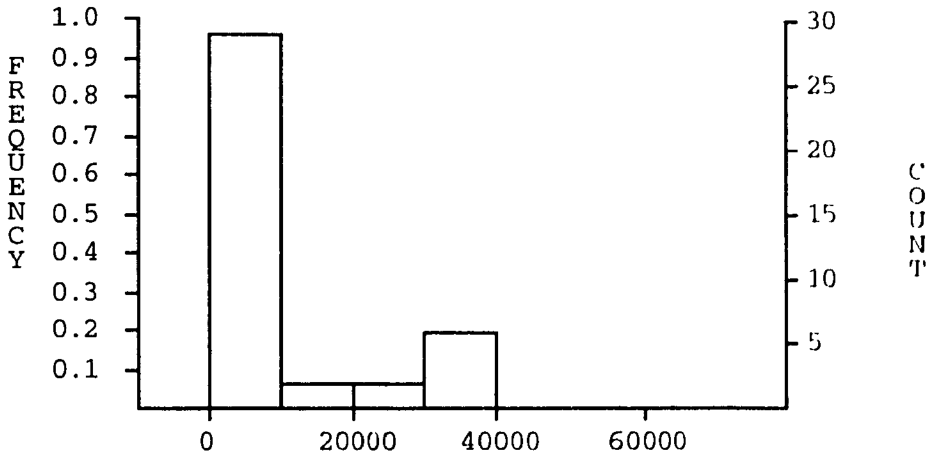


Figure 60. Basin areas for downstream hydrometric stations (N. B.)

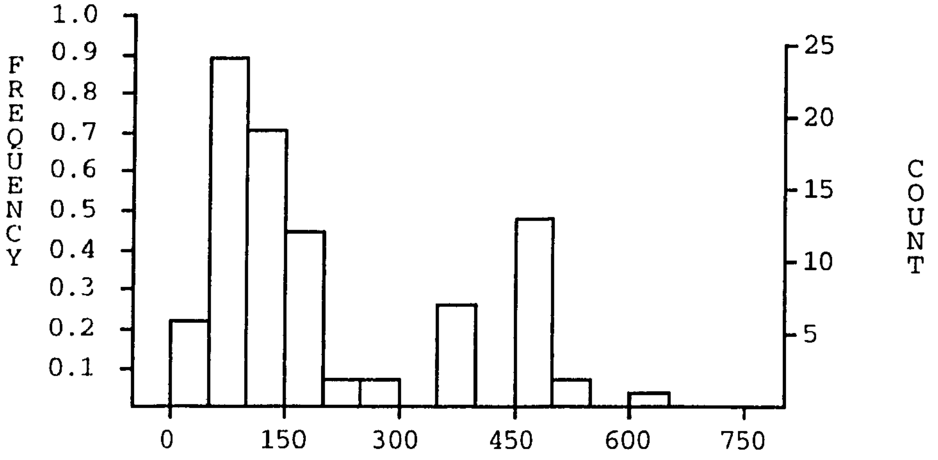


Figure 61. Channel length from source to upstream hydrometric stations (New Brunswick)

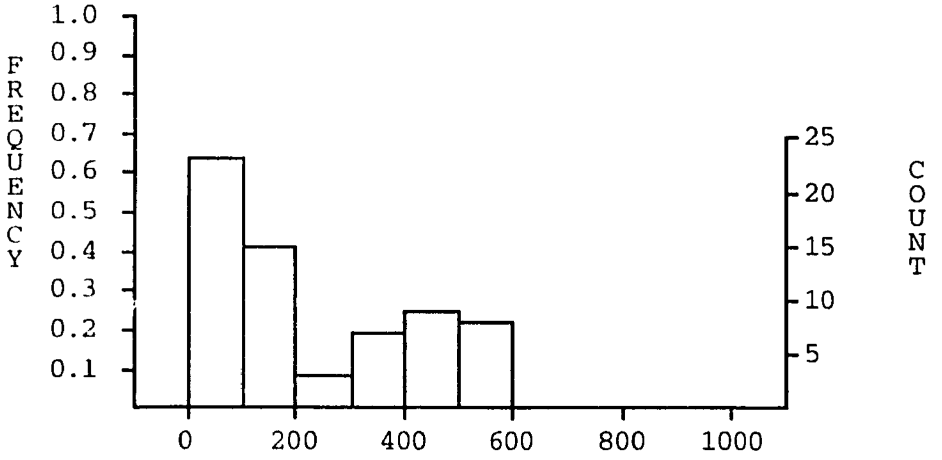


Figure 62. Channel length from source to downstream hydrometric stations (New Brunswick)

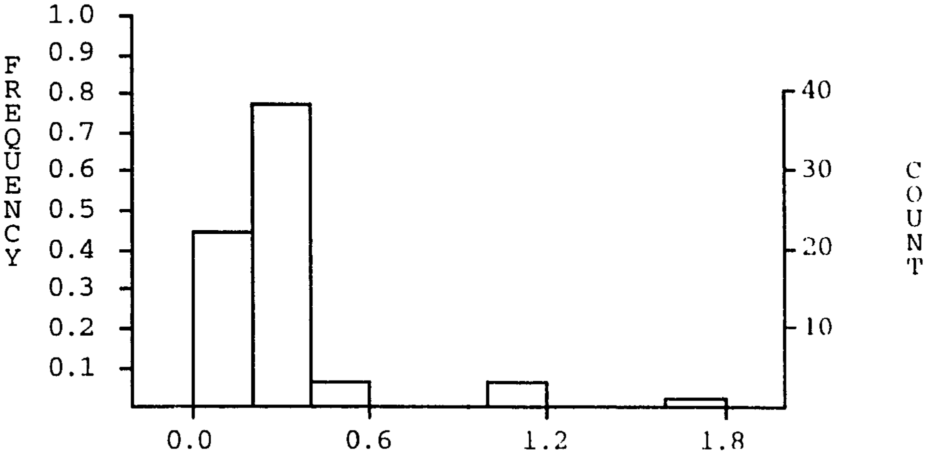


Figure 63. Improved shape factor for upstream hydrometric stations (N. B.)

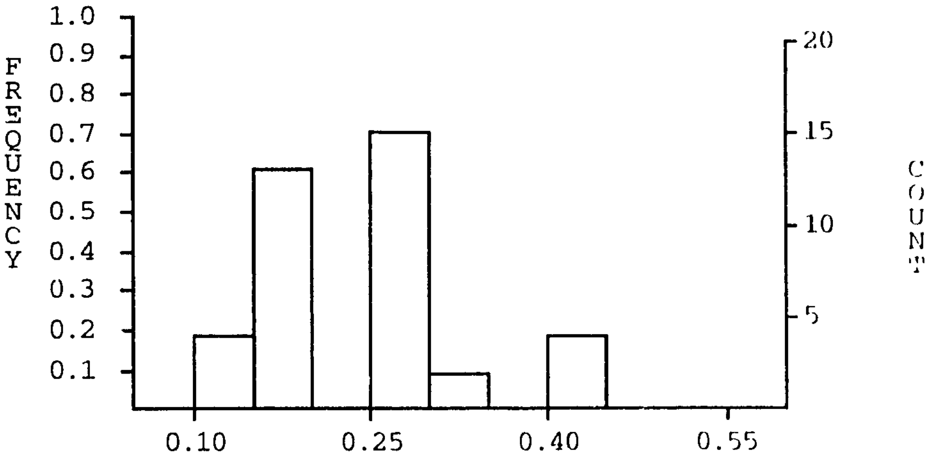


Figure 64. Improved shapefactor for downstream hydrometric stations (N. B)

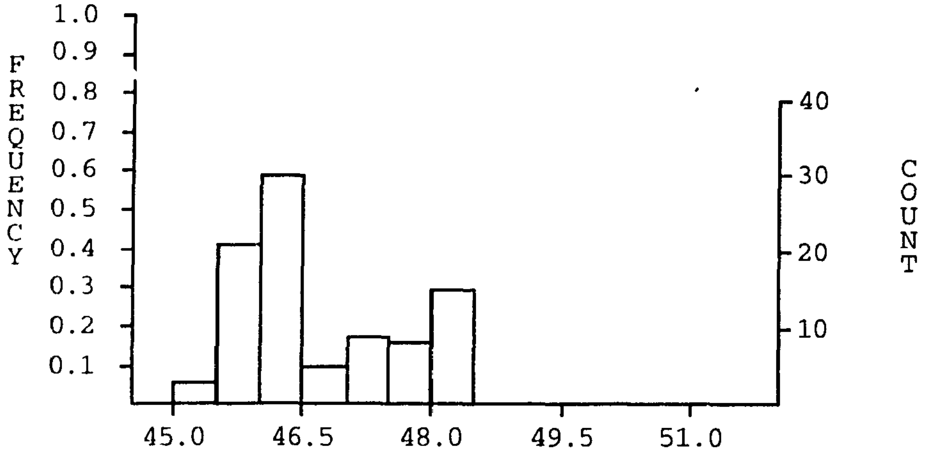


Figure 65. Latitudinal location of upstream hydrometric stations (N. B.)

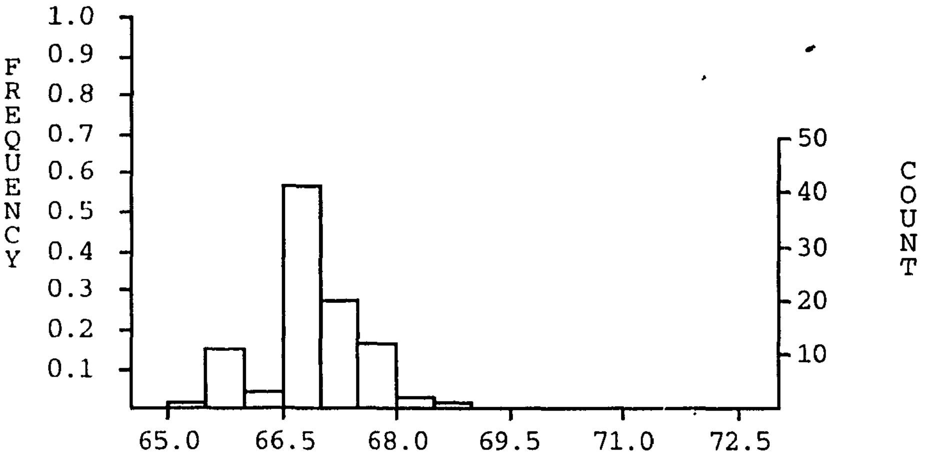


Figure 66. Longitudinal location of upstream hydrometric stations (New Brunswick)

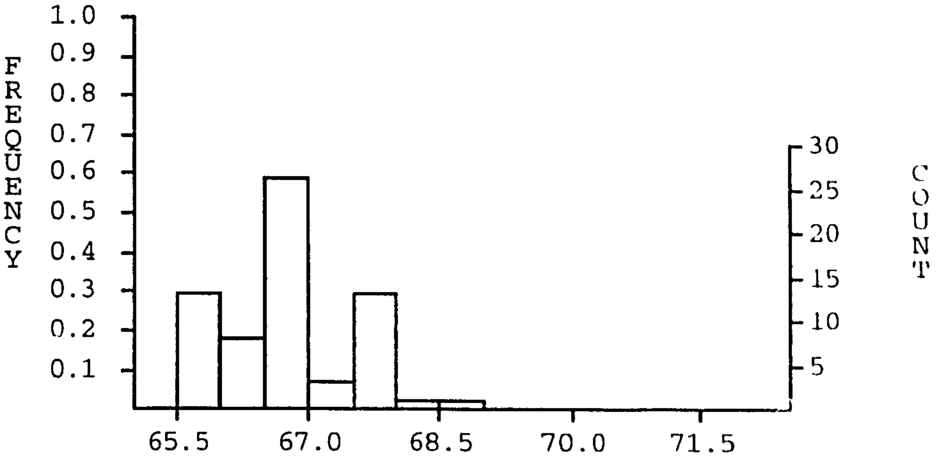


Figure 67. Longitudinal location of downstream hydrometric stations (New Brunswick)

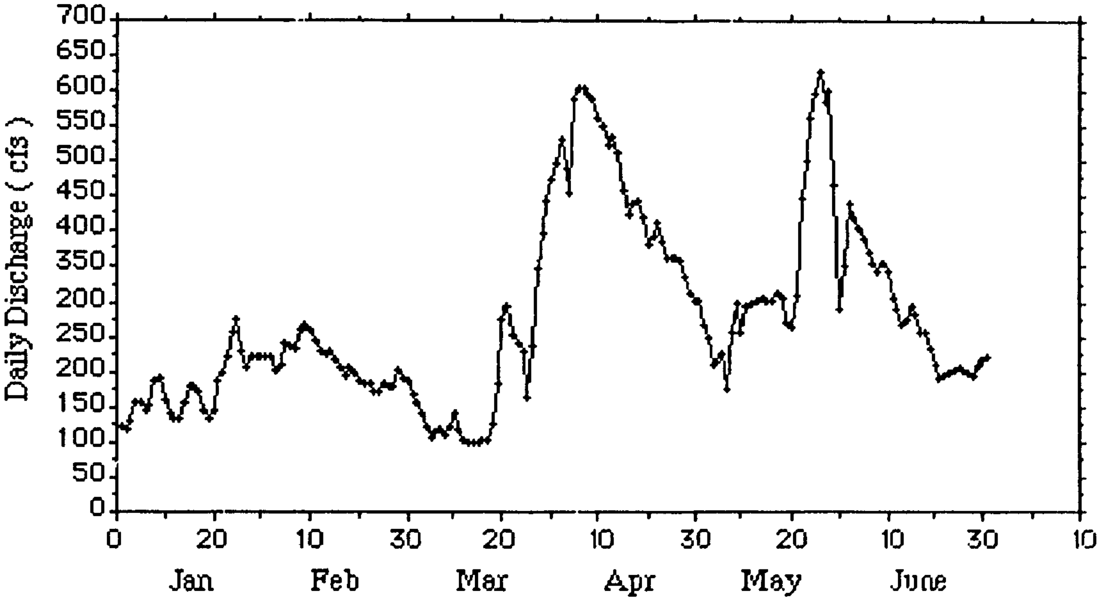


Figure 68. Discharge variations from winter to spring season (Mille Iles river at Bois-De-Filion)

