MEASUREMENT OF ICE GROWTH ON THE SAINT JOHN RIVER AT FREDERICTON, N.B.

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INTRODUCTION

This paper presents information concerning the vertical growth of an ice sheet on the Saint John River at Fredericton, N.B. during the winter of 1975.

The primary objectives of the study were:

1. To determine if there was any creep of the ice sheet in the downstream direction during the winter period,
2. To record the growth of the ice thickness at a river cross section during the winter period, and
3. To develop some simple empirical relationships to estimate average ice thickness as a function of daily mean air temperature.

Supplementary information related to ice strength and local thermal erosion are also presented. Additional detailed information related to this study is presented in a report by Boyer (1975).

LOCATION OF THE CROSS SECTION FOR THE STUDY

The cross section selected for the observations is located about 300 m upstream of the railway bridge across the Saint John River at Fredericton. At this location the river is about 600 m wide at the low stages experienced during the winter months.

HYDRAULIC CHARACTERISTICS DURING THE PERIOD OF OBSERVATION

The Water Survey of Canada hydrometric station, O1AK004, is located on the Saint John River below Mactaquac Dam and about 15.6 km above the cross section under study at Fredericton. The drainage area of the Saint John River basin above the cross section is about 40 900 km^2 and the drainage area above the hydrometric station is about 39 900 km^2.

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In addition, the Water Survey of Canada stage recording station, 01AK003, is located at the Fredericton pumping station which is about 1500 m upstream of the cross section.

A summary of the average discharges and river stages for the period during which the observations of ice thickness were observed is presented as follows:

Month	Average Discharge for Month at 01AK004, m^3/s	Average Stage for Month at 01AK003, m (GSC)
January 1975	349	1.56
February 1975	217	1.32
March 1975	363	1.73
Average for Period	310	1.54

It is recognized that the above values of discharges and stages are average values over the stated period. Field observations were made between Jan. 21 and Mar. 5, 1975 and during this period the discharge at station 01AK004 ranged from 74.4 m^3/s to 456 m^3/s. During the same period the stages at station 01AK004 ranged from 1.04 m (GSC) to 1.83 m (GSC).

Based on surveys of the river cross section reported by Bray and Phinney (1974), the following values of the geometric elements were determined for a free surface with a stage of 1.54 m (GSC), and for an ice covered surface with the bottom at 1.17 m (GSC) assuming an average ice thickness of 0.37 m based on observations reported later in this paper:

Geometric Element	Free Surface 1.54 m (GSC)	Bottom of Ice Cover 1.17 m (GSC)
Cross sectional area, A	1980 m^2	1830 m^2
Wetted perimeter, P	604 m	1180 m
Top width, T	603 m	N.A.
Hydraulic mean depth, D = A/T	3.28 m	N.A.
Hydraulic radius, R = A/P	3.28 m	1.55 m

The average velocity under the ice cover during the period Jan. to Mar. 1975 was about 0.17 m/s. A Froude number based on an equivalent free surface condition was about 0.028, where the Froude number is defined as $Fr = V/(gD)^{\frac{1}{2}}$

The temperature of the water varied from about 0.0°C to 0.1°C during the period of observation. Precise temperature measurements were not made in the field.

ICE MEASUREMENTS AT THE SELECTED CROSS SECTION

When the cross section was established, 12 stations were located at the cross section with a spacing of 50.0 m between stations. Six 19 mm diameter wooden dowels were frozen into the ice at 100.0 m intervals along the cross section. A theodolite was used to ensure that the dowels were initially set in a straight line.

Holes for ice thickness measurements were drilled by hand with a 152 mm diameter ice auger at the 12 stations on the cross section. The river cross section obtained from sounding through the ice is presented in Figure 1.

Measurements of snow depth and ice thickness were made at the 12 stations on the cross section on Jan. 21, Jan 28, Feb. 13, Feb. 20, Feb. 28, and Mar. 5, 1975. The data at station 1 on the north side of the river were not used in any analysis since that station was located near a site which was used for the disposal of snow from city streets. Data related to the average ice thickness for stations 2 to 12 are presented in Table 1.

A brief description of the sequence of events in the formation of the ice sheet and during the field measurements is now outlined. From field observations it is estimated that the ice sheet was initially formed on December 26, 1974. The ice sheet appeared to be primarily formed by the development of shore ice rather than by an upstream progression of an ice cover.

The second series of holes were drilled at the same location as those for the first series of holes. When the ice sheet was covered with snow, the ice surface would flood when a hole was drilled through the ice. Attemps were made to overcome the effects of local flooding by drilling subsequent holes a short distance away from the previous holes. Flooding occurred over most of the ice sheet on a broad scale due to natural causes after Feb. 13, 1975.

