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ICE FREEZE UP AND BREAKUP IN THE LOWER THAMES RIVER: 1979-80 OBSERVATIONS

by
S. Beltaos

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S. Beltaos

Environmental Hydraulics Section
Hydraulics Division
National Water Research Institute
Canada Centre for Inland Waters
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ABSTRACT

The first year's ice observations on the lower Thames River are described and partially interpreted. Freeze up commenced in early January and breakup was complete by March 20, 1980. Though the 1980 ice season was not associated with flooding, several interesting events were documented, i.e. freeze up jams, initiation of breakup, breakup jams. In the upper portion of the study reach, breakup progressed in the downstream direction but the ice cover through and below Chatham moved out before arrival of the upstream ice run. Significant spring jams formed at five locations, including two bridge sites and the river mouth. Analysis of the observations indicated that there is merit in using the water stage as an index to forecast initiation of breakup; and that the present data support the existing theory of floating equilibrium jams.

SOMMAIRE

Les observations des glaces du cours inférieur de la rivière Thames durant la première année sont décrites et expliquées en partie. L'embâcle a commencé au début de janvier et la débâcle était terminée le 20 mars 1980. Bien que la saison des glaces de 1980 n'ait pas été marquée par des crues, on a rendu compte de plusieurs phénomènes intéressants, à savoir embâcles dus au gel, déclenchement du dégel, embâcles dus au dégel. Dans la partie supérieure du tronçon d'étude, le dégel s'est fait en direction de l'aval, mais la couverture de glace dans Chatham et en aval de cette ville s'est déplacé avant la dérive de glace d'amont. DImportants embâcles printaniers se sont formés à cinq endroits, notamment à deux ponts et à l'embouchure de la rivière. L'analyse des observations indique d'une part qu'il est bien fondé de se servir du niveau de l'eau en tant qu'indice permettant de prévoir le déclenchement du dégel et d'autre part que les données actuelles soutiennent la théorie des embâcles flottants en équilibre.

MANAGEMENT PERSPECTIVE

Systematic analysis of field data reveals a pattern which may prove productive for management of river floods and ice jams in the future. Data to date seems to show there may be a way to use the water stage as an index to forecast breakup. More data and studies are required. Furthermore, the available data supports the use of existing theory for floating ice jams in equilibrium.

More data on a national basis is required.

T. Milne Dick
Chief, Hydraulics Division
December 18, 1981

PERSPECTIVE - GESTION

Une analyse systématique des données receuillies sur le terrain révèle des caractéristiques qui peuvent s'avérer utiles en vue de la gestion des crues et des embâcles à l'avenir. Les données actuelles tendent à indiquer qu'il existe peut-être une méthode permettant de se servir du niveau de l'eau en tant qu'indice de prévision de la débâcle. Des données et des études supplémentaires sont toutefois nécessaires. Par surcroît, les données disponibles soutiennent l'utilisation de la théorie actuelle des embâcles flottant en équilibre.

Il et nécessaire d'obtenir d'autres données à l'échelle du pays.

T. Milne Dick
Chief - Division de l'hydraulique
Le 18 décembre 1981

1.0 INTRODUCTION

A major consequence of ice cover formation in northern rivers is the jamming that occurs during the spring breakup of the cover and clearance of the ice from the river. Due to their large thickness and hydraulic resistance relative to those of sheet ice, ice jams tend to cause unusually high water stages; this has repercussions in many operational and design problems, such as overturning moment due to moving ice floes on river structures, forces on ice booms, spring flooding and associated stage-frequency curves, etc.

At present, there exists a very limited capability for engineering predictions related to breakup and jamming problems (e.g. forecasting time of breakup, occurrence of ice jams, features of jams that may occur, maximum stages during breakup, etc.). Only crude estimates of jam stage are possible in cases where it is given that a jam has formed, is floating and has attained equilibrium. Undoubtedly, the relative underdevelopment of the state of the art arises from the complexity of the phenomena involved. Indeed, most of the problems mentioned above can only be approached statistically (see also Beltaos 1980b).

From the viewpoint of research, what is needed to improve the state of the art can be summarized as follows:

- Quantitative field data to test and calibrate the existing theory.
- Systematic annual breakup documentations at selected river reaches to build needed statistical records, assign probabilities to various events of interest and explore possible correlations of such probabilities with measurable stream characteristics.
- Qualitative field observations to identify or postulate important physical mechanisms that can be studied by theory and laboratory experiments, and
- Laboratory experiments to clarify or quantify aspects of the problem that cannot be efficiently studied in the field (e.g. mechanics of grounded jams; formation, release and re-formation of jams; hydraulic roughness of jam underside; effects of river geometry both in plan and cross section).