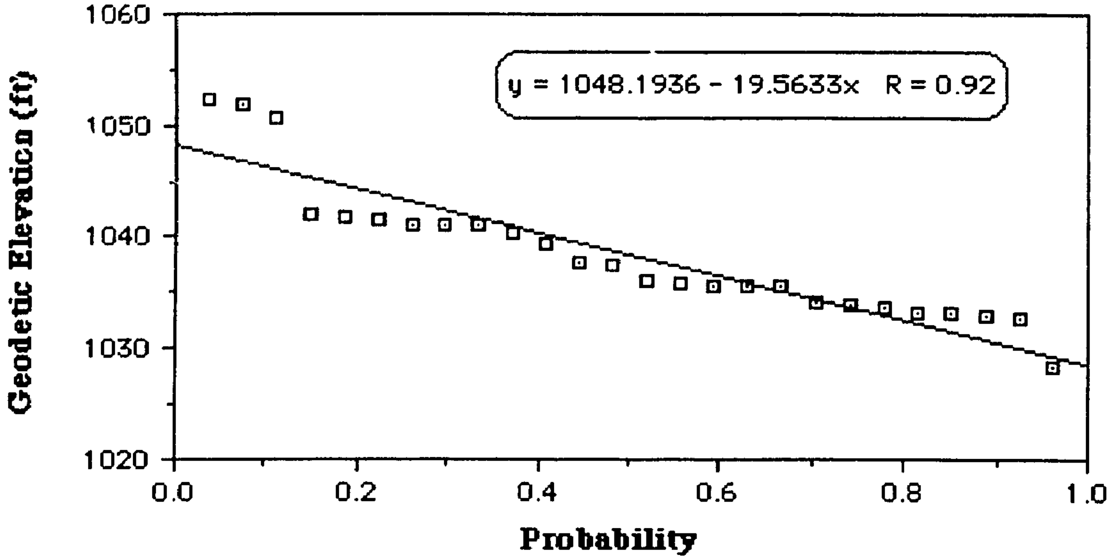


Figure 69. Frequency analysis of Maximum water level elevation at jam

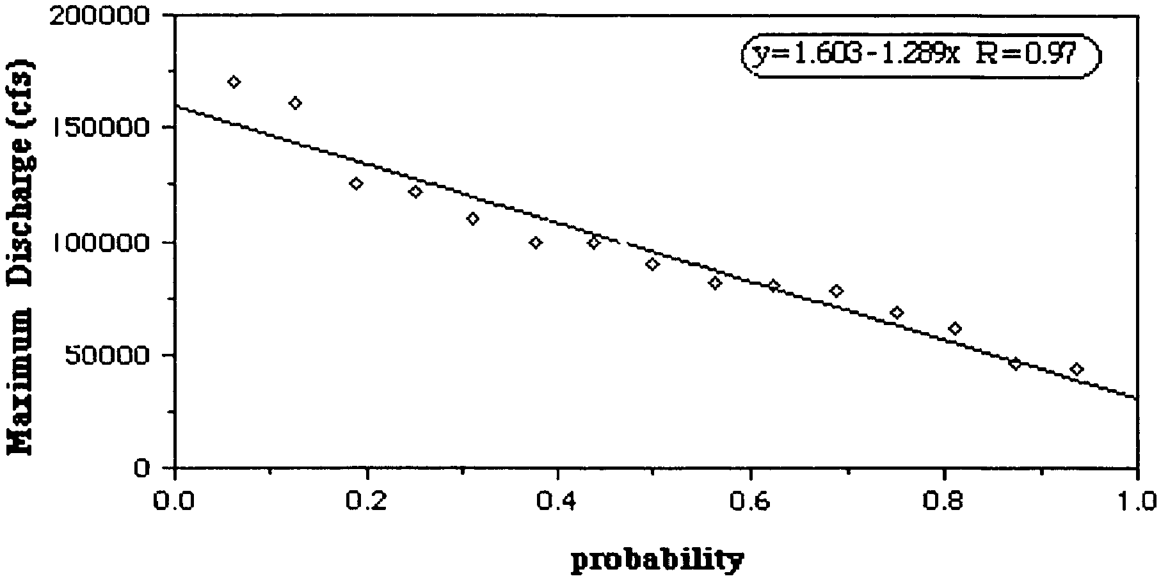


Figure 70. Frequency analysis of Maximum discharge at jam

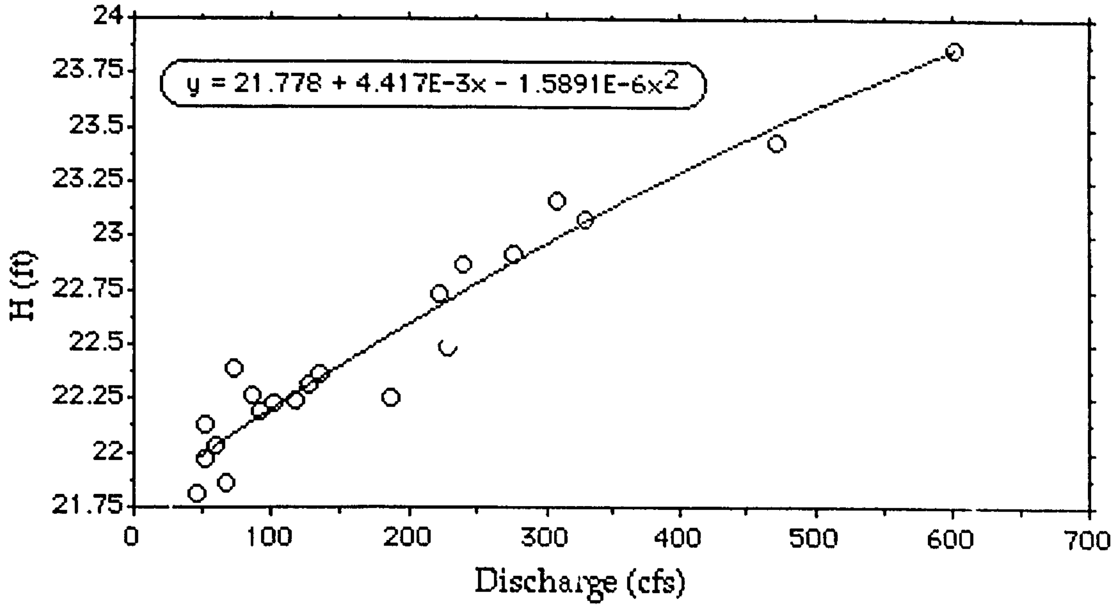


Figure 71. Winter rating curve for Chateauguay river at Chateauguay.

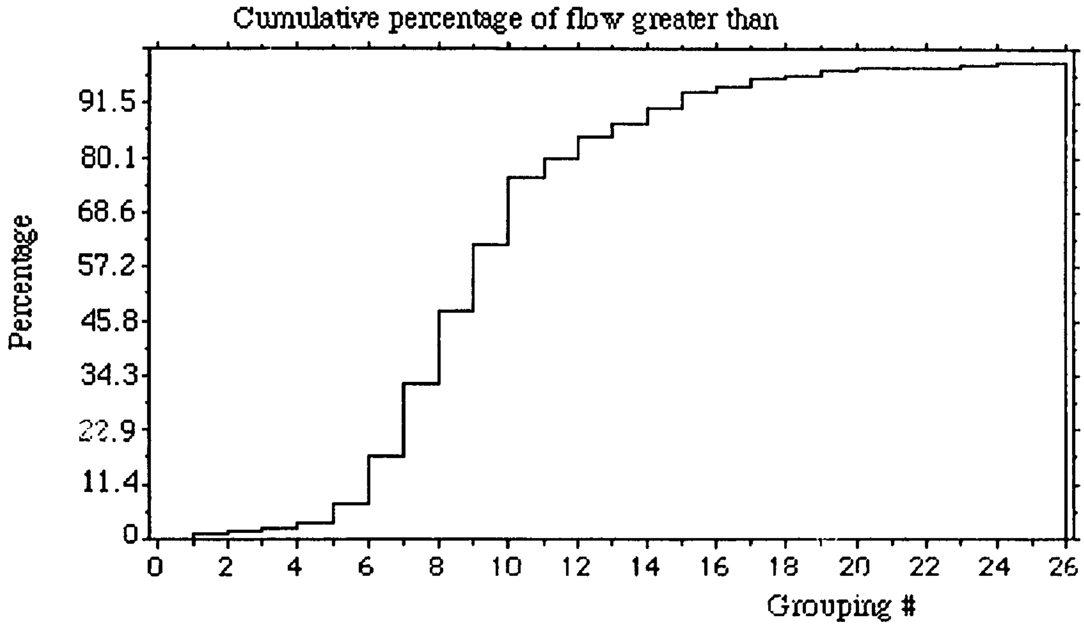


Figure 72. Cumulative percentage of flow Greater than (Chateauguay River)

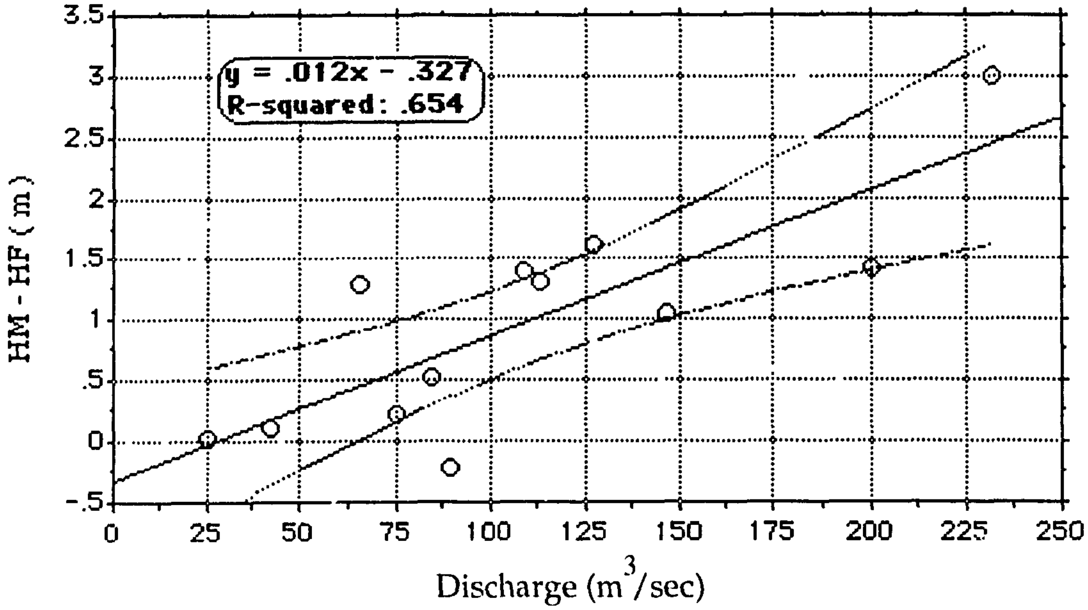


Figure 73. Effect of HM-HF on Discharge (Meduxnekeag River)

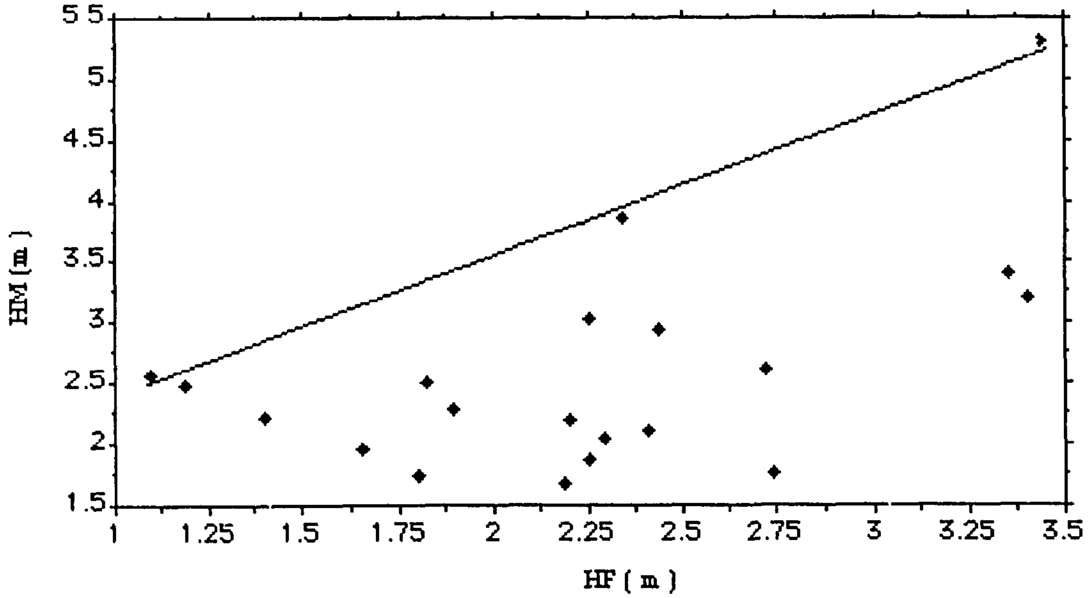


Figure 74. Upper envelope curve for Maximum depth at ice jam vs Freeze up flow depth (Meduxnekeag River)