DOWNSTREAM CREEP OF THE ICE SHEET

Theodolite shots were taken on the dowels in the ice sheet on Jan. 21, Feb. 5 and Feb. 28, 1975. There was no detectable movement of the dowels from the initial line established on Jan. 21, 1975. It was concluded that there was no downstream movement of the ice sheet due to creep during the period of observation.

ICE GROWTH

The growth of the ice sheet is shown in Figure 2 as a function of location and as a function of time. The thickness is only shown for the dates of Jan. 21, Feb. 5, Feb. 28, and Mar. 5, 1975 so that the diagram is not cluttered. The maximum average ice thickness was measured on Feb. 28, 1975. The variability of the ice sheet is only in the order of 10 percent of the ice thickness over the 0.6 km wide cross section.

The variation of the average depth of snow and the average ice thickness based on data for stations 2 to 12 are presented in Figure 3. For the series of measurements on Jan. 21 and Jan. 28, 1975, no snow ice was

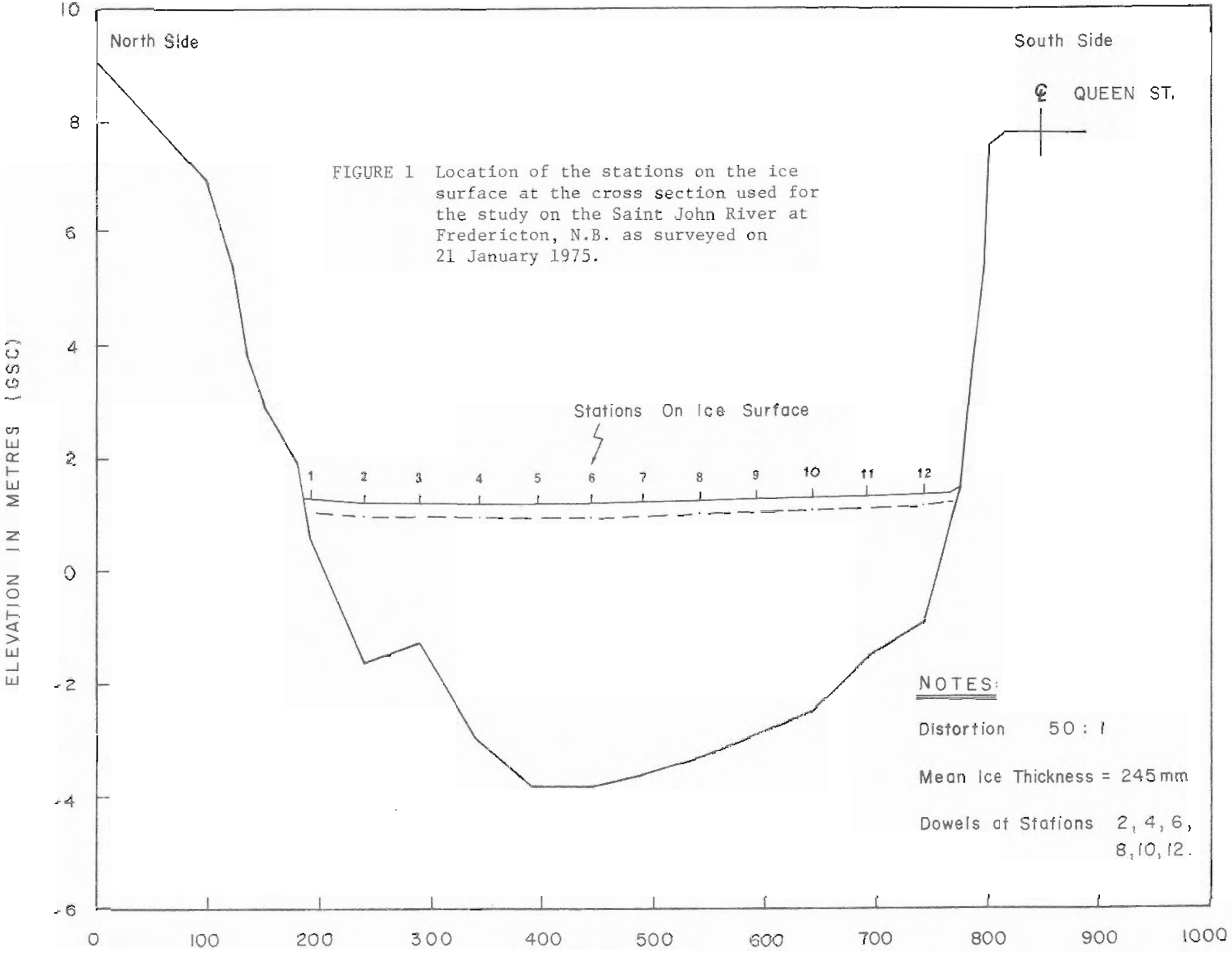


FIGURE 1 Location of the stations on the ice surface at the cross section used for the study on the Saint John River at Fredericton, N.B. as surveyed on 21 January 1975.