To address the first three of the above items, a long-term field research program was initiated in 1979. The objective is to improve methodologies for deterministic and statistical solutions to problems related to flooding. Specific goals are:

- To develop an index for forecasting the time of breakup.
- To identify channel features that are conducive to ice jamming and assess associated frequencies.
- To provide a data base for statistical analysis of peak breakup stages and develop a methodology to transpose the results to sites where little or no historical information exists.
- To obtain quantitative data for testing and improving existing theories.
- To improve qualitative understanding as a means of guiding laboratory and theoretical research.

Ideally, observations should be carried out at about ten reaches that are representative of Canadian conditions and should comprise complete documentations of the river regime during the entire ice season. However, manpower limitations have restricted the observations to mainly hydraulic aspects of breakup at only one reach. The reach selected for study is the lower Thames River from about Thamesville to the mouth (Fig. 1). This reach is reputed for relatively frequent jamming and flooding; in addition, there is excellent ground access, there are several hydrometric gauges and aerial reconnaissance can be conveniently arranged at the nearby Chatham Airport. Moreover, the selected reach has a feature that is encountered frequently in the Great Lakes area; its lower portion - from the mouth to above Chatham - is subject to lake control so that flow tends to be deep and slow relative to normal river flows. Very likely, this feature influences the breakup and jamming regime of the river and it is considered desirable to study this influence. It is noted that the upstream limit of the study reach is not a strict one, that is, interesting occurrences that may be noticed above Thamesville are documented as opportunity permits. No observations are made above Middlemiss (Fig. 1).

This report presents the results of the first observation season, January to March 1980. Before proceeding to describe this season's ice regime, a brief description of the lower Thames River is considered appropriate. Figure 2 is an approximate water surface profile of the river from the mouth to Middlemiss. Water surface elevations have been obtained from a series of 1:25,000 topographic maps at the intersections of elevation contours with the stream boundaries. Straight lines have been drawn between points representing successive contour intersections. Relevant information, such as river crossings, towns, tributaries and the like are also shown in Fig. 2. Table 1 summarizes average river slopes between contour intersections.

Characteristic river flows for three pertinent gauges are summarized in Table 2 for the period 1970-79. At Thamesville, the minimum and maximum flows recorded are 4.9 m^3/s (1971) and 946 m^3/s (1977). The ten-year average value of the annual average discharge is 55.2 m^3/s. At this flow, the average open-water width, depth and velocity at this site are 38 m, 2.1 m and 0.7 m/s. These values are based on hydrometric surveys in a reach extending from the Highway 21 bridge to 5 km upstream. The average river slope in this reach was measured at 0.23×10^{-3}. The Manning coefficient of the river bed, n_b, is 0.037 at Q (=discharge)=55.2 m^3/s and decreases to 0.034 when $Q \geq 180$ m^3/s.

Water Survey of Canada records for the Thamesville gauge indicate that, normally, an ice cover forms in late December and breaks up in mid-March. However, seasons with intermittent periods of ice cover are not rare; this is caused by winter thaws accompanied by sufficient runoff to lift and break the cover. This effect should be less pronounced in downstream reaches due to increasing lake control.

In the following sections, the observations for the 1979-80 ice season are described and interpreted. Of course, it is impossible to present all of the information gathered during the field observations and surveys. In addition to the data presented in this report, the following items are available on request: Numerous photographs and slides, edited movie film of various breakup events, and several river cross sections surveyed in February and June 1980.

2.0 FREEZE UP OBSERVATIONS

A small amount of ice formed in mid-December but was removed following a warming trend and rain. Cold temperatures set in and the river began freezing up in early January. An ice cover formed first in the reach mouth-Chatham, where the flow is extremely tranquil owing to lake control. This type of ice cover may be classified as static (Michel, 1975). Dynamic ice cover occurs generally above Chatham and is formed by slush that jams against the static cover and later freezes in place.

Figure 3 shows daily average stage plotted versus time at four Water Survey of Canada gauge sites (Water Survey of Canada, Guelph office, preliminary data). The solid lines are observed stages; the dashed lines are "effective" gauge heights, i.e. stages that would occur had open water conditions prevailed. Effective gauge heights were determined based on discharge estimates provided by Water Survey of Canada; where possible, flows at Byron outside the period of ice conditions were transposed to Dutton and Thamesville based on empirical correlations derived from past data. Also shown in Fig. 3 are relevant meteorological data taken at Ridgetown, about 15 km southeast of Thamesville as reported by Atmospheric Environment.

The following features are noteworthy in Fig. 3:

(i) The period of ice conditions at Byron is much shorter than those of the other gauges. This is a typical occurrence, caused by warm effluents (gauge located at south end of the city of London) and local rapids*.