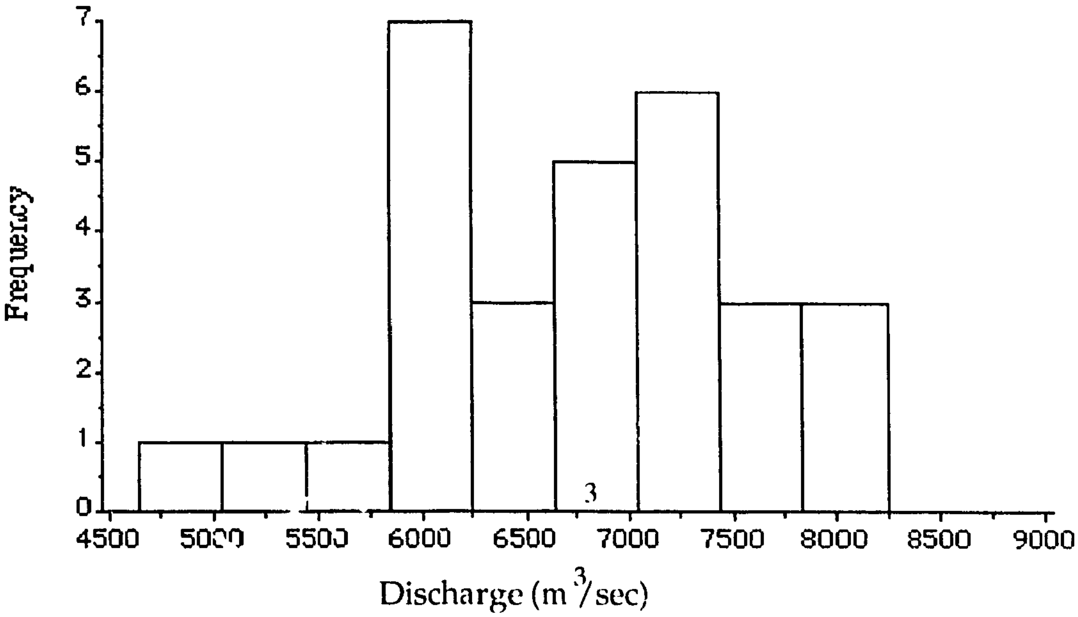


Figure 75. Distribution of discharge during ice jam (Yukon river at Dawson)

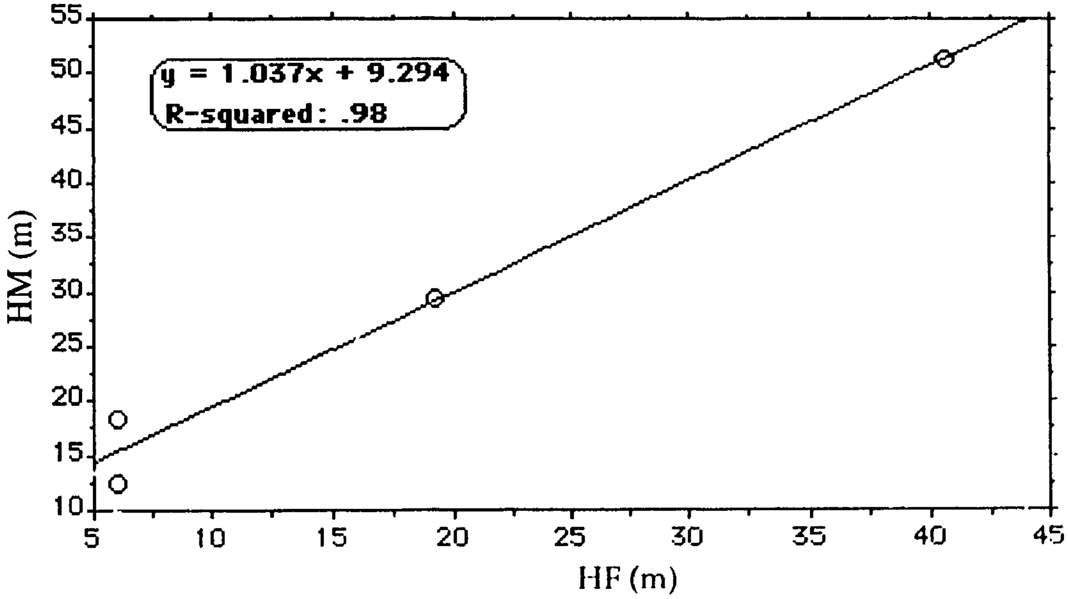


Figure 76. The relationship between maximum depth at ice jam and Freeze up depth (Yukon river at Dawson)

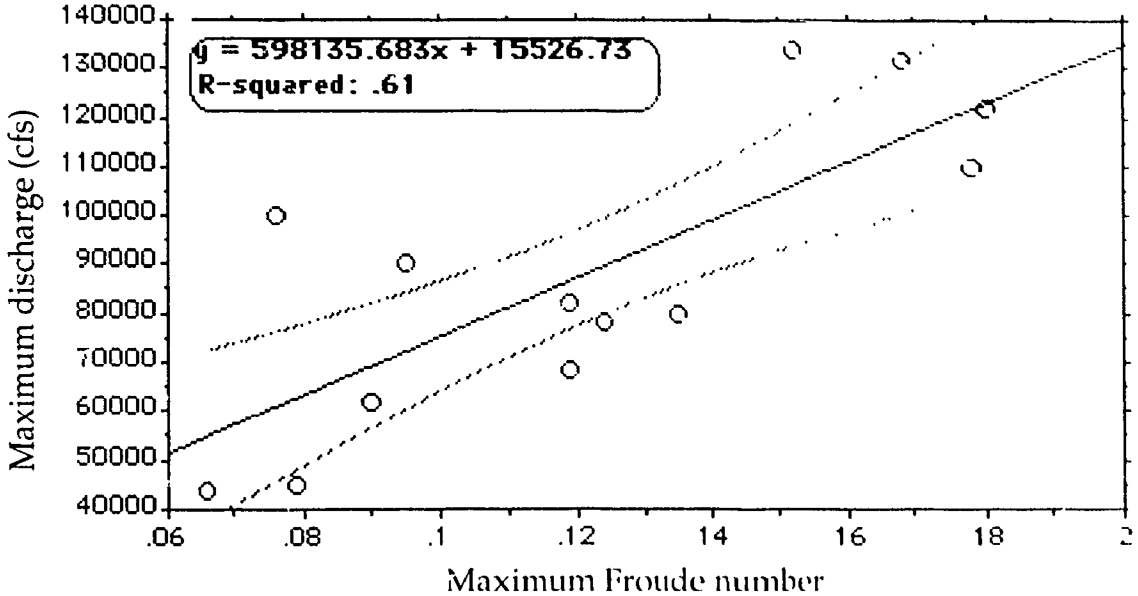


Figure 77. The relationship between maximum discharge and Froude number at ice jam (Yukon river at Dawson)