TABLE 1 AVERAGE SNOW DEPTHS AND ICE THICKNESSES FOR STATIONS 2-12 FOR THE CROSS SECTION ON THE SAINT JOHN RIVER AT FREDERICTON, N.B.

Date	Snow Depth		Total Ice Thickness		Black Ice Thickness		Snow Ice Thickness		River Stage
	Average	C. of V.	Average	C. of V.	Average	C. of V.	Average	C. of V.	m
	mm		mm		mm		mm		
Jan. 21, 1975	None	—	245	0.101	245	0.101	None	—	1.56
Jan. 28	140	See Note 2	284	0.109	284	0.109	None	—	1.50
Feb. 5	177	0.30	322	0.119	Not Obs.	—	See Note 3	—	1.28
Feb. 13	147	0.41	421	0.131	Not Obs.	—	See Note 4	—	1.48
Feb. 20	190	0.29	434	0.128	Not Obs.	—	Not Obs.	—	1.23
Feb. 28	91	0.70	452	0.078	282	0.107	170	0.225	1.44
Mar. 5	112	0.25	445	0.073	251	0.121	194	0.168	1.38

NOTES:

1. Averages and coefficients of variation are based on data from stations 2 to 12 since Station 1 on the North side of the river was located near a site which was used for the disposal of snow from city streets.
2. On Jan. 28, 1975, the snow depth was based on a couple of measurements only.
3. On Feb. 5, 1975, it was noted that some snow ice was beginning to form, but no measurements were made.
4. On Feb. 13, 1975 it was noted that about 70 mm of snow ice was at Station 10, but no other measurements were made.
5. River stages measured at Water Survey of Canada Station, 01AK003, located 1.5 km above the cross section under study.