(ii) Effective gauge height is not shown for Chatham. Due to partial lake control, a discharge rating curve is not available for this gauge.

(iii) The first day of ice effect at Thamesville is January 7. However, the "beginning of freeze up", as defined herein, is January 6, this being the day on which the solid and dashed lines begin to deviate from each other.

(iv) With reference to the Thamesville gauge, a rather typical occurrence during the first few days of freeze up is illustrated in Fig. 3: while the discharge (and thence the effective gauge height) continues to drop, the water stage first increases to a peak and then decreases again. (This also happened at Dutton but is not as clearly shown in Fig. 3). This sequence reflects the dynamic nature of river freeze up, i.e. the frazil slush generated while the river is still open agglomerates into pans and floes that

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* J. Ritchie (personal communication).

eventually jam and freeze together. The jamming causes a stage rise to accommodate the thickness of the jam and the increased resistance to flow caused by the underside of the jam. As the jam freezes, however, its underside becomes smoother and the stage drops.

(v) Rainfall on Jan. 10 and 11 caused a moderate flood wave that resulted in partial breakup of the ice cover that had already formed in the river. Field surveys on January 13 to 15 and January 29 indicated the following conditions:

- Continuous ice cover from the river mouth to above Kent Bridge (see also Fig. 1).
- Mostly open water near Thamesville; slush ice jam below the Highway 21 bridge extending to next bridge; open water above this jam to a point about 1200 m above the bridge, followed by an 800 m long slush ice jam.
- Slush ice jams were also observed at the Bothwell W. and Middlemiss Crossings while the river was open at the remaining crossings between Thamesville and Middlemiss.
- The various slush jams released shortly after January 15 and a new ice cover formed; at Thamesville, the beginning of the new freeze up is estimated as January 23. Figure 4 gives photographs of the various slush jams observed during January 14 and 15. Quantitative data and analysis pertaining to these jams are presented in a later section.

Based on air temperature records at Ridgetown, the accumulated degree-days of frost, up to and including the date signifying the beginning of freeze up, is calculated as 34 and 16 ^{o}C-days for the respective freeze up days identified in Fig. 3 for the Thamesville gauge (January 6 and January 23).

As can be seen in Fig. 3, the ice cover that formed in the second half of January 1980 remained in place until the spring breakup. Ice thickness was measured at several locations during February 5 to 7 and the results are summarized in Table 3. It is seen that the cover was thicker downstream of Chatham than upstream owing to much lower flow speeds. Despite comparable flow speeds at Kent Bridge and Thamesville, the cover was somewhat thicker at the former location. This was probably caused by the fact that the mid-January breakup that occurred at Thamesville did not take place at Kent Bridge.

3.0 BREAKUP OBSERVATIONS

Following warm weather and rainfall in mid-March, the water level began to rise rapidly. Breakup observations commenced on March 18, 1980 and ended on March 20, 1980. A day-by-day description of breakup events is given below.

3.1 March 18, 1980

0400-0545: Open water at the Highway 21 crossing, extending to about 1 km upstream; alternating open-water and ice-covered sections below Highway 21 to the railway bridge. The open-water section was probably caused by construction activities near the highway bridge earlier in the winter.

0650: Breakup had commenced at Bothwell W; there was a small jam upstream of the bridge, held by a section of natural ice cover which in turn was held by the bridge piers. At 1145 h, it was found that the jam had advanced, being held by the piers and the water level had risen. At 1145, the ice sheet lifted, cracked and moved forward at a speed of 0.6 to 0.9 m/s. This movement lasted until 1156 when a few large floes jammed against the piers. Ice floes were seen to emerge at the downstream end of the new jam.

0720: Undisturbed ice cover at Kent Bridge with side strips of open water.

0820-1030: No change at Highway 21 bridge except for a rise in water level.

1100-1130: An ice jam was noticed and partially documented near Fairfield Museum (see also Fig. 5). At 1212, the head (upstream end) of the jam was observed to advance at an estimated speed of 0.9 m/s. The thickness of various ice floes near the river bank ranged between 3 and 25 cm with an average value of about 18 cm.

1230: No change at Highway 21 bridge except for the rising water level. At 1250, the ice cover upstream began moving and arrived at the bridge 20 minutes later (average speed $\simeq 1000/20x60=0.8$ m/s). Figure 6 shows the variation of the water level with time along with pertinent notes on ice conditions at Highway 21. The water level at initiation of breakup was assumed equal to that which caused movement of the ice cover 1 km upstream of the bridge; the corresponding gauge height at Highway 21 was taken as that which occurred on arrival of the ice cover (13.26 m).