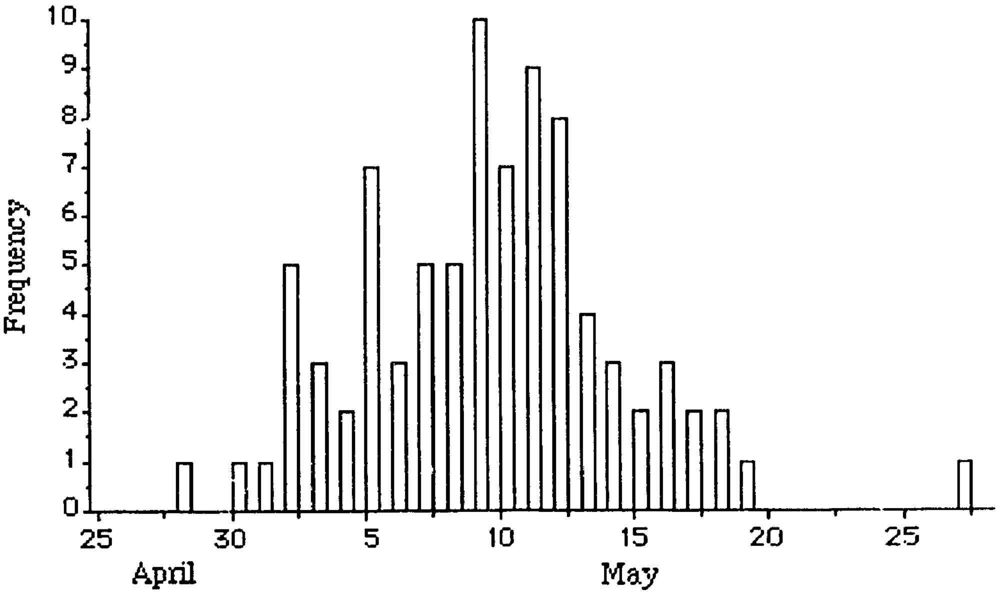


Figure 78. Distribution of probable break-up dates on Yukon River at Dawson

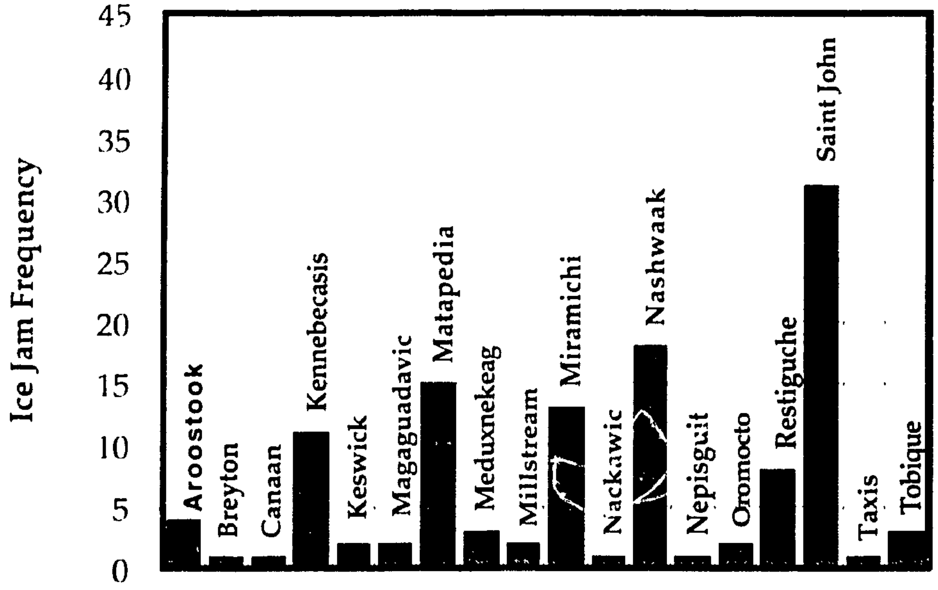


Figure 79. Ice jam frequency in New Brunswick rivers

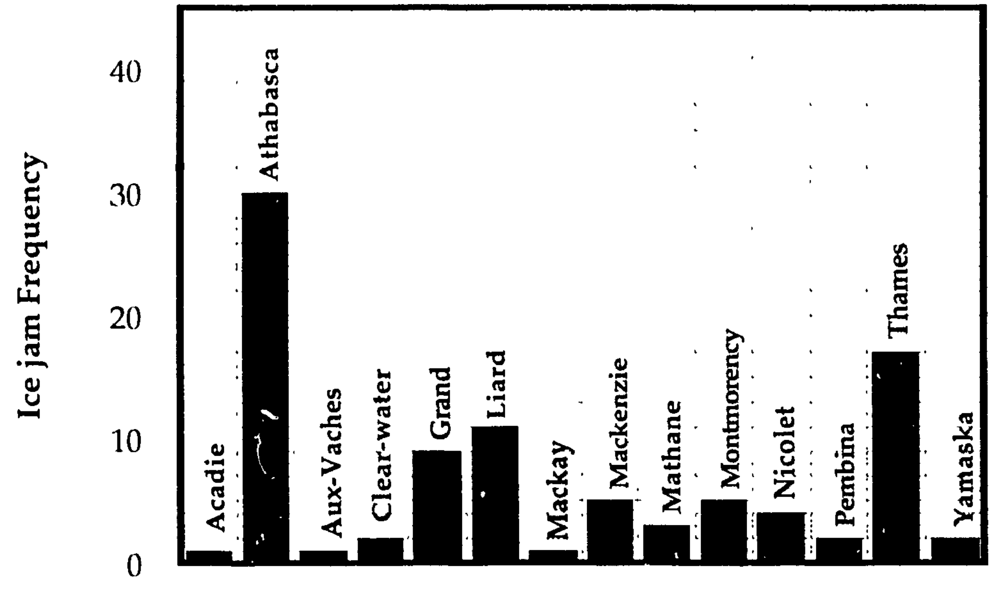


Figure 80. Ice jam frequency in Québec and Alberta rivers

APPENDIX V - TABLES

Table 4. 1 List of ice jams in Alberta, South Ontario, N. W. T. and Qué

No.	River	Jam date	Upstream hydrometric station	Downstream hydrometric station	Meteorology station
1	Grand	820330	Waldemar	Upper Belwood	Waldemar
2	Grand	820325	Waldemar	Upper Belwood	Waldemar
3	Grand	820330	Upper Belwood	Shand dam	Waldemar
4	Grand	820330	Marsville	Upper Belwood	Waldemar
5	Grand	820330	Marsville	Upper Belwood	Waldemar
6	Grand	820330	Marsville	Upper Belwood	Waldemar
7	Grand	820330	Upper Belwood	Shand dam	Fergus sd
8	Grand	820330	Marsville	Upper Belwood	Waldemar
9	Grand	820331	Legatt	Waldemar	Waldemar
10	Thames	800318	Dutton	Thamesville	Delhi
11	Thames	800318	Dutton	Thamesville	Delhi
12	Thames	800318	Thamesville	Chatham	Simcoe
13	Thames	800319	Thamesville	Chatham	Simcoe
14	Thames	800320	Chatham	N/A	Harrow
15	Thames	810218	Dutton	Thamesville	Delhi
16	Thames	810219	Thamesville	Chatham	Simcoe
17	Thames	810220	Thamesville	Chatham	Simcoe
18	Thames	810220	Thamesville	Chatham	Simcoe
19	Thames	810221	Chatham	N/A	Harrow
20	Thames	810222	Chatham	N/A	Harrow
21	Thames	820313	Dutton	Thamesville	Delhi
22	Thames	820316	Thamesville	Chatham	Simcoe
23	Thames	820319	Thamesville	Chatham	Simcoe
24	Thames	820318	Thamesville	Chatham	Simcoe
25	Thames	820319	Chatham	N/A	Harrow
26	Thames	830205	Thamesville	Chatham	Simcoe

W. T. and Québec rivers and their relevant parameters

Meteorology station	Upstream drainage area (km2)	Downstream drainage area (km2)	Length from source to u/s hyd. stn (km)	Length from source to d/s hyd. stn (km) (km)	Latitude of upstream station	Longitude of upstream station
Waldemar	655	756	54.3	62.8	43.897	80.283
Waldemar	655	756	54.3	62.8	43.897	80.283
Waldemar	756	N/A	62.8	74.6	43.829	80.299
Waldemar	694	756	57	62.8	43.862	80.273
Waldemar	694	756	57	62.8	43.862	80.273
Waldemar	694	756	57	62.8	43.862	80.273
Fergus sd	756	N/A	62.8	74.6	43.829	80.299
Waldemar	694	756	57	62.8	43.862	80.273
Waldemar	381	655	38	54.3	43.966	80.35
Delhi	3760	4300	120	182.6	42.731	81.579
Delhi	3760	4300	120	182.6	42.731	81.579
Simcoe	4300	4610	182.6	217.4	42.545	81.968
Simcoe	4300	4610	182.6	217.4	42.545	81.968
Harrow	4610	N/A	217.4	N/A	42.414	82.178
Delhi	3760	4300	120	182.6	42.731	81.579
Simcoe	4300	4610	182.6	217.4	42.545	81.968
Simcoe	4300	4610	182.6	217.4	42.545	81.968
Simcoe	4300	4610	182.6	217.4	42.545	81.968
Harrow	4610	N/A	217.4	N/A	42.414	82.178
Harrow	4610	N/A	217.4	N/A	42.414	82.178
Delhi	3760	4300	120	182.6	42.731	81.579
Simcoe	4300	4610	182.6	217.4	42.545	81.968
Simcoe	4300	4610	182.6	217.4	42.545	81.968
Simcoe	4300	4610	182.6	217.4	42.545	81.968
Harrow	4610	N/A	217.4	N/A	42.414	82.178
Simcoe	4300	4610	182.6	217.4	42.545	81.968

Latitude of upstream station	Longitude of upstream station	Latitude of downstream station	Longitude of downstream station	Bed slope	Ice thickness (cm)	Jam length (km)	AFDD
43.897	80.283	43.829	80.299	0.0014	28	0.6	754
43.897	80.283	43.829	80.299	0.0014	28	0.55	745
43.829	80.299	43.731	80.343	0.0014	28	N/A	754
43.862	80.273	43.829	80.299	0.0014	28	0.23	754
43.862	80.273	43.829	80.299	0.0014	28	0.2	754
43.862	80.273	43.829	80.299	0.0014	28	0.15	754
43.829	80.299	43.731	80.343	0.00073	28	0.9	884
43.862	80.273	43.829	80.299	0.00073	28	0.6	754
43.966	80.35	43.897	80.283	0.0014	28	0.12	753
42.731	81.579	42.545	81.968	9.5E-05	34		558
42.731	81.579	42.545	81.968	9.5E-05	12		558
42.545	81.968	42.414	82.178	9.5E-05	18		539
42.545	81.968	42.414	82.178	0.00024	20		534
42.414	82.178	N/A	N/A	N/A	21		422
42.731	81.579	42.545	81.968	9.5E-05	25	0.6	827
42.545	81.968	42.414	82.178	0.00024	31	3.2	558
42.545	81.968	42.414	82.178	0.00024	32	5	558
42.545	81.968	42.414	82.178	0.00024	33	5.7	558
42.414	82.178	N/A	N/A	N/A	34	1.9	485
42.414	82.178	N/A	N/A	N/A	40	3.9	485
42.731	81.579	42.545	81.968	9.5E-05	45	0.7	633
42.545	81.968	42.414	82.178	0.00024	33.4	1.8	535
42.545	81.968	42.414	82.178	0.00024	45.7	1.9	535
42.545	81.968	42.414	82.178	0 00024	45.7	1.5	5359
42.414	82.178	N/A	N/A	N/A	31		576
42.545	81.968	42.414	82.178	0.00024	39.4		

Ice thickness (cm)	Jam length (km)	AFDD	Upstream Freezeup date	Downstream Freezeup date	Upstream break up date	Downstream break up date
28	0.6	754				
28	0.55	745				
28	N/A	754		Jan. 10		Mar. 16
28	0.23	754	Dec. 9		Mar. 31	
28	0.2	754	Dec. 9		Mar. 31	
28	0.15	754	Dec. 9		Mar. 31	
28	0.9	884		Jan. 10		Mar. 16
28	0.6	754	Dec. 9			
28	0.12	753				
34		558	Dec. 20		Mar. 18	
12		558	Dec. 20		Mar. 18	
18		539	Dec. 19		Mar. 18	
20		534	Dec. 19		Mar. 18	
21		422				
25	0.6	827	Dec. 15	Dec. 15	Feb. 21	Feb. 20
31	3.2	558	Dec. 15		Feb. 20	
32	5	558	Dec. 15		Feb. 20	
33	5.7	558	Dec. 15		Feb. 20	
34	1.9	485				
40	3.9	485				
45	0.7	633	Dec. 19	Dec. 19	Mar. 19	Mar. 19
33.4	1.8	535	Dec. 19		Mar. 19	
45.7	1.9	535	Dec. 19		Mar. 19	
45.7	1.5	5359	Dec. 19		Mar. 19	
31		576				
39.4			Jan. 18		Feb. 20	

Table 4. 1 Continued ....

No.	River	Jam date	Upstream hydrometric station	Downstream hydrometric station	Meteorology station
28	Liard	830426	10ED001	10ED002	F. Nelson
29	Liard	830429	10ED002	10GC001	F. Simpson
30	Liard	830430	10ED002	10GC001	F. Simpson
31	Liard	840429	10ED002	10GC001	F. Simpson
32	Mackenzie	840504	10GC001	10HC001	F. Simpson
33	Liard	850424	10BE005	10ED001	F.Nelson
34	Liard	850502	10BE005	10ED001	F.Nelson
35	Liard	850505	10ED001	10ED002	Muncho L.
36	Liard	850508	10ED002	10GC001	F. Simpson
37	Liard	850509	10ED001	10ED002	F. Simpson
38	Mackenzie	850510	10GC001	10HC001	F. Simpson
39	Athabasca	770414	07DA001	07DD001	Bitumont
40	Athabasca	770416	07DA001	07DD001	Bitumont
41	Athabasca	770416	07DA001	07DD001	Ells Lo.
42	Clearwater	770415	07CD005	07CD001	F. Mcmurray
43	Clearwater	770415	07CD005	07CD001	F. Mcmurray
44	Athabasca	780415	07BE001	07DA001	F. Mcmurray
45	Athabasca	780419	07BE001	07DA001	F. Mcmurray
46	Athabasca	780419	07BE001	07DA001	F. Mcmurray
47	Athabasca	780419	07BE001	07DA001	F. Mcmurray
48	Athabasca	790426	07BE001	07DA001	Grande Lo.
49	Athabasca	790428	07BE001	07DA001	Livock Lo.
50	Athabasca	790428	07BE001	07DA001	F. Mcmurray
51	Athabasca	790429	07DA001	07DD001	F. Mcmurray
52	Athabasca	790429	07DA001	07DD001	F. Mcmurray
53	Mackay	790430	07DB001	N/A	Mildred L.

Meteorology station	Upstream drainage area (km2)	Downstream drainage area (km2)	Length from source to u/s hyd. stn (km)	Length from source to d/s hyd. stn (km) (km)	Latitude of upstream station	Longitude of upstream station
F. Nelson	222000	277000	705.5	1017	60.243	123.479
F. Simpson	277000	1270000	1017	336	61.747	121.224
F. Simpson	277000	1270000	1017	336	61.747	121.224
F. Simpson	277000	1270000	1017	336	61.747	121.224
F. Simpson	1270000	N/A	336	580	61.869	121.357
F.Nelson	119000	222000	561	705.5	59.743	124.476
F.Nelson	119000	222000	561	705.5	59.743	124.476
Muncho L.	222000	277000	705.5	1017	60.243	123.479
F. Simpson	277000	1270000	1017	336	61.747	121.224
F. Simpson	222000	277000	705.5	1017	60.243	123.479
F. Simpson	1270000	N/A	336	580	61.869	121.357
Bitumont	133000	155000	1109.7	1282.1	56.781	111.4
Bitumont	133000	155000	1109.7	1282.1	56.781	111.4
Ells Lo.	133000	155000	1109.7	1282.1	56.781	111.4
F. Mcmurray	17700	30800	372	385.8	56.661	110.928
F. Mcmurray	17700	30800	372	385.8	56.661	110.928
F. Mcmurray	74600	133000	720.5	1109.7	54.722	113.286
F. Mcmurray	74600	133000	720.5	1109.7	54.722	113.286
F. Mcmurray	74600	133000	720.5	1109.7	54.722	113.286
F. Mcmurray	74600	133000	720.5	1109.7	54.722	113.286
Grande Lo.	74600	133000	720.5	1109.7	54.722	113.286
Livock Lo.	74600	133000	720.5	1109.7	54.722	113.286
F. Mcmurray	74600	133000	720.5	1109.7	54.722	113.286
F. Mcmurray	133000	155000	1109.7	1282.1	56.781	111.4
F. Mcmurray	133000	155000	1109.7	1282.1	56.781	111.4
Mildred L.	5570	N/A	150		57.211	111.693