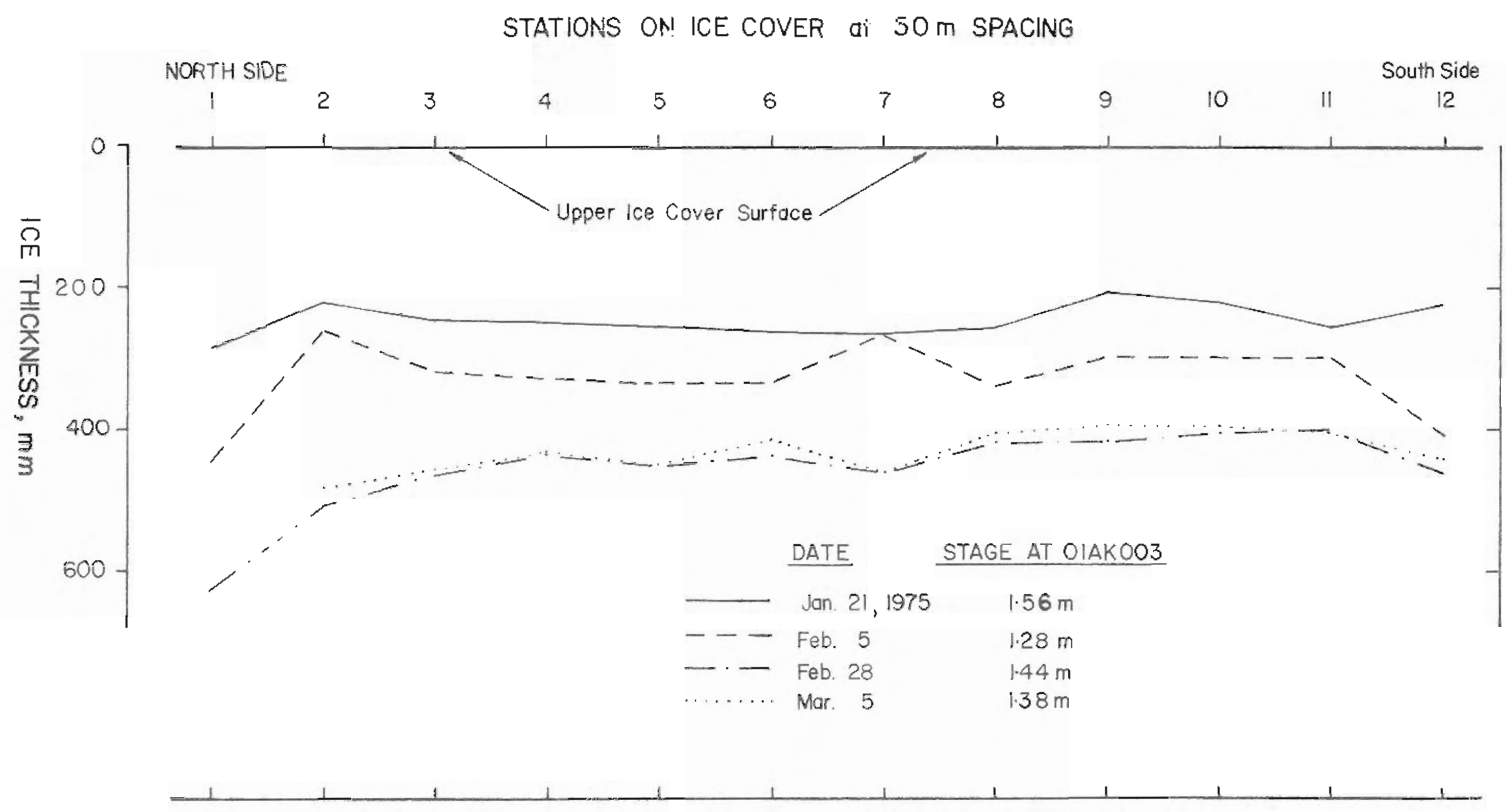
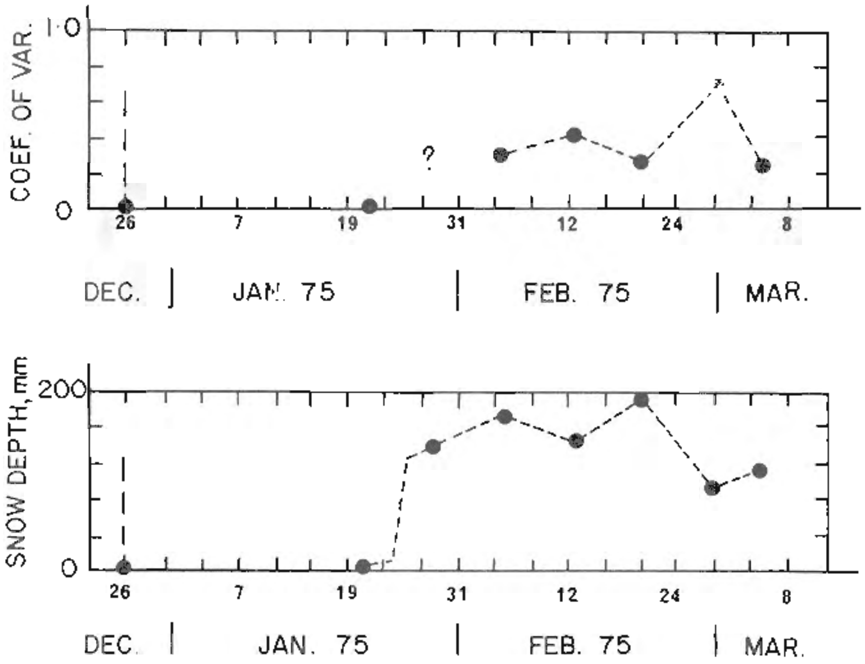
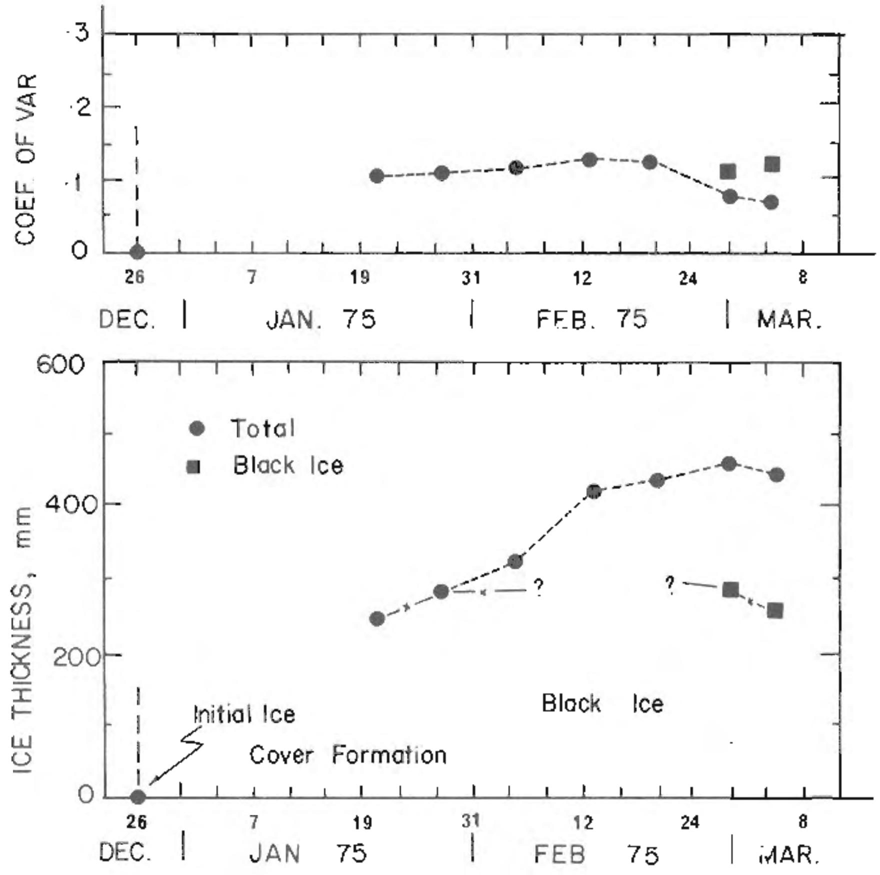