1515: A 200 m long open-water section had developed at Kent Bridge, starting at the first bend above the bridge. After brief, intermittent movements, the ice cover moved out at 1615 and broken ice approached the bridge 13 minutes later; at 1641, the ice run was arrested by a few large floes that jammed against the bridge piers. The resulting jam released at 1731 and its main portion had passed under the bridge by 1800; scattered ice fragments followed until 1930 when observations were discontinued. Figure 7 gives the variation of water level with time at Kent Bridge during the above events.

1530-1550: An ice run was observed (broken ice filling the channel) about 2 km above the Highway 21 bridge. This was probably ice from the jam that released earlier near the Fairfield Museum.

1550-1610: Open water was noted at Fairfield Museum and at Bothwell E. and W. crossings.

1620: Ice running at Wardsville.

1640-1730: Open water at the following bridges: Simpson's, Walker's, Willy's and Middlemiss (Fig. 1).

2230: Undisturbed ice cover at Sherman Brown Bridge.

3.2 <u>March 19, 1980</u>

0700: An open-water section had developed near Sherman Brown Bridge, starting beneath the bridge and ending 200 m downstream. Figure 8 gives the variation of the water level at Sherman Brown Bridge during 1000-1800, along with notes on ice conditions.

0730-0830: The river through and below Chatham was still mostly ice-covered but with an open-water strip at midstream.

1010-1050: The river was observed from the air using a small airplane chartered at the nearby Chatham Airport. Ice conditions through and below Chatham were mostly as described above; however, there were occasional locations where large ice floes had jammed for distances not exceeding a few river widths. Upstream of Chatham to a point about 2 km above the Sherman Brown Bridge, there were alternating open-water and ice-covered sections (Fig. 9). Upstream of this point, there was a minor jam followed by a 7.5 km long ice run (broken ice), as shown in Fig. 9; the latter was probably caused by the release of a major ice jam upstream and was advancing at an estimated speed of 0.9 m/s. The river was open upstream of the ice run to at least Kent Bridge. Figure 10 gives photographs illustrating ice conditions during the air survey. By 1200, the ice was jammed behind large ice sheets wedged against the piers of Sherman Brown Bridge (Fig. 11).

1200-1400: The jam above Sherman Brown Bridge was documented from various ground access points. Slow movement (< 0.3 m/s) was noticed at one location, probably caused by consolidating and packing within the jam. The thickness of ice floes on the river banks varied between 6 and 24 cm and had an average value of about 14 cm.

1430: The jam released at Sherman Brown Bridge; the ensuing ice run lasted until 1650 and had an average speed of about 0.9 m/s (see also Fig. 11). The run was followed downstream and, by noting its advance at different times, its speed was estimated again as 0.9 m/s. At 2140, the river was filled with broken ice at Prairie Siding but there was open water at the Yacht Club (Fig. 1).

3.3 March 20, 1980

0750: Broken ice was jammed at the river mouth. The jam extended about 300 m into Lake St. Clair and as far upstream as could be seen from the lighthouse. The water level variation with time near the river mouth is shown in Fig. 12 along with notes on ice conditions.

1010-1020: The jam was documented from the air (see also Figs. 13 and 14).

1330: River ice had moved into Lake St. Clair and observations were discontinued.

3.4 Summary of Breakup Observations

In general, the March 1980 breakup progressed in the downstream direction. Breakup appears to have been initiated near Fairfield Museum where an ice jam formed for an unknown period of time but is known to have released by noon of March 18. Downstream of this location, there were alternating open-water and ice-covered sections until a few kilometres below Thamesville. Near Thamesville, the ice cover began moving independently of the Fairfield Museum jam, at 1250 on March 18. Significant jamming occurred later at Kent Bridge and this jam released at about 1730.

During the night of March 18 to 19, the broken ice in the river must have been arrested at some point below Kent Bridge, forming a major single jam. This jam was observed while in motion in the morning of March 19 a few kilometres upstream of Sherman Brown Bridge; it was eventually arrested at this location but released at 1430 on March 19. Subsequently, the broken ice moved virtually unimpeded to the river mouth where it jammed sometime during the night of March 19 to 20. Frequent checks on the position of the moving ice during March 18 and 19 indicated a fairly constant average speed of 0.9 m/s.

It is noteworthy that the breakup through and below Chatham occurred independently of upstream ice conditions. Early on March 19, an open-water strip was noted in this reach at midstream. It was learned later from staff at the OMNR (Ontario Ministry of Natural Resources) dock that the ice cover had become candled by March 18, being 18 cm thick at the sides and 3 cm thick at midstream; it was easily broken by a small tug that ventured on the river on March 18.