Longitude of upstream station	Latitude of downstream station	Longitude of downstream station	Bed slope	Ice thickness (cm)	Jam length (km)	AFDD	Upstream Freezeup date	Down Fre d
123.479	61.747	121.224			3	2699	Nov. 7	
121.224	61.869	121.357			6	3508	Oct. 29	
121.224	61.869	121.357			21.5	3508	Oct. 29	
121.224	61.869	121.357			11.1	2969	Oct. 25	
121.357	63.266	123.6				2969	Nov. 18	
124.476	60.243	123.479				2474		
124.476	60.243	123.479				2488		
123.479	61.747	121.224			15	1663	Oct. 30	
121.224	61.869	121.357			37	3153	Oct. 27	
123.479	61.747	121.224				3153	Oct. 30	
121.357	63.266	123.6				3147	Nov. 6	
111.4	58.205	111.39	0.0014		23	1576	Nov. 6	
111.4	58.205	111.39	0.0014		9	1576	Nov. 6	
111.4	58.205	111.39	0.0014		18	1576	Nov. 3	
110.928	56.685	111.254			26	1575	Nov. 3	
110.928	56.685	111.254			3	1575	Nov. 3	
113.286	56.781	111.4	0.0011		9	2267	Nov. 15	
113.286	56.781	111.4	0.0011		4	2271	Nov. 15	
113.286	56.781	111.4	0.0011			2271	Nov. 15	
113.286	56.781	111.4	0.0014		22	2271	Nov. 15	
113.286	56.781	111.4	0.0011			2665	Nov. 21	
113.286	56.781	111.4	0.0011		8	2665	Nov. 21	
113.286	56.781	111.4	0.0011			2665	Nov. 21	
111.4	58.205	111.39	0.0014		25	2665	Nov. 8	
111.4	58.205	111.39	0.0014			2665	Nov. 8	
111.693			0.0014		6	2842	Nov. 6	

pe	Ice thickness (cm)	Jam length (km)	AFDD	Upstream Freezeup date	Downstream Freezeup date	Upstream break up date	Downstream break up date
		3	2699	Nov. 7	Oct. 29	Apr. 30	May-12
		6	3508	Oct. 29	Nov. 6	May-12	May-22
		21.5	3508	Oct. 29	Nov. 6	May-12	May-22
		11.1	2969	Oct. 25	Nov. 18	May-04	May-10
			2969	Nov. 18		May-10	
			2474		Oct. 30	May-12	May-09
			2488		Oct. 30	May-12	May-09
		15	1663	Oct. 30	Oct. 27	May-09	May-16
		37	3153	Oct. 27	Nov. 3	May-16	May-17
			3153	Oct. 30	Oct. 27	May-09	May-16
			3147	Nov. 6		May-17	
14		23	1576	Nov. 6		Apr. 29	Apr. 25
14		9	1576	Nov. 6		Apr. 29	Apr. 25
14		18	1576	Nov. 3		Apr. 29	Apr. 25
		26	1575	Nov. 3	Nov. 12	Apr. 25	Apr. 28
		3	1575	Nov. 3	Nov. 12	Apr. 25	Apr. 28
11		9	2267	Nov. 15	Nov. 13	Apr. 18	Apr. 28
11		4	2271	Nov. 15	Nov. 13	Apr. 18	Apr. 28
11			2271	Nov. 15	Nov. 13	Apr. 18	Apr. 28
14		22	2271	Nov. 15	Nov. 13	Apr. 18	Apr. 28
11			2665	Nov. 21	Nov. 8	May-04	May-11
11		8	2665	Nov. 21	Nov. 8	May-04	May-11
11			2665	Nov. 21	Nov. 8	May-04	May-11
14		25	2665	Nov. 8	Nov. 9	May-11	
14			2665	Nov. 8	Nov. 9	May-11	
14		6	2842	Nov. 6		May-07	

Table 4. 1 Continued ....

No.	River	Jam date	Upstream hydrometric station	Downstream hydrometric station	Meteorology station
54	Athabasca	830418	07BE001	07DA001	F. Mcmurray
55	Athabasca	830419	07BE001	07DA001	F. Mcmurray
56	Athabasca	840409	07BE001	07DA001	Smith
57	Athabasca	840409	07BE001	07DA001	F. Mcmurray
58	Athabasca	840410	07BE001	07DA001	Grande Lo.
59	Athabasca	840410	07BE001	07DA001	Grande Lo.
60	Athabasca	840410	07DA001	07DD001	Tar Island
61	Athabasca	840410	07BE001	07DA001	F. Mcmurray
62	Pembina	850406	07BC002	N/A	Cross L.
63	Athabasca	850410	N/A	N/A	Smith
64	Athabasca	850412	N/A	N/A	Wandering
65	Athabasca	850413	07BE001	07DA001	Wandering
66	Athabasca	850413	N/A	N/A	Calling L.
67	Athabasca	850413	N/A	N/A	F. Mcmurray
68	Athabasca	850413	07BE001	07DA001	F. Mcmurray
69	Athabasca	850414	07BE001	07DA001	Smith RS
70	Athabasca	850413	07BE001	07DA001	F. Mcmurray
71	Athabasca	850417	07BE001	07DA001	May Lo.
72	Athabasca	850414	07BE001	07DA001	F. Mcmurray
73	Pembina	850406	07BC002	N/A	Athabasca
74	Mackenzie	820519	10KA001	10KD001	Normanwell
75	Mackenzie	820520	10KA001	10KD001	Normanwell
76	Mackenzie	820524	10LA003	10LC006	Inuvik
77	Mackenzie	820524	10LC006	N/A	Inuvik
78	Nicolet	740305	30103	N/A	Nicolet
79	Nicolet	760326	30103	N/A	Nicolet

Meteorology station	Upstream drainage area (km2)	Downstream drainage area (km2)	Length from source to u/s hyd. stn (km)	Length from source to d/s hyd. stn (km) (km)	Latitude of upstream station	Longitude of upstream station
F. Mcmurray	74600	133000	720.5	1109.7	54.722	113.286
F. Mcmurray	74600	133000	720.5	1109.7	54.722	113.286
Smith	74600	133000	720.5	1109.7	54.722	113.286
F. Mcmurray	74600	133000	720.5	1109.7	54.722	113.286
Grande Lo.	74600	133000	720.5	1109.7	54.722	113.286
Grande Lo.	74600	133000	720.5	1109.7	54.722	113.286
Tar Island	133000	155000	1109.7	1282.1	56.781	111.4
F. Mcmurray	74600	133000	720.5	1109.7	54.722	113.286
Cross L.	13100		597.3		54.356	114.011
Smith						
Wandering						
Wandering	74600	133000	720.5	1109.7	54.722	113.286
Calling L.						
F. Mcmurray						
F. Mcmurray	74600	133000	720.5	1109.7	54.722	113.286
Smith RS	74600	133000	720.5	1109.7	54.722	113.286
F. Mcmurray	74600	133000	720.5	1109.7	54.722	113.286
May Lo.	74600	133000	720.5	1109.7	54.722	113.286
F. Mcmurray	74600	133000	720.5	1109.7	54.722	113.286
Athabasca	13100		597.3		54.451	113.992
Normanwell	157000		910	990	65.282	126.849
Normanwell	157000		910	990	65.282	126.849
Inuvik	166000		1455	1650	67.358	133.558
Inuvik			1650		68.397	133.983
Nicolet	1540				46.056	72.306
Nicolet	1540				46.056	72.306

of m n	Longitude of upstream station	Latitude of downstream station	Longitude of downstream station	Bed slope	Ice thickness (cm)	Jam length (km)	AFDD	Upstream Freezeup date	Do I
2	113.286	56.781	111.4	0.0011		6	2034		
2	113.286	56.781	111.4		81	6	2034	Nov. 26	
2	113.286	56.781	111.4	0.00026	81	3	1261	Nov. 26	
2	113.286	56.781	111.4	0.0011	81	8	1753	Nov. 26	
2	113.286	56.781	111.4	0.00068	81	39	1756	Nov. 26	
2	113.286	56.781	111.4	0.0011	81	39	1756	Nov. 26	
1	111.4	58.205	111.39	0.0014	81	41	1756	Nov. 23	
2	113.286	56.781	111.4	0.0011	81		1756	Nov. 26	
6	114.011			0.00026		10	1891	Oct. 23	
				0.00038		4	1752		
				0.0014		9	1996		
2	113.286	56.781	111.4	0.00038		5	1996	Nov. 28	
				0.00068		13	1996		
				0.00068		8	2174		
2	113.286	56.781	111.4	0.0011		3	2174	Nov. 28	
2	113.286	56.781	111.4	0.00068		9	1752	Nov. 28	
2	113.286	56.781	111.4	0.0011		18	2174	Nov. 28	
2	113.286	56.781	111.4	0.00068		5	1996	Nov. 28	
2	113.286	56.781	111.4	0.00011			2176	Nov. 28	
1	113.992			0.0026		10	1729	Oct. 23	
2	126.849	65.765	128.751				3538		
2	126.849	65.765	128.751				3538		
3	133.558	68.397	133.983				4358		
7	133.983						4358		
6	72.306					4			
6	72.306							Dec. 21	

Ice thickness (cm)	Jam length (km)	AFDD	Upstream Freezeup date	Downstream Freezeup date	Upstream break up date	Downstream break up date
	6	2034			Apr. 21	Apr. 25
81	6	2034	Nov. 26	Nov. 23	Apr. 21	Apr. 25
81	3	1261	Nov. 26	Nov. 23	Apr. 9	Apr. 17
81	8	1753	Nov. 26	Nov. 23	Apr. 9	Apr. 17
81	39	1756	Nov. 26	Nov. 23	Apr. 9	Apr. 17
81	39	1756	Nov. 26	Nov. 23	Apr. 9	Apr. 17
81	41	1756	Nov. 23		Apr. 17	
81		1756	Nov. 26	Nov. 23	Apr. 9	Apr. 17
	10	1891	Oct. 23		Apr. 8	
	4	1752				
	9	1996				
	5	1996	Nov. 28	Oct. 27	Apr. 14	Apr. 26
	13	1996				
	8	2174				
	3	2174	Nov. 28	Oct. 27	Apr. 14	Apr. 26
	9	1752	Nov. 28	Oct. 27	Apr. 14	Apr. 26
	18	2174	Nov. 28	Oct. 27	Apr. 14	Apr. 26
	5	1996	Nov. 28	Oct. 27	Apr. 14	Apr. 26
		2176	Nov. 28	Oct. 27	Apr. 14	Apr. 26
	10	1729	Oct. 23		Apr. 8	
		3538			May-24	
		3538			May-24	
		4358			Jun-04	
		4358				
	4					
			Dec. 21		Jan. 27	

Table 4. 1 Continued ....

No.	River	Jam date	Upstream hydrometric station	Downstream hydrometric station	Meteorology station	Upstr drain are (km
80	Nicolet	800230	30103	N/A	Nicolet	1
81	Nicolet	800230	30103	N/A	Nicolet	1
82	Mathane	760402	21601	N/A	Mathane	1
83	Mathane	610529	21601	N/A	Mathane	1
84	Mathane	1974	21601	N/A	Mathane	1
85	Acadie	740404	30421	N/A	N/A	
86	Montmorency	640415	51008	51001	Montmorency	
87	Montmorency	641228	51008	51001	Montmorency	
88	Montmorency	1973	51008	51001	Montmorency	
89	Montmorency	7801	51008	51001	Montmorency	
90	Montmorency	780209	51008	51001	Montmorency	
91	Aux Vaches	1979	N/A	N/A	N/A	
92	Yamaska	780414	O30309	0303A0	Cowansville	
93	Yamaska		30415	N/A	Cowansville	

y	Upstream drainage area (km2)	Downstream drainage area (km2)	Length from source to u/s hyd. stn (km)	Length from source to d/s hyd. stn (km) (km)	Latitude of upstream station	Longitude of upstream station	Latitude of downstream station
	1540				46.056	72.306	
	1540				46.056	72.306	
	1650				48.774	67.542	
	1650				48.774	67.542	
	1650				48.774	67.542	
	325				45.39	73.371	
cy	121	1100			47.406	71.186	
cy	121	1100			47.406	71.186	
cy	121	1100			47.406	71.186	
cy	121	1100			47.406	71.186	
cy	121	1100			47.406	71.186	
e	153				45.416	72.622	45.324
e	257				45.49	73.187	

e of m	Latitude of downstream station	Longitude of downstream station	Bed slope	Ice thickness (cm)	Jam length (km)	AFDD	Upstream Freezeup date	Downstream Freezeup date	U b
							Dec. 4		
					3.2				
	45.324	72.812							

ope	Ice thickness (cm)	Jam length (km)	AFDD	Upstream Freezeup date	Downstream Freezeup date	Upstream break up date	Downstream break up date
				Dec. 4		Apr. 12	
		3.2					