FIGURE 2 Variation of ice thickness across the Saint John River at Fredericton at four dates during the winter of 1975.



a) VARIATION OF AVERAGE SNOW DEPTH WITH TIME



b) VARIATION OF AVERAGE ICE THICKNESS WITH TIME

FIGURE 3 Variation of average snow depth and average ice thickness at the cross section during the winter of 1975.

observed at any station. The presence of snow ice was observed on Feb. 5, Feb. 13 and Feb. 20, 1975 but only the total ice thickness was measured. On Feb. 28, and on Mar. 5, 1975, the thickness of the snow ice and the thickness of the black ice were measured separately to give the total ice thickness at each station. No frazil slush was observed at any station during the period of observation.

As shown in Figure 3, the growth of black ice appeared to stop shortly after Jan. 28, 1975 when the snow cover increased to about 140 mm or about one-half of the thickness of the black ice. This observation is in agreement with the theoretical consideration presented by Michel (1971) where he states that

> "a very small amount of deposited snow is sufficient to stop the growth of black ice underneath; snow about half the thickness of the black ice sheet sufficies."

RELATIONSHIPS BETWEEN ICE THICKNESS AND AIR TEMPERATURE

The air temperature data utilized in the following analyses were obtained from the Canada Department of Agriculture Research Station located about 5 km downstream and about 35 m above the elevation of the ice surface at the site of cross section under study. The assumption was made that the daily mean air temperature at the Research Station was representative of the daily mean air temperature at the cross section under study.

The basic temperature data utilized for this study are summarized as follows:

Date	N Days	FD* Days	FD Days	°C-days	S °C-days
Jan. 21, 1975	26	23	20	187	180
Jan. 28, 1975	33	30	27	256	250
Feb. 5, 1975	41	38	35	407	400
Feb. 13, 1975	49	46	43	522	516
Feb. 20, 1975	56	53	50	576	570
Feb. 28, 1975	64	57	50	594	582
Mar. 5, 1975	69	62	55	620	608

N = number of days after freeze-up. Freeze-up is estimated to have occurred on December 26, 1974. Therefore, December 27, 1974 is taken to be the first day after freeze-up or the first day after the beginning of the ice cover formation.

FD* = number of freezing days since freeze-up. A freezing day is a day for which the daily mean air temperature is equal to or less than 0°C.

FD = net number of freezing days since freeze-up. That is the number of freezing days, FD*, minus the number of days for which the daily mean air temperature is greater than 0°C.

S* = the cumulative number of freezing degree days since freeze-up.

$= \Sigma(T_t - T_i^*)$

where: T_t is the threshold temperature for freezing, 0°C.

T_i^* is the daily mean air temperature for the i-th day.

In this case T_i^* can only be negative.

S = the cumulative net number of freezing degree days since freeze-up.

$= \Sigma(T_t - T_i)$

where: T_t is the threshold temperature for freezing, 0°C.

T_i is the daily mean air temperature for the i-th day.

In this case T_i can be positive or negative.

Three methods were used to make estimates of average ice thickness over the period during which ice growth was taking place. Only the first six of the seven series of data were used in the analyses since the ice sheet had begun to decay by March 5, 1975.