4.0 DATA ANALYSIS AND INTERPRETATION

4.1 Freeze Up Period

The beginning of freeze up as defined herein, is in fact the last day of a period during which there are no measurable ice effects on the flow. Usually, ice forms in the river before this day but has no measurable effect so long as it moves freely and its flux is a small fraction of the water discharge. The ice effect is thus expected to become measurable at a given site when the ice flux is arrested somewhere downstream and the backwater from the resulting ice cover begins to be "felt" at the site under consideration. Subsequently, the water level at this site will continue to rise until the edge of the ice cover arrives at the site. This can be easily shown to be the case under conditions of constant discharge but is known to occur even when the discharge is decreasing slightly (see also Fig. 3). In such instances, the backwater due to the newly formed ice cover is larger than the stage reduction caused by the reduced discharge. Initially, the ice cover consists of a loose accumulation of ice floes and slush. These subsequently freeze together to form a continuous ice cover; thermal effects are also demonstrated in progressive smoothening of the underside of the ice cover. The water level drops because the hydraulic resistance is reduced. It is thus expected that, shortly after the beginning of freeze up at a given gauge site, the water level record should have a peak (see also Fig. 3) which would correspond to the time and stage of the initial ice cover formation. This also coincides with the writer's experience in analyzing many years' records at Thamesville. Though typical, this sequence occasionally may not occur, due to peculiarities in meteorological and hydrological conditions.

The peak freeze up stage on a (daily average) water level versus time graph such as those of Fig. 3 is herein defined as the maximum stable freeze up stage (H_F). It has been suggested (Shulyakovskii 1963, 1972; Gerard 1979; Beltaos 1980a) that H_F may be used as a tentative index for breakup forecasting. For the two freeze up periods indicated at Thamesville in Fig. 3, H_F had respective values of 12.40 m and 12.05 m.

4.2 Initiation of Breakup

An important problem in river ice hydraulics is the forecasting of the initiation of breakup. Several methods have been proposed to date (see, for example, Shulyakovskii 1963) based on criteria involving hydrometeorological parameters. These methods are empirical and site specific; they require detailed historical information for any given site while the results cannot be transposed to other sites. Nevertheless, the previous investigations have identified two significant water levels as governing parameters: the stage H_B (gauge height, say) at the beginning of breakup and stage H_F, the maximum stage during the preceding period of a stable ice cover. Shulyakovskii (1963) states: "If the ice breakup develops during a rise in the water stage, the stage (H_B) at which the ice push occurs is determined mainly by the highest position of the ice cover during the winter, i.e., by the maximum winter stage (H_F)". In the same reference, examples are given of site-specific relationships between H_B and H_F. Figure 15 is an attempt to illustrate the significance of H_F. Figure 15a shows ice conditions in early winter when the stage attains a maximum. It is this stage at which the width of the ice cover, W_i, is fixed and is approximately equal to the corresponding channel width. Later on, the stage drops and more ice may form but the ice cover width does not change appreciably (Fig. 15b). So long as H remains less than H_F, the ice cover is supported by the channel banks. The driving forces (water shear stress plus downstream component of the cover's own weight) can be shown to be very small to cause breaking under these boundary conditions. When warm weather sets in and a sufficiently high flood wave travels downstream due to increased runoff, the stage will exceed H_F in the upper portion of the river though it will remain lower than H_F elsewhere. These two portions are separated by section A where $H=H_F$ (Fig. 15c). Upstream of A, the cover is no longer supported by the banks and thus may be considered a floating beam cantilevered at point A. At this configuration cracks will eventually develop given that point A moves downstream and the stresses in the cover thus increase in the downstream direction*. If the formation of cracks is defined as the initiation of breakup, then H_B will be somewhat larger then H_F. This is essentially Shulyakovskii's (1972) theoretical development which showed that, for a given reach, H_B should depend on H_F, h_i (=ice thickness) and σ_i (=ice strength; compressive or tensile depending on the governing condition).

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* It should be understood that this discussion is a highly simplified description of what occurs in reality. Complexities are introduced by the lack of uniformity of natural streams and the existence of bars and islands. These, however, do not alter the essense of the argument, that is, H must exceed H_F before the ice cover looses its boundary supports, provided there is no significant melting at the sides.

As the flood wave advances, new cracks will appear so that eventually the river will be covered by large separate ice sheets which cannot be broken down to smaller pieces by the available forces. However, general breakup does not necessarily follow from this condition because the ice sheets may be too large to move downstream for any significant distance; they may be simply realigned into a loose but stable arrangement, as illustrated in Fig. 16. Though a considerable portion of the river surface is now open, large ice sheets are lodged against the banks and cannot yet advance. With a further increase in stage, the channel width will also increase, thus allowing some of the sheets to "clear" the bends (or other obstacles) and move for a considerable distance. These sheets pick up speed and on impact with stationary ones cause further breaking and fragmentation. Small ice jams begin to form causing additional stage rises, new dislodgements, etc. Therefore, it is reasonable to define the beginning of breakup at a given site as the time when a sustained movement of the ice cover takes place.