Table 4 2 List of ice jams in N B and their relevant parameters

No	River	Jam date	Upstream hydrometric station	Downstream hydrometric station	Meteorology station	Upstream drainage area (km2)	Downstream drainage area (km2)	Length from source to u/s hyd stn (km)	Length from source to d/s hyd stn (km) (km)	Latitude of upstream station	Longitude of upstream station	Latitude of downstream station	Longitude of downstream station	Shape factor
1	Tobique	16-24 4 34	01AH002	01AH003	N/A	2230	3130	43 7	86 8	47 173	67 21	46 905	67 395	0 415
2	Tobique	16-24 4 34	01AH002	01AH003	N/A	2230	3130	43 7	86 8	47 173	67 21	46 905	67 395	0 629
3	Saint John	16-24 4 34	01AK004	01AK003	Chipman	39900	N/A	477 8	492 8	45 962	66 831	45 965	66 645	
4	Saint John	16-24 4 34	01AK003	01AP003	Chipman	N/A	N/A	492 8	584 9	45 965	66 645	45 52	66 079	
5	Matapedia	16-24 4 34	011507Q	N/A	Charlo F.	2760	N/A	115		48 087	67 101			0 209
6	Restigouche	16-24.4 34	01BJ007	N/A	Charlo F	7740	N/A	158 5		47 908	66 948			0 308
7	Miramichi	16-24 4.34	N/A	01BO001	Chipman	N/A	5050		180 4			46 736	65.827	0 155
8	Miramichi	16-24 4 34	01BP001	N/A	Chipman	1340	N/A	84 9		46 936	65 907			0 186
9	Saint John	9-12.1 35	01AP003	N/A	Sussex	N/A	N/A	584 9		45 52	66 079			
10	Saint John	20-24 4.35	01AK003	01AO002	Sussex	N/A	N/A	492 8	512 4	45 965	66 645	45 866	66 461	
11	Kennebacasis	20-24.4 35	N/A	01AP004	Sussex		1100		65 1			45 702	65 601	0 26
12	Restigouche	20-24 4 35	01BJ007	N/A	Kedgewick	7740		158 5		47 908	66 948			0 308
13	Miramichi	20-24.4 35	N/A	01BO001	Chipman		5050		180.4			46 736	65 827	0 155
14	Miramichi	20-24 4 35	N/A	01BO001	Chipman		5050		180 4			46.736	65 827	0 155
15	Saint John	16-25 3 36	01AK003	01AO002	Fred unb	N/A	N/A	492 8	512 4	45 965	66 645	45 866	66 461	
16	Saint John	16-25.3 36	01AO002	01AP003	Fred cda	N/A	N/A	512 4	584 9	45 866	66 461	45 52	66.079	
17	Saint John	16-25.3.36	01AO002	01AP003	Harvey	N/A	N/A	512 4	584 9	45 866	66 461	45 52	66.079	
18	Saint John	16-25 3.36	01AK004	01AK003	Harvey	39900	N/A	477 8	492 8	45 962	66 831	45.965	66 645	0 175
19	Saint John	16-25 3.36	01AK009	01AK004	Harvey	N/A	39900	475 3	477 8	45.957	66 865	45.962	66 831	0.175
20	Saint John	16-25 3.36	01AK009	01AK004	Fred. cda	N/A	39900	475.3	477 8	45 957	66 865	45.962	66 831	0 175
21	Oromocto	16-25.3 36	01AM001	01AM002	Harvey	557	N/A	32	52 4	45 674	66 683	45.766	66.551	0 514
22	Nashwaak	16-25.3 36	01AL002	01AL001	Fred. cda	1450	1660	97	112	46.126	66 612	46 009	66 583	0 154
23	Nackawic	16-25 3.36	01AK007	N/A	Woodstock	240	N/A	12		46.049	67 24			
24	Meduxnekeag	16-25.3.36	01AJ003	N/A	Woodstock	1210	N/A			46 216	67 728			
25	Tobique	16-25.3.36	01AH002	01AH003	Woodstock	2230	3130	43 7	86 8	47.173	67 21	46 905	67 395	0 115
26	Saint John	16-25.3.36	01AD004	01AF002	Kedgwick	15500	21900	215 8	280 5	47 361	68 327	47 04	67.742	0 333
27	Matapedia	16-25 3 36	011507Q	N/A	Kedgwick	2760		115		18 087	67 101			0 209
28	Matapedia	16-25 3 36	011507Q	N/A	Kedgwick	2760		115		48.087	67 101			0 209
29	Restigouche	16-25.3.36	01BJ007	N/A	Kedgwick	7740		158 5		47.908	66 948			0 308
30	Miramichi	16-25 3.36	N/A	01BP001	Fred cda		1310		84 9			16 936	65 907	0.186
31	Miramichi	16-25.3.36	N/A	01BQ001	Fred cda		918		89 5			47 095	65 837	0 118
32	Magaguadavic	16-25 3 36	01AQ002	01AQ009	Harvey	1420		68 5	88 6	45.273	66 807	45 16	66 828	0 303
33	Magaguadavic	16-25 3 36	01AQ009	NO	Harvey			88 6		15 16	66 828			
34	Nashwaak	20 4.39	01AL009	01AL002	Fred unb	N/A	1450	82 5	97	46.211	66 613	46 126	66 612	0 154
35	Nashwaak	24 4.39	01AL009	01AL002	Fred unb	N/A	1450	82 5	97	46 211	66 613	46 126	66 612	0 154
36	Nashwaak	24.4 39	01AL009	01AL010	Fred unb	N/A		82 5	89 5	46 241	66 613	46 183	66 619	
37	SW Miramichi	29-30 4 39	01BO001	N/A	Aroostook	5050		180 4		46.736	65 827			0 155
38	Nashwaak	11.4 40	01AL008	01AL009	Fred unb	641		64	82 5	46 283	66 738	16 241	66 613	0 156

Table 4. 2 Continued ....

No.	River	Jam date	Upstream hydrometric station	Downstream hydrometric station	Meteorology station	Upstream drainage area (km2)	Downstream drainage area (km2)	Length from source to u/s hyd stn (km)	Length from source to d/s hyd stn (km)	Latitude of upstream station	Longtude of upstream station	Latitude of downstream station	Longtude of downstream station	Shape factor
39	Nashwaak	15-20.4.40	01AL002	N/A	Fred unb	1450		97		46.126	66.612			0.154
40	Aroostook	15-20.4.40	US gauge	01AG003	Aroostook		6060		145			48.814	67.754	0.288
41	Aroostook	15-20.4.40	US gauge	01AG003	Aroostook		6060		145			48.814	67.754	0.288
42	Saint John	15-20.4.40	01AK009	01AK003	Fred cda			475.3	492.8	45.957	66.865	45.965	66.645	
43	Saint John	15-20.4.40	01AK003	01AO002	Fred unb	N/A	N/A	492.8	512.4	45.965	66.645	45.866	66.461	
44	Saint John	15-20.4.40	01AK003	01AO002	Fred unb			492.8	512.4	45.965	66.645	45.866	66.461	
45	Miramichi	15-20.4.40	01BO001	N/A	Fred unb	5050		180.1		46.736	65.827			0.155
46	Kennebacasis	2-3.2.47	N/A	01AP004	Sussex		1100		65.1			45.702	65.601	0.26
47	Kennebacasis	5-6.2.47	01AP004	N/A	Sussex	1100		65.1		45.702	65.601			0.26
48	Kennebacasis	5-6.2.47	01AP004	N/A	Sussex	1100		65.1		45.702	65.601			0.26
49	Nepisiguit	Jan 1950	01BK003	N/A	Camp.	1840		96.3		47.407	65.795			0.198
50	Matapedia	20-25.4.50	011507Q	N/A	Camp	2760		115		48.087	67.101			0.209
51	Matapedia	20-25.4.50	011507Q	N/A	Camp	2760		115		48.087	67.101			0.209
52	Kennebacasis	7-8.2.51	01AP004	N/A	Sussex	1100		65.1		45.702	65.601			0.26
53	Saint John	5-14.4.51	N/A	01AD002	Edmun		14700		182.8			47.257	68.593	0.44
54	Saint John	5-14.4.51	01AK009	01AK004	Fred unb	N/A	39900	475.3	477.8	45.957	66.865	45.962	66.831	0.175
55	Saint John	5-14.4.51	01AK004	01AK003	fred unb	39900	N/A	477.8	492.8	45.962	66.831	45.965	66.645	0.175
56	Restigouche	5-14.4.51	01BJ007	N/A	Camp	7740		158.7		47.908	66.948			0.308
57	Miramichi	5-14.4.51	01BO001	N/A	Fred unb	5050		180.1		46.736	65.827			0.155
58	Kennebecasis	24-25.1.52	01AP004	N/A	Sussex	1100		65.1		45.702	65.601			0.26
59	Kennebecasis	7-8.2.53	01AP004	N/A	Sussex	1100		65.1		45.702	65.601			0.26
60	Saint John	26.3-3.4.53	01AK003	01AO002	Fred cda	N/A	N/A	492.8	512.4	45.965	66.645	45.866	66.461	
61	Nashwaak	27.3.53	01AL010	01AL002	Fred cda	N/A	1450	89.7	97	46.183	66.619	46.126	66.612	0.151
62	Nashwaak	27.3.53	01AL008	01AL010	Fred cda	641	N/A	64	89.5	46.283	66.738	46.183	66.619	0.156
63	Nashwaak	12.1.56	01AL009	01AL002	N/A	N/A	1450	82.7	97	46.241	66.613	46.126	66.612	
64	Nashwaak	16.1.56	01AL002	01AL001	N/A	1450	1660	97	112	46.126	66.612	46.009	66.583	0.154
65	Matapedia	23.4.59	011507Q	N/A	Camp	2760		115		48.057	67.101			0.209
66	Matapedia	23.4.59	011507Q	N/A	Camp	2760		115		48.057	67.101			0.209
67	Nashwaak	8.1.60	01AL002	01AL001	N/A	1450	1660	97	112	46.126	66.612	46.009	66.583	0.154
68	Nashwaak	12.4.60	01AL008	01AL009	N/A	641	N/A	64	82.7	46.283	66.738	46.241	66.613	0.156
69	Nashwaak	15.4.64	01AL001	N/A	Doak	1660	N/A	112		46.009	66.583			0.132
70	Nashwaak	16-18.4.64	01AL001	N/A	Doak	1660	N/A	112		46.009	66.583			0.132
71	Nashwaak	16-18.4.64	01AL001	N/A	Fred	1660	N/A	112		46.009	66.583			0.132
72	Miramichi	16-18.4.64	N/A	01BO001	Doak		5050		[illegible]			46.736	65.827	0.155
73	Miramichi	16-18.4.64	N/A	01BO001	Doak		5050		[illegible]			46.736	65.827	0.155
74	Matapedia	Mar [illegible]	011507Q	N/A	N/A	2760		[illegible]		48.057	67.101			0.209
75	Saint John	[illegible]	01AJ[illegible]	01AK[illegible]	Centre	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	67.577	0.276
76	Miramichi	[illegible]	01BO001	NO	Chatham	5050		[illegible]		[illegible]	65.827			0.155

Table 4 2 Continued

No	River	Jam date	Upstream hydrometric station	Downstream hydrometric station	Meteorology station	Upstream drainage area (km2)	Downstream drainage area (km2)	Length from source to u/s hyd stn (km)	Length from source to d/s hyd stn (km) (km)	Latitude of upstream station	Longitude of upstream station	Latitude of downstream station	Longitude of downstream station	Shape factor
77	Saint John	20-22 12 73	01AF002	01AJ001	N/A	21900	34200	280 5	352 3	47 04	67 742	46 47	67 59	0 28
78	Aroostook	20-22 12.73	US gauge	01AG003	N/A		6060		145			48 814	67 754	0 288
79	Matapedia	19-24 1.74	011507Q	N/A	Charlo A.	2760		115		48 087	67 101			0 209
80	Saint John	29 4-18 5 74	01AD002	01AD004	Edmunston	14700	15500	182 8	215 8	47 257	68 593	47 361	68 327	0 41
81	Matapedia	29 4-18 5 74	011507Q	N/A	Charlo A.	2760		115		48 087	67 101			0 209
82	Restigouche	29 4-18 5 74	01BJ007	N/A	Charlo A.	7740		158 5		47 908	66 948			0 308
83	Nashwaak	9-10 12 74	01AL002	01AL001	N/A	1450	1660	97	112	46 126	66 612	46 009	66 583	0 154
84	Oromocto	27-28 1 76	N/A	01AM002	Royal				52 4			45 766	66 551	
85	Kennebecasis	27-28 1 76	N/A	01AP004	Sussex		1100		65 1			45 702	65 601	0 26
86	Nashwaak	3.4 76	01AL008	01AL010	Royal Rd	641		64	89 5	46 283	66 738	46.183	66 619	0 156
87	Nashwaak	3.4.76	01AL001	N/A	Royal Rd	1660		112		46 009	66 583			0 132
88	Saint John	31 3-5 4.76	01AJ008	01AK009	Woodstock	N/A		374 6	475 3	46 298	67 529	45 957	66 865	
89	Saint John	31 3.76	01AJ008	01AK009	Beechwood	N/A		374 6	475 3	46 298	67 529	45 957	66 865	
90	Saint John	3 4 76	01AF002	01AJ001	Beechwood	21900	34200	280 5	352 3	47 04	67 742	46 47	67 59	0 28
91	Saint John	31 3-5 4.76	01AD004	01AF002	Edmunston	15500	21900	215 8	280 5	47 361	68 327	47.04	67 742	0 333
92	Matapedia	1.4 76	011507Q	N/A	Charlo A.	2760		115		48 087	67.101			0 209
93	Matapedia	31 3-5 4.76	011507Q	N/A	Charlo A.	2760		115		48 087	67 101			0 209
94	Saint John	31 3-5 4.76	01AJ009	01AJ008	Beechwood	35000		369 8	374 6	46 3.38	67.555	46 298	67 529	0 256
95	Kennebecasis	25-28 1 78	N/A	01AP004	Sussex		1100		65 1			45.702	65 601	0 26
96	Kennebacasis	25-28 1.78	N/A	01AP004	Sussex		1100		65.1			45.702	65 601	0 26
97	Saint John	25-28.1.78	01AP005	NO	Sussex			619 9		45 271	66 089			
98	Saint John	25-28.1 78	N/A	N/A	Sussex									
99	Meduxnekeag	27.3 79	01AJ003	N/A	Woodstock	1210				46.216	67 728			
100	Restigouche	26 3.79	01BJ007	N/A	Charlo A.	7740		158 5		47 908	66.948			0 308
101	Restigouche	26 3.79	01BJ007	N/A	Charlo A.	7740		158 5		47 908	66 948			0 308
102	Canaan	15-16 3 79	01AP002	N/A	Sussex	668		41 3		46 072	65 367			0 392
103	Saint John	24-27.2 81	01AJ009	01AJ008	Beechwood	35000	N/A	369 8	374 6	46 3.38	67 555	46 298	67.529	0.256
104	Saint John	24-27.2 81	01AJ009	01AJ008	Beechwood	35000	N/A	369 8	374 6	46 338	67 555	46 298	67 529	0 256
105	Saint John	24-27 2 81	01AJ009	01AJ008	Beechwood	35000	N/A	369 8	374 6	46 3.38	67 555	46.298	67.529	0.26
106	Aroostook	24-27 2.81	US gauge	01AG003	Aroostook		6060		145			48.811	67 754	0 288
107	Kennebecasis	11-13 2.81	N/A	01AP004	Sussex		1100		65 1			45.702	65 601	0 26
108	Matapedia	17.4 83	011507Q	N/A	Charlo A.	2760		115		48 087	67 101			0 209
109	Meduxnekeag	11-12 4.83	01AJ003	N/A	Woodstock	1210				46 216	67.728			
110	Restigouche	18 4 84	01BC001	01BJ007	N/A	3160	7740	75 8	158 5	47 667	67 484	47.908	66.948	0 308
111	Matapedia	18 4 81	011507Q	N/A	N/A	2760		115		48 087	67.101			0 209
112	Matapedia	18 4 81	011507Q	N/A	N/A	2760		115		48 087	67.101			0 209