The first expression for estimating ice thickness is based on the following linear regression model:

$$T = 99.2 + 6.94\ FD \qquad \text{... Eq. 1}$$

where: T = the average ice thickness in mm
FD = the net number of freezing days since freeze-up or since the beginning of ice cover formation.

The correlation coefficient, r, was 0.984 and the standard error of estimate, S_e, was 17.2 mm for the relationship presented in Equation 1.

The second expression for estimating ice thickness is based on the following linear regression model:

$$T = 148 + 0.507\ S \qquad \text{... Eq. 2}$$

where: T = the average ice thickness in mm
S = the cumulative net number of freezing degree days since freeze-up or since the beginning of ice cover formation.

The correlation coefficient, r, was 0.985 and the standard error of estimate, S_e, was 16.8 mm for the relationship presented in Equation 1.

The third method for estimating ice thickness is based on the following simplified Stefan type expression:

$$T = \alpha S^{\frac{1}{2}} \qquad \text{... Eq. 3}$$

where: T = the average ice thickness in mm
S = the cumulative net number of freezing degree days since freeze-up
α = a coefficient

The coefficient, α, is dependent upon many factors some of which include the relative magnitude of black ice and snow ice in the ice sheet. Michel (1971) quotes typical values of the coefficient, α, which for the units utilized in Equation 3 are presented as follows:

For an average river with snow: $14 < \alpha < 17$
For an average lake with snow: $17 < \alpha < 24$

For this study the average value of the coefficient, α, was found to be 18.0 and the coefficient of variation for the six data points used to obtain α was 0.053. The value of 18.0 compares favourable with the upper value for rivers and lower value for lakes which seems reasonable for the cross-section under study.

In addition to the above analyses, Equation 1 was evaluated using FD* rather than FD, and Equation 2 and 3 were evaluated using S* rather than S. These results are not reported herein since the definition of FD and S seem to be more physically realistic than FD* and S*. The results obtained by using FD and S were generally slightly better but not significantly different than the results obtained by using FD* and S*.

The data utilized for estimating ice thickness by the last two of the three methods are presented graphically in Figure 4. The linear relations assumed by the first two methods given by Equation 1 and Equation 2 are only applicable if the ice thickness is greater than about 150 mm. The third method given by Equation 3 should be applicable after the ice cover is initially formed.

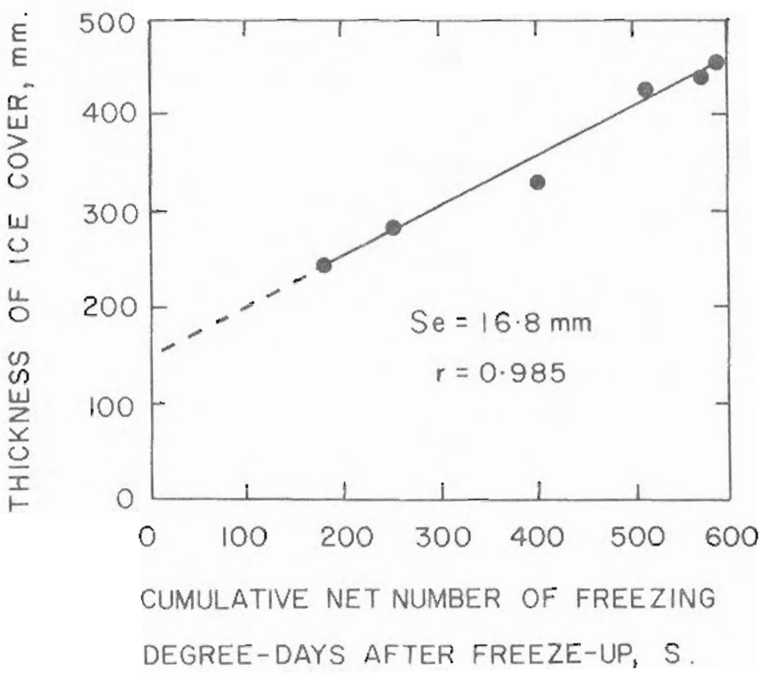
Two factors that could result in a small change in the constant terms in Equation 1 and Equation 2 and the coefficient, α, in Equation 3 are:

1. An improper estimate of the date of initial formation of the ice cover, and

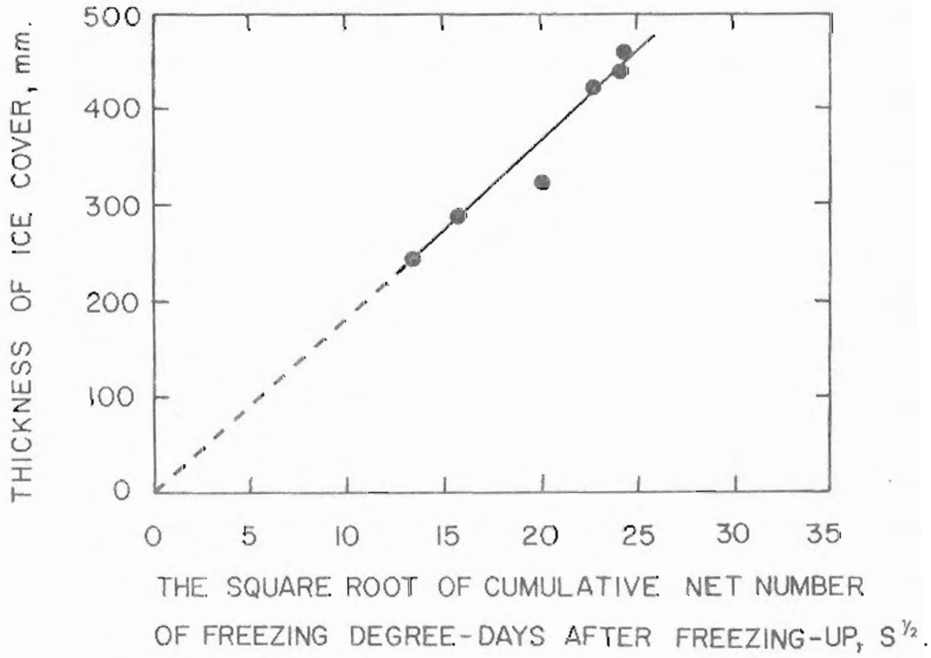
2. A difference in the temperature at the ice level and at the site of the meteorological station.

STRENGTH OF ICE

On Feb. 21, 1975 a 0.5 m by 0.5 m block of ice was cut from the Saint John River near station 6. The bottom of the ice block in contact with the



a) ICE THICKNESS VERSUS CUMULATIVE NET NUMBER OF FREEZING DEGREE-DAYS



b) ICE THICKNESS VERSUS (CUMULATIVE NET NUMBER OF FREEZING DEGREE-DAYS) $^{1/2}$

FIGURE 4 Variation of ice thickness as a function of the cummulative net number of freezing degree days after freeze-up or after the beginning of ice cover formulation.

water was very smooth. Several 50 mm x 50 mm x 50 mm cubes were cut from the black ice portion of the ice block. These specimens were tested in such a way that a compressive load was applied normal to the initial ice sheet orientation. In all cases the load was applied at a relatively uniform rate by a hand pump on a small hydraulic jack loading system. The only results utilized to obtain ice strength were for those cubic specimens which failed in a period of 4 seconds. Based on a sample of 5 specimens the mean compressive ice strength was 3000 kN/m^2 and the standard deviation was 340 kN/m^2. The tests were carried out in a cold room with the temperature at about -1°C on the same day on which the block of ice was obtained.

Typical design values of ice strength for impact loading of winter ice in compression are given by Michel (1970) to be 2760 kN/m^2. The average value obtained for the cubic ice specimens from the black ice compares favourably with the design value, however, it must be recognized that ice strength depends on many factors including ice type, specimen shape, specimen size, direction of loading, temperature at loading and thermal history.

Schwarz (1975), Chairman of the IAHR Task-Committee on Standardizing Testing Methods for Ice recommends that cubic specimens not be used to determine ice strength due to the occurrence of end-effect stress perturbations. The Task Committee recommends that cylindrical specimens (or prismatic specimens) of 70 mm to 100 mm diameter (or width) be used with a length/diameter (length/width) ratio equal to 2.5.

It is recognized that the strength of the ice reported herein for the Saint John River cross section is not obtained under ideal conditions. However, the reported ice strength may be adjusted to standard values from reference curves which may be established in separate systematic investigations and may be utilized to provide some additional information concerning the ice sheet at the cross section under study.

THERMAL EROSION OF ICE

A secondary observation made in the field is related to the thermal erosion of one drilled hole through the ice sheet. The initial shape of the drilled hole and the shape of the hole on March 5, 1975 is presented in Figure 5. The results indicate that more heat transfer takes place from the water to the ice on the downstream side than on the upstream side of the drilled hole. The process may be explained by noting that a turbulent eddy is formed in the zone of separation at the upstream edge of the hole. The resulting eddy then comes in contact with the downstream wall of the circular hole causing the thermal erosion of the ice at that location. Perhaps in the future field experiments could be designed using this idea to make detailed studies of heat transfer for such situations.

SUMMARY

This paper has presented data related to the growth of a 450 mm thick ice sheet at a 0.6 km wide cross section of the Saint John River at Fredericton, N.B. during the winter to 1975.