In the foregoing, it has been implicitly assumed that the ice remains competent in thickness, width and strength during the pre-breakup period; this leads to the conclusion that H_B must exceed H_F. However, there are instances of warm weather occurring with very little runoff to cause significant stage increases. The ice cover then deteriorates by thermal effects until it can be broken by the available driving forces. This is the "overmature" type of breakup (Deslauriers 1968) which may occur even if $H < H_F$ but is not expected to cause any problems or damage. This qualification is probably reflected in the previously given quotation from Shulyakovskii (1963) by stipulating the condition "If the ice breakup occurs during a rise in the water stage" ...

Direct measurement of H_B at any given site requires continuous monitoring of ice conditions and water levels. Intermittent monitoring or past gauge records can only provide ranges of or probable H_B values. For gauge records, a lower limit for H_B may be taken as the fairly steady water stage that preceeds the final rise leading to breakup; an upper limit may often be identified where the record begins to exhibit irregularities that cannot be attributed to runoff variations. These ideas apply where breakup is partly caused by rising stage and discharge.

Figure 17 shows historical data for the Thamesville gauge (Beltaos and Poyser 1981) plotted in the form H_B versus H_F; the data points are accompanied by a number indicating the thickness of the ice cover in centimetres*. The data of Fig. 17 are subdivided into three groups:

(i) Cases where only upper and lower limits can be identified for H_B, as indicated earlier. Often the lower limit is taken as the fairly steady pre-breakup stage which is generally less than H_F. Occasionally, a brief thaw may cause H to rise above H_F without effecting breakup. The peak stage during such events may then be used as the lower limit of H_B since it indicates the maximum stage known to have occurred without causing breakup.

(ii) Cases where a single, probable value of H_B can be identified based on the gauge record as well as on descriptions of simultaneous ice conditions by local observers.

(iii) Cases where H_B has been positively identified by detailed monitoring (1979-80 data).

Figure 17 indicates that H_B has a tendency to increase with H_F, while this increase seems more pronounced when h_i increases. To illustrate the effect of h_i, the difference H_B-H_F is plotted versus h_i in Fig. 18. A general trend for H_B-H_F to increase with h_i is apparent. Also shown in Fig. 18 are data for the Smoky River at Watino (Beltaos 1980a); these do not fit the trend of the Thames River data.

Apart from uncertainties in determining H_B, the scatter in Fig. 18 is probably caused by errors in estimating h_i and variations in the value of ice strength, σ_i. Ice thickness has been obtained from discharge measurement notes as provided by Water Survey of Canada. The time of measurement may be a few days to a few weeks before the time of breakup while the location of measurement is practically fixed.

As a preliminary means of understanding the effects of the various pertinent factors and possibly generalizing the present results, the qualitative description of the breakup process that was given earlier, is quantified as follows.

Let ℓ_i be a length representative of the longitudinal dimensions of the separate ice sheets illustrated in Fig. 16b. At the beginning of breakup, the

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* Where no ice thickness measurements were available, estimates were made based on a plot of measured ice thickness versus time since the date of H_F. Errors of ±30 percent are possible in such estimates.

channel width, W_B, must be such that it "just" permits the stationary ice sheets to "clear" the various obstructions*. One could then write:

$$W_B = f_1 (W_F, \ell_i; \quad \ell_1, \ell_2, ..., \ell_K; \quad \theta_1, \theta_2, ..., \theta_n) \tag{1}$$

in which $\ell_1, ..., \ell_K$ and $\theta_1, ..., \theta_n$ are series of lengths and angles that define river geometry. The length ℓ_i may be expressed as:

$$\ell_i = f_2 (\tau, \sigma_i, W_F, h_i; \ell_1, ..., \ell_K; \theta_1, ..., \theta_n) \tag{2}$$

in which σ_i=ice strength (generally flexural) and τ=sum of driving forces per unit area of cover=$\tau_i + \omega_i$ (τ_i=water shear stress on bottom of cover, ω_i=downstream component of the cover's weight per unit area). At this point, a question arises as to the stage at which τ should be evaluated. Clearly, this stage is greater than H_F and less than H_B. Considering that the ice cover becomes a cantilevered beam as soon as H_F is exceeded, it is reasonable to approximate τ with τ_F, the value at $H=H_F$. Combining Eqs. 1 and 2 and applying the pi-theorem gives then:

$$W_B/W_F = f_3 (\tau_F/\sigma_i, h_i/W_F; ... \ell_K/W_F; ... \theta_n) \tag{3}$$