Table 4.3 Statistical parameters for hourly water level and discharge data for Southern ontario, Alberta and N. W. T. rivers

Variable	Jam no.	1st	3rd	Mean Stage	Mean Disch.	CV	Std. dev.	Max.	Min.	Range	Kurtos	Skew	Mode	Median
hfr1	39	2	2.34	2.203		12.896	0.284	1.646	2.941	1.295	-0.307	0.38	2.247	2.238
hfr2		1.73	2.13	1.968		18.127	0.357	1.289	3.074	1.785	0.521	0.566	1.92	1.945
hbr1		2.45	3.04	2.779		17.518	0.487	2.36	4.507	2.147	3.026	1.762	2.377	2.569
hbr2		1.21	3.63	2.296		51.263	1.177	1.141	4.367	3.226	-1.157	0.667	1.205	1.91
qfr1		615	751		688.3	11.294	77.744	532	789	257	-1.226	-0.46	751	723
qfr2		713	837		770.5	5.19	84.052	569	883	314	-0.851	-0.599	817	799
qbr1		340	816		643.7	51.756	333.13	255	1820	1565	3.07	1.414	774	681
qbr2		816	1010		917	11.067	101.49	808	1150	342	-1.055	0.522	810	889
hfr1	42	3.73	3.95	3.892		5.698	0.222	3.631	4.501	0.87	0.838	1.302	4.496	3.824
hfr2		2.75	3.5	3.164		12.841	0.406	2.573	3.802	1.229	-1.462	0.046	3.286	3.272
hbr1														
hbr2														
qfr2		41.9	148		102.9	48.41	49.83	33.4	163	129.6	-1.757	-0.333	133	133
qbr1														
qbr2		188	193		190.7	1.653	3.151	185	197	12	-0.943	0.168	192	191
hfr2	44	1.98	3.02	2.491		21.514	0.536	1.575	3.705	2.13	-1.326	0.099	1.977	2.507
hbr1		2.58	3.06	2.995		15.204	0.455	2.425	4.746	2.321	3.135	1.563	2.579	3.007
qfr2		576	1080		831.1	40.623	337.6	435	1540	1105	-0.908	0.711	595	599.5
qbr1		317	493		427.7	21.128	90.365	267	574	307	-1.146	-0.448	299	452
hfr1	48	1.16	2.29	1.695		47.613	0.807	0.322	3.719	3.397	-0.408	0.741	2.263	1.308

Table 4.3 Continued ....

Variable	Jam no.	1st	3rd	Mean Stage	Mean Disch.	CV	Std. dev.	Max.	Min.	Range	Kurtos	Skew	Mode	Median
hfr2	48	2.1	3.1	2.445		20.545	0.502	2.062	3.392	1.33	-0.863	1.029	2.089	2.169
hbr1		1.93	3.36	2.855		24.19	0.691	1.746	4.71	2.964	-0.877	-0.434	2.893	3.086
hbr2		2.65	2.86	2.751		3.575	0.098	2.635	2.892	0.257	-1.678	0.253	2.644	2.723
qfr1		201	680	548.9		88.105	483.58	88.2	2070	1981.8	1.586	1.547	1700	333.5
qfr2		8	24		222.3	194.38	432.02	1	1740	1739	4.348	2.249	1	16
qbr1		261	1295		653.7	73.914	483.19	210	1460	1250	-1.378	0.698	239	401
qbr2		243	321		278.9	13.055	36.415	238	331	93	-1.686	0.274	240	267.5
hfr1	51	2.21	3.22	2.588		20.424	0.528	1.728	3.719	1.991	-1.147	0.589	2.263	2.315
hfr2		2.02	2.21	2.116		7.933	0.168	1.81	2.468	0.658	-0.533	0.034	2.133	2.134
hbr1		2.59	2.88	2.725		7.064	0.192	2.315	3.157	0.842	-0.575	0.596	2.644	2.652
hbr2		2.14	2.26	2.2		2.865	0.063	2.11	2.309	0.199	-1.311	0.212	2.11	2.194
qfr1		642	1340		998.1	42.874	427.91	561	2070	1509	-1.052	0.659	1700	730
qfr2		16.5	911		568	76.5	434.49	1	1060	1059	-1.715	-0.462	906	842.5
qbr1		229	331		282.2	24.313	68.614	210	443	233	-0.635	0.849	241	246.5
hfr1	53	1.85	2.12	1.99		9.986	0.199	1.494	2.355	0.861	-0.293	-0.455	2.074	2.041
hfr2														
hbr1														
hbr2														
qfr1		18.6	32.5	25.97		32.143	8.346	10.9	43.2	32.3	-0.838	0.281	27.5	26.1
hfr1	54	1.04	1.49	1.276		27.259	0.348	0.315	1.891	1.576	-0.202	-0.458	1.487	1.323

Table 4.3 Continued ....

Variable	Jam no.	1st	3rd	Mean Stage	Mean Disch.	CV	Std. dev.	Max.	Min.	Range	Kurtos	Skew	Mode	Median
hfr2	54	1.93	2.24	2.122		13.624	0.289	1.631	2.996	1.365	1.021	1.082	2.153	2.06
hbr1		1.3	1.75	1.53		19.643	0.301	1.048	2.375	1.327	0.219	0.784	1.156	1.474
hbr2		2.18	2.65	2.45		12.718	0.312	2.07	3.541	1.471	0.355	0.913	2.23	2.412
qfr1		235	415		330	39.632	130.78	81.7	602	520.3	-0.767	0.231	236	313
qfr2		331	583		476.6	32.991	157.24	197	742	545	-1.164	-0.211	581	514
qbr1		364	614		482.8	31.317	151.2	328	804	476	-0.836	0.854	410	414
qbr2		207	619	396.3		57.147	226.45	165	876	711	-0.905	0.734	165	298
hfr1	56	0.91	1.14	1.138		40.746	0.463	0.794	2.745	1.951	4.964	2.508	0.948	0.97
hfr2		1.76	1.86	1.817		4.593	0.083	1.698	2.042	0.344	-0.087	0.879	1.786	1.787
hbr1		1.03	1.53	1.242		24.237	0.301	0.919	2.297	1.378	0.963	1.204	0.928	1.171
hbr2		1.88	2.59	2.496		32.173	0.803	1.777	5.085	3.308	1.514	1.541	1.874	2.426
qfr1		213	264		241.6	14.929	36.064	185	348	163	-0.199	0.83	228	229
qfr1		473	513		497.5	7.634	37.985	446	611	165	0.578	1.113	485	485
qbr1		220	305		259.5	16.772	43.52	137	425	288	-0.72	0.057	219	258.5
qbr2		508	545		525.7	4.803	25.25	481	575	94	-0.859	-0.034	526	527
hfr1	60	1.76	1.9	1.882		11.892	0.224	1.698	2.745	1.047	4.972	2.389	1.786	1.794
hfr2		1.12	2.1	1.715		54.485	0.934	1.03	3.941	2.911	-0.01	1.279	1.03	3.941
hbr1		1.88	2.59	2.496		32.173	0.803	1.777	5.085	3.308	1.514	1.541	1.874	2.426
hbr2		1.55	2.04	1.797		15.74	0.283	1.395	2.48	1.085	-0.936	0.441	1.545	1.735
qfr1		473	513		497.5	7.634	37.985	446	611	165	0.578	1.113	485	485

Table 4.3 Continued ....

Variable	Jam no.	1st	3rd	Mean Stage	Mean Disch.	CV	Std. dev.	Max.	Min.	Range	Kurtos	Skew	Mode	Median
qfr2	60	566	1410		1034	47.54	491.48	472	1870	1398	-1.436	0.303	1870	915
qbr1		508	545		525.7	4.803	25.25	481	575	94	-0.859	-0.034	526	527
hfr1	62	0.94	1.06	1.004		10.825	0.109	0.813	1.324	0.511	0.439	0.745	1.061	0.986
hbr1		2.01	2.56	2.373		23.037	0.547	1.713	3.618	1.905	-0.146	0.547	2.099	2.175
qfr1		20	33.3		27.8	34.763	9.665	10.6	53.5	42.9	-0.186	0.436	33.8	26.9
qbr1		102	128		115.2	16.586	19.1	83.4	177	93.6	0.399	0.537	122	114
hfr1	65	1.55	2.31	1.935		27.87	0.539	0.355	3.545	3.19	1.123	-0.138	2.346	2.113
hfr2		2.75	2.98	2.853		6.091	0.174	2.473	3.314	0.841	-0.282	-0.345	2.754	2.867
hbr1		2.61	3.02	2.852		9.071	0.259	2.495	3.46	0.965	-0.945	0.395	2.496	2.806
hbr2														
qfr1		271	743		490.6	48.482	0.238	63.7	878	814.3	-1.668	0.072	264	398.5
qfr2		6.5	18.5		12.5	55.416	6.927	1	24	23	-1.204	0	1	12.5
qbr1		986	1090		1038	6.053	62.801	940	1150	210	-1.19	0.113	1030	1035

Table 4.4 Statistical parameters for hourly water level and discharge data for New Brunswick rivers

Variable	Jam no.	1st	3rd	Mean Stage	Mean Disch.	CV	Std. dev.	Max.	Min.	Range	Kurtos	Skew	Mode	Median
hfr1	76	1.622	1.993	1.802		12.35	0.224	1.392	2.208	0.816	-1.01	0.391	1.58	1.723
hbr1		1.508	2.311	2.26		60.07	1.357	1.469	8.363	6.894	8.066	2.803	1.51	1.819
qbr1		239.5	575.5		518.91	89.14	462.55	200	2440	2240	5.693	2.419	200	341
hfbr2	77	2.645	3.932	3.266		22.6	0.738	1.213	4.421	3.208	-0.476	-0.475	2.5	3.318
qibr2		1495	1920		1685.8	12.1	204.01	1360	1950	590	-1.508	-0.002	1950	1690
hfr1	80	1.229	1.416	1.498		45.57	0.683	0.893	4.209	3.316	4.526	2.322	1.25	1.312
hbr1		3.337	5.19	4.365		25.54	1.115	2.987	6.811	3.824	-0.856	1.618	3.14	4.117
qfr1		175.5	315		256.35	33.62	86.176	157	505	348	-0.398	0.606	167	253
hfr1	82	0.855	0.905	0.88		5.167	0.045	0.751	0.97	0.219	0.018	-0.252	0.89	0.884
hbr1		2.51	3.51	3.03		24.46	0.741	2.339	5.265	2.926	0.343	1.196	2.54	2.578
qfr1		53.8	65.7		59.644	16.5	9.839	34.8	76.4	41.6	-0.333	-0.347	60.1	60.8
qbr1		670.5	1595		1041.1	47.4	493.53	605	1910	1305	-1.34	0.714	1890	711.5
hfr1	83	1.332	1.652	1.555		25.11	0.39	0.997	2.919	1.922	1.982	1.5	1.3	1.428
qfr1		53.6	121		98.049	60.47	59.291	42.2	261	218.8	0.673	1.303	42.3	75.85
hfr1	85	1.067	1.512	1.32		23.65	0.312	0.914	2.295	1.381	0.939	1.071	1.09	1.231
qfr1		41.35	77.2		59.465	39.19	23.307	30.9	106	75.1	-0.866	0.565	30.9	53.4
hfr1	86	41.55	42.533	41.93		1.966	0.824	39.84	43	3.161	-0.015	-1.05	40.8	42.18
hbr1		42.29	44.962	43.54		3.809	1.659	40.47	47.87	7.352	-0.509	0.428	40.5	43.298
hfr2	91	89.56	89.971	89.71		0.42	0.377	88.59	90.08	1.495	0.757	-1.378	90	89.891
hbr1		1.866	2.92	2.411		21.41	0.516	1.694	3.477	1.783	-1.44	0.061	1.82	2.41

Table 4. 4 Continued ....