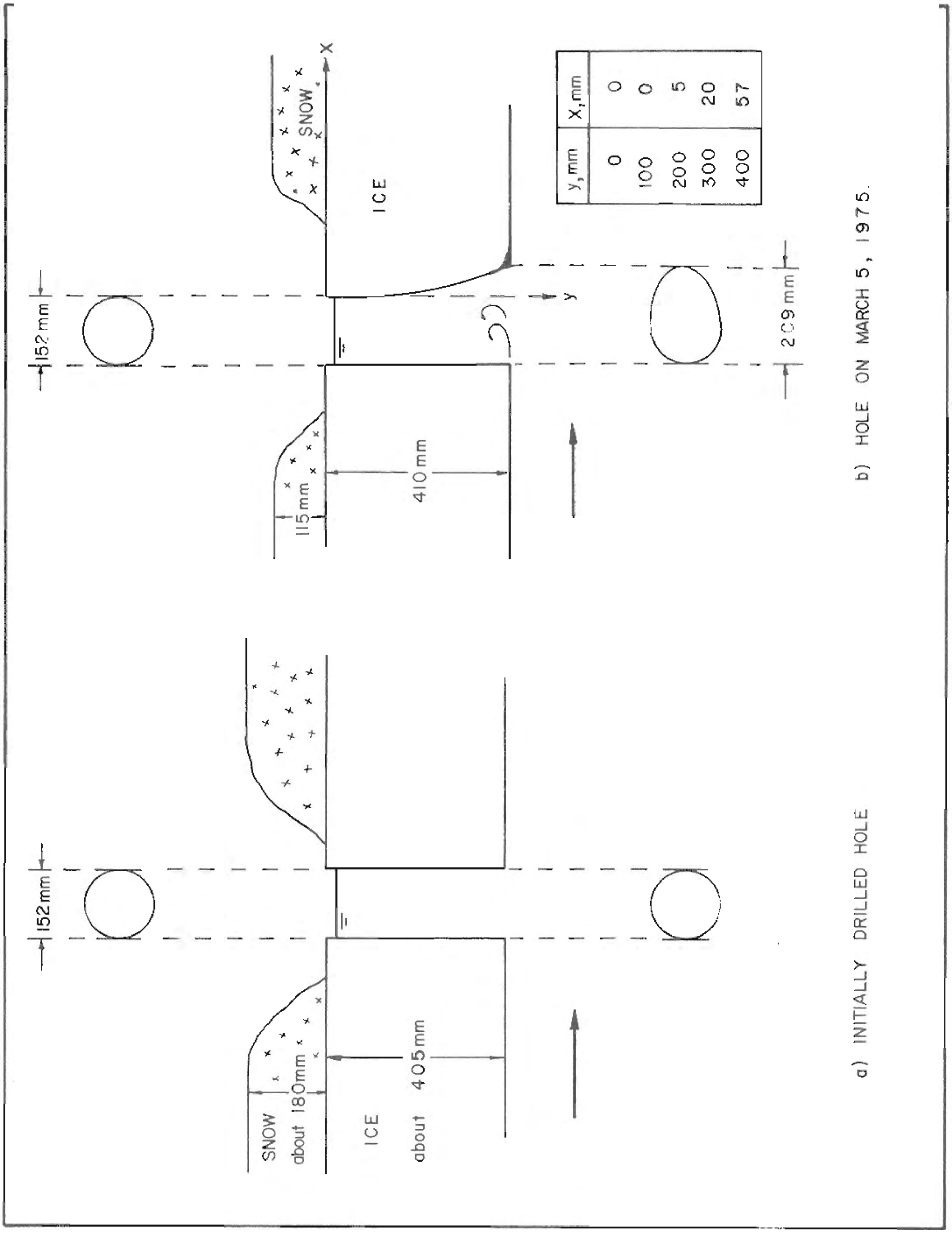


FIGURE 5 Measurement of the effect of thermal erosion at the bore hole at Station #10 on the cross section.

Field measurements indicated that there was no detectable downstream creep of the ice sheet over the period of observation. The basic ice thickness data and daily mean air temperature were used to obtain three simple empirical equations for estimating ice growth.

Supplementary measurements of ice strength indicated that the compressive strength of the black ice in the ice sheet was about 3000 kN/m^2. Some data were obtained to demostrate the thermal erosion which occurred at one of the holes used for ice thickness measurement.

Similar data could be obtained at river cross sections in the Atlantic region of Canada to obtain generalized relationships related to ice growth in natural rivers.

LIST OF REFERENCES

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