Variable	Jam no.	1st	3rd	Mean Stage	Mean Disch.	CV	Std. dev.	Max.	Min.	Range	Kurtos	Skew	Mode	Median
hbr2		89.05	93.966	91.61		2.689	2.463	88.57	95.28	6.702	-1.712	0.09	89	91.991
qfr2		141.5	222		171.9	35.96	61.809	27	226	199	-0.283	-1.061	226	201.5
hfr1	93	42.67	44.669	43.52		2.557	1.113	41.88	45.36	3.474	-1.279	0.413	43.2	43.158
hfr2		41.55	42.533	41.93		1.966	0.824	39.84	43	3.161	-0.015	-1.05	40.8	42.18
hbr1		44.5	46.667	45.57		2.789	1.271	43	48.06	5.064	-0.989	-0.008	46.6	45.631
hbr2		0.264	0.998	0.499		1.809	0.28	0.002	0.998	0.996	-1.2	-0.019	0.47	0.513
qfr1		176	517		354.66	56.81	201.46	94.9	707	612.1	-1.218	0.328	679	334
hfr1	94	89.56	89.971			0.42	0.377	88.59	90.08	1.495	0.757	-1.378	90	89.891
hbr1		89.05	93.966			2.689	2.463	88.57	95.28	6.702	-1.712	0.09	89	91.991
hbr2		3.669	5.214	4.5		23.12	1.041	2.01	6.339	4.329	-0.984	0.126	3.67	4.525
qfr1		141.5	222		171.9	35.96	61.809	27	226	199	-0.283	-1.061	226	201.5
qbr1		220	685		434.94	66.96	291.24	0	999	999	-0.899	0.573	250	360
qbr2		2490	5055		3658.8	35.4	1295.2	1700	5700	4070	-1.406	0.145	1840	3415
hfr1	95	0.068	0.895	0.081		27.16	21.923	0.054	0.171	0.117	4.963	2.021	0.07	0.075
hbr1		2.44	3.004	2.968		24.05	0.714	2.219	4.945	2.726	0.887	1.407	2.4	2.75
qfr1		17.45	26.55		22.468	23.51	5.282	14.8	32.8	18	-1.135	0.356	17.3	21.9
hfr1	99	0.434	0.54	0.487		15.49	0.075	0.363	0.719	0.356	-0.01	0.81	0.44	0.458
hbr1		2.548	3.476	3.016		23.72	0.715	1.242	4.39	3.148	0.068	-0.235	3.17	3.01
qfr1		3.39	7.545		5.155	43.63	2.249	2.49	9.18	6.69	-1.273	0.59	3.69	3.94
hfr1	100	0.54	0.655	0.6		16.64	0.099	0.468	0.87	0.402	0.535	1.16	0.55	0.559

Table 4.4 Statistical parameters for hourly water level and discharge data for N. B. rivers

Variable	Jam no.	1st	3rd	Mean Stage	Mean Disch.	CV	Std. dev.	Max.	Min.	Range	Kurtos	Skew	Mode	Median
hbr1		1.623	2.655	2.139		25.47	0.545	1.445	3.264	1.819	-1.389	0.277	1.48	2.018
qfr1		12.45	16.7		14.949	17.26	2.581	10.1	20.8	10.7	-0.893	-0.54	16.7	16.3
qbr1		254.5	492		420.46	54.52	229.23	220	1170	950	1.912	1.605	232	330.5
hfr1	102	0.838	0.909	0.885		7.66	0.068	0.803	1.07	0.267	0.397	1.096	0.81	0.87
hbr1		1.626	2.163	1.988		27.19	0.54	1.433	3.655	2.222	1.638	1.518	1.8	1.799
qfr1		3.355	5.695		5.149	52.77	2.717	2.51	13.6	11.09	1.444	1.51	6.25	4.325
hfr1	103	1.53	1.869	1.715		14.8	0.254	1.185	2.359	1.174	-0.3	-0.069	1.87	1.755
hbr1		1.058	1.673	1.497		49.71	0.744	1.045	3.141	2.096	0.132	1.376	1.06	1.064
qfr1		62.05	87.55		74.819	20.49	15.327	52.6	110	57.4	-0.874	0.447	52.8	71.5
hfbr1	104	44.64	45.809	45.23		1.772	0.802	43.85	48.36	4.513	-0.002	0.734	44.9	45.068
hfbr2		42.5	44.321	43.49		2.823	1.228	41.38	46.75	5.372	-0.586	0.511	44	43.274
hfbr1	107	4.594	5.104	4.773			0.504	2.436	5.988	3.552	3.488	-1.36	4.24	4.848
qfbr1		142	229		186.77	26.62	49.722	128	312	184	-1	0.543	131	176
hfr1	108	1.37	1.838	1.606		21.06	1.606	1.104	2.586	1.482	-0.45	0.629	1.18	1.531
qfr1														
hfr1	110	1.444	1.691	1.589		11.89	0.189	1.338	2.154	0.81	0.401	1.007	1.44	1.545
hfr2		1.389	1.567	1.482		10.41	0.154	1.144	1.865	0.721	-0.026	0.502	1.4	1.453
hbr1		2.225	2.706	2.511		14.47	0.363	1.762	3.366	1.604	-0.577	0.379	2.45	2.475
hbr2		2.378	2.831	2.866		35.33	1.012	2.06	6.322	4.262	4.915	2.409	2.28	2.461
qfr1		107	154		134.46	24.75	33.272	86.7	214	127.3	-0.568	0.604	153	127.5

Table 4.4 Statistical parameters for hourly water level and discharge data for N. B. rivers

Variable	Jam no.	1st	3rd	Mean Stage	Mean Disch.	CV	Std. dev.	Max.	Min.	Range	Kurtos	Skew	Mode	Median
qfr2		245.5	332		287.67	19.18	55.186	191	396	205	-0.943	0.237	229	279.5
qbr1		287	437.5		364.62	20.8	75.835	261	520	259	-1.472	0.214	278	342
qbr2		598	735		681.01	16.7	113.7	572	946	374	0.234	1.239	598	637

Table 4. 5 AFDD values for various location of ice jam occurences

River	Province	Location	AFDD
Aroostook	N. B.	near Masaradis	1319.3
		Caribou(Maine)	1319.3
		50 km west of Florenceville	1087.4
Athabasca	Alberta	us end of Poplar island	1576
		toe at head of Inglis island	1576
		toe ds of Ellis river	1576
		ds of long rapids	2266.5
		3 km us of Crooked rapids	2270.5
		Cascade rapids	2270.5
		3km us of Macewan br	2270.5
		4 km ds of Grand rapids	2664.9
		4 km us of Mountain rapids	2664.9
		5 km ds of Cascade rapids	2664.9
		28 km ds of McEwan	2664.9
		16 km ds of McEwan	2664.9
		ds of crooked rapids	2034.1
		14 km us of upper wells	2034.1
		Rourke creek	1261.1
		ds of long rapids	1753.2
		us of house river	1756.3
		ds of house river	1756.3
		ds of gauge	1756.3
		moberly rapids	1756.3
		mouth of Hondo creek	1752
		ds of island below bridge	1995.6
		56 km ds of town of Athabasca	1995.6
		Duncan creek	1996.1
		mouth of parallel creek	2173.5
		algar river mouth	2173.5
		stony rapids	1752
		us of Mountain rapids	2173.5
		14 km us of Joli fou	1996.4
		us of cascade rapids	2176.1
Canaan	N. B.	several locations	750.1
Clearwater	Alberta	ds of clearwater	1575
		mouth	1575

Table 4. 5 Continued ....

River	Province	Location	AFDD
Grand	Ontario	Marsville	754
		150m d/s to 400m us of br.@Mars	744.9
		just us of upperBelwood crossing	754
		200m us to 30m ds of br ds of Mars	754
		500m us of sec crossing & ds of Mars	754
		300m of ds of second crossing	754
		600m and 1.5 km ds of belwood br.	884.1
		300m us & 900m us of belwood br.	754
		toe located us of Grand valley	753
Kennebecasis	N. B.	Sussex corner of Trout creek br.	1114.9
		Trout creek	422.8*
		Norton at highway bridge	442.3*
		Norton 2 miles d/s of community	442.3*
		Norton 2 miles d/s of community	372.7*
		Midway between Norton & Bloomfield	446.2*
		2 miles west of Norton	381*
		.5 miles d/s of Sussex	431.9*
		Roachville br. area	431.9*
		Roachville area	764*
Liard	N. W. T.	.5 km us of petit Liard confluence	2698.5
		6km us FortLiard,12 km us lkp 323	2698.5
		between lkp 13 and lkp07	3507.6
		liard-Mackenzie confluen to lkp22	3507.9
		lkp 19.5 to lkp8(ds of Ferry crossin)	2969.1
		near snake river tributary	2474
		us of Petitot river	2487.8
		at lkp270 near Flett rapids	1663.1
		Liard river mouth	3152.9
		near blackstone tributary	3152.9
Mackenzie	N. W. T.	ds of mkp355	2969.1
		near Fort Simpson	3147
		at dpw dock mkp905 Normanwell	3538.2
		near radar island mkp937	3538.2
		just before Kalinek channl offtake	4357.8
		entrance to east channel mkp1500	4357.8
Mackay	Alberta	Athabasca confluence	or 1728.9

Table 4. 5 Continued ....

River	Province	Location	AFDD
Magaguadavic	N. B.	second falls just d/s of bridge	953.8
		st. George near pulp mill	953.8
Matapedia	Québec	Routhierville	1436.1
		Matapedia bridge	1436.1
		Matapedia bridge	1401.5
		between broadlands & Tidehead	1401.5
		St. Alexis station	1433.6
		Matapedia bridge	1433.6
		Routhierville	605.2*
		Flatlands east of village	1300.8
		near Routhierville	1429.5
		around Mann settlement	1431.5
		Matapedia	1049.2
Meduxnekeag	N. B.	Duties interval	638.4
		Woodstock	993.8
		woodstock	827.1
Miramichi	N. B.	Mcnamee	1691.6
		Doaktown	1477.1
		Mcnamee	1477.1
		Little SE Miramichi	896.2
		Cassilis on NW Miramichi	896.2
		d/s of Boietown	805.9
		d/s of Doaktown	805.9
		Newcastle at Morrisey bridge	585.2*
Nackawic	N. B.	cullerton	638.4
Nashwaak	N. B.	just below durham bridge	967.8
		mouth of Tay river	1095.1
		between durham & Nashwaak br.	1095.1
		8 km above tay mouth	1095.1
		mouth of cross creek & covered br	933.9
		at Penniac	933.9
		between Tay mouth & durham br.	571.5
		near Nashwaak br.	571.5
		near Nashwaak village	1161.7
		Marysville	1161.7
Oromocto	N. B.	near Blissville	953.8

Table 4. 5 Continued ....

River	Province	Location	AFDD
		around Hoyt	709.2*
Restigouche	N. B.	south channel d/s of Matapedia	1837.9
		west of Campbellton on the island	1436.1
		old interprovincial bridge	1300.8
		at the raiway bridge below matape	792.7
		flat lands	1136.4
Saint John	N. B.	at sugar island	1691.6
		Gilbert island to Maugerville	1691.6
		Mouth of March creek	365.9*
		Victoria mill & expermental station	1477.1
		CNR bridge at Fredericton	967.8
		Sheffield to Maugerville	896.2
		Long reach	896.2
		Keswick island	896.2
		Long's creek	896.2
		Mackinley ferry	896.2
		at Quisibis	1436.1
		Mackinley ferry	1022.5
		above experimental station	1022.1
		Oromocto islands	1022.1
		Connors	970
		Long's creek	609.3
		Crokus point	609.3
		experimental station	771.6
		near Florenceville	1249.3
		Fort kent	1259.9
		grafton bridge north of Woodstock	1162.2
		Hartland to Flemming	1162.2
		perth andover	1161.7
		Anne de madawska	1397.3
		Hartland at Sproll's island	1164.5
		near strescon	431.9*
		March creek	431.9*
		Hartland above flemming	1024.7
		at Flemming	1024.7
		lower end of sproll's island	1024.7

Table 4. 5 Continued ....

River	Province	Location	AFDD
Thames	Ontario	us of Bothwell	558.4
		near Fairfield museum	558.4
		us of kent bridge	539.1
		d/s of kent br & u/s of Shermann br.	539.9
		at river mouth	422.1
		near fairfield museum	826.7
		kent br	558
		near golf course	558
		near Louisville	558
		near yacht club	485
		near the mouth	485
		near Fairfield museum	633.3
		kent br.	534.9
		ds of kent br.	534.9
		near Louisville	534.9
		near prairie siding	575.9
		near golf course, 6km below kent	196.7

* - only partial temperature data avilable

Table 4. 6 The range of AFDD values that induce formation of ice jams

River	Province	Min. AFDD	Max. AFDD
Aroostook	N. Brunswick	1087	1319
Athabasca	Alberta	1576	2665
Canaan	N. Brunswick	750	
Clearwater	Alberta	1575	
Grand	Ontario	745	884
Kennebecasis	N. Brunswick	373	1115
Liard	N. W. T.	2474	3153
Mackenzie	N. W. T.	2969	4358
Mackay	Alberta	1891	
Magaguadavic	N. Brunswick	954	
Matapedia	Québec	1049	1436
Meduxnekeag	N. Brunswick	638	994
Miramichi	N. Brunswick	806	1692
Nackawic	N. Brunswick	638	
Nashwaak	N. Brunswick	572	1162
Oromocto	N. Brunswick	954	
Restigouche	N. Brunswick	793	1838
Saint John	N. Brunswick	609	1692
Thames	Ontario	422	827