Since channel width changes with stage, the parameters ℓ_K/W_F will change from year to year; however, this change should be limited, considering that W is a mild function of stage and the range of H_F is limited (early winter flows). Thus, the ratios ℓ_K/W_F can be considered river "constants" as a first approximation and Eq. 3 may be written as:

$$W_B/W_F = f_4 (\tau_F/\sigma_i; h_i/W_F; \text{dimensionless river constants}) \tag{4}$$

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* Clearly, over a given reach with many sheets, ℓ_i will have a statistical distribution rather than being a constant as assumed in the analysis. Our thinking may be made more precise by stipulating that breakup begins when W_B is such that a fixed (though unknown) percentage of the ice sheets are able to move. Then ℓ_i will be the length characterizing this percentage.

The parameter τ_F/σ_i is unknown because no measurements of ice strength are available. At the same time, W_B/W_F is impractical for application and could be replaced by $\Delta H_B/\Delta H_F$ (ΔH=stage in excess of stage at zero discharge) or by y_B/y_F (y=average flow depth). Note that in most streams W and y are related by a power-type expression and ΔH is a rough measure of y. Figure 19a shows y_B/y_F plotted versus h_i/W_F while a similar plot using $\Delta H_B/\Delta H_F$ is shown in Fig. 19b. These two graphs show a slight improvement over Fig. 18 with respect to the Thames River data. At the same time, the Smoky River data are now much more consistent with the Thames River data than they were in Fig. 18. This gives a measure of support to the dimensionless expressions that were derived earlier. The scatter in Figs. 19a and 19b could, by Eq. 4, be partly attributed to the effects of τ_F/σ_i and river geometry. Though τ_F could be estimated from the available information, σ_i is unknown and an attempt to measure it at the time of breakup would seem impractical. A more convenient, though indirect, measure of σ_i might be the amount of heat absorbed by the cover since the start of warm weather, based on meteorological data. River geometry is described by series of dimensionless lengths, ℓ_K/W_F, and angles, θ_n. The ℓ_K's define such dimensions as meander length and amplitude, island length and width, etc; while θ_n may be used to define the angles of river bends. In practice, it would be inconvenient to work with such parameters but some qualitative inferences could eventually be made by identifying similarities in the geometry of different rivers.

4.3 Ice Jams

Several ice jams were observed and documented during both the freeze up and breakup periods. Freeze up jams were observed during the period January 13-15 at river sections near Thamesville, Bothwell and Middlemiss (see also Fig. 4). Of these, the Thamesville jam was documented in considerable detail, including a survey of the water level in the jammed reach. Thickness measurement had been planned but the jams released before freezing in place so as to permit safe access. Breakup jams were documented near Fairfield Museum; Sherman Brown Bridge; and river mouth. Water levels along these jams were obtained from photographic records (as described by Beltaos 1978) and by spot-checking of water levels from nearby benchmarks. For all jams, supplementary hydrometric data (e.g. cross sections, open-water slope, disharge) were obtained later from open-water surveys and from Water Survey of Canada gauge data.

The available data have been analyzed according to two methods in an attempt to test the existing theory of ice jams which, with certain assumptions, gives the equilibrium thickness of an ice jam. As has already been pointed out (Beltaos, 1978), a complete analysis is not possible in cases where thickness measurements are not available, because the number of unknowns exceeds that of available equations by one. In such cases, one can only explore "probable" values of jam thickness h_j, and examine the corresponding ranges of hydraulic roughness and internal friction parameters. This detailed method of analysis is illustrated in Appendix A by outlining the procedure used for the January 1980 jam near Thamesville. At the same time, a simpler analysis can be performed as follows.

Beltaos (1978) showed that the conventional theory of ice jam equilibrium (Pariset et al 1966; Uzuner and Kennedy 1976) results in the following equation:

$$\mu \rho_i (1 - s_i)\, g h_j^2 = W (\tau_i + \rho_i g S h_j) \qquad (5)$$

in which μ=dimensionless coefficient that depends on the internal friction of the jam; ρ_i=ice density; s_i=specific gravity of ice; g=acceleration of gravity; W=channel width at the bottom surface of the jam; τ_i=water shear stress at the bottom of the jam; and S=water surface slope in the jammed reach. Because Eq. 5 has been derived for an equilibrium jam (steady-state condition, uniform jam thickness and uniform flow under the jam), the slope S should be equal to the channel bed slope if the channel were a prismatic one. In the case of river reaches that are not subjected to control influences, the concept of uniform flow can be applied by considering reach-average quantities over sufficiently long distances. The slope S may then be taken as the water surface slope under open-water conditions. In Eq. 5, the jam is assumed cohesionless (see also later discussion). The overall depth of water, h_T, in the jammed reach, is:

$$h_T = y + s_i h_j \qquad (6)$$

in which y=depth of flow under the jam. Equation 5 can be solved for h_j and the result substituted in Eq. 6. Using also a resistance equation for y, an expression for h_T may be found, in which h_j is not present. (Note that Pariset et al's (1966) final equation relates Q^2/Wh_T^4 to h_j/h_T which is difficult to work with in practice because h_j is not known.) This operation results in the following dimensionless equation (see derivation in Appendix B):

$$h_T/WS\ (\equiv \eta) = \underbrace{0.63\, f_o^{1/3}\ \xi}_{=\ y/WS} + \underbrace{\frac{5.75}{\mu}\left\{1 + \sqrt{1 + 0.11\ \mu f_o^{1/3} \left(\frac{f_i}{f_o}\right) \xi}\right\}}_{=s_i\, h_j/WS} \tag{7}$$

in which s_i has been fixed at 0.92 and f_o, f_i are the composite and ice jam friction factors respectively (note that $2f_o = f_i + f_b$; f_b=channel bed friction factor). The significance of the two terms on the RHS of Eq. 7 is also indicated. The parameter ξ is defined as:

$$\xi \equiv (q^2/gS)^{1/3} \ / \ WS = y_c/WS^{4/3} \tag{8}$$

with q=discharge intensity=Q/W and y_c=critical flow depth. Equation 7 shows that h_T/WS depends primarily on ξ and, to a lesser degree, on μ, f_o and f_i/f_o. The effects of f_o and f_i/f_o are the least important because f_o appears raised to a small power while f_i/f_o appears under the square-root sign. The effect of μ is important for relatively thick jams (small ξ's) but decreases for increasing ξ's.

It is felt that Eq. 7 is more practical than Pariset et al's (1966) dimensionless relationship between Q^2/Wh_T^4 and h_j/h_T for two reasons: (i) in practice, it is usually desired to compute h_T given Q, W and S and this may be accomplished more directly using Eq. 7. (ii) ice jam data such as those available herein, include estimates of h_T, W, S and Q but not of h_j; Eq. 7 is particularly suitable for testing the theory in this case because both η and ξ can be calculated from the available information, i.e., they are measurable. The same does not hold for Pariset et al's expression which involves h_j.

With this discussion, we now proceed to interpret the ice jam data of the 1979-80 ice season.

Slush ice jam near Thamesville, Jan. 1980: A river plan showing the location of the jam is given in Fig. 20a while photos of the jam surface have been presented in Fig. 4. Figure 20b shows water surface profiles during the jam survey (January 15, 1980) and during two additional surveys; river cross sections, located as shown in Figs. 20a and 20b, are presented in Fig. 20c. With reference to the open-water condition, it is noted that a significant reduction in slope and velocity occurs at about 1740 m above the Highway 21 bridge. This reduction in slope probably contributed to the formation of the jam but it is unknown to what extent. Figure 20b shows that the water surface profile along the jam is similar to the open-water profile but elevated by about 3.5 m. Considering the water surface slope, it is noted that S_i(=slope under ice conditions) is equal to S_o (slope under open-water conditions = .000767) in the reach 1980 m to 1740 m; $S_i > S_o$ in the reach 1740 m to 1390 m; and $S_i \to 0$ in the reach 1390 m to 20 m. These findings suggest the following: in the first reach the ice jam was in equilibrium (see also Uzuner and Kennedy 1976); the last reach was influenced by backwater of the jam below the bridge; and the intermediate reach was a transitional zone.

Using data applicable to the equilibrium reach, an approximate analysis was performed to estimate thickness and roughness characteristics of the jam, based on the method outlined by Beltaos (1978; 1979). The relationship between n_b (=Manning roughness coefficient for the river bed) and R_b (=hydraulic radius applicable to the river bed) was derived from the open-water data, based on the following assumptions:

- The discharge in the reach 1980 m to 1740 m is equal to the discharge at the gauge site (Highway 21 bridge).
- Under open-water, steady-flow conditions, the water surface rises with increasing discharge but remains parallel to itself. This assumption provides a means of transposing the rating curve of a nearby gauge to the reach of interest and fixes the channel slope*.

This calculation indicated that n_b decreases slightly with R_b in the range $R_b \leq 2$ m and assumes a constant value of 0.0495 in the range 2 m $\leq R_b \leq$ 4.5 m.

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* This assumption derives from an extrapolation of the concept of uniform flow to natural streams and is therefore an approximation. Non-uniformities are ever present in rivers and the concept only applies in an "average" sense in reaches where such non-uniformities are not excessive and may be considered random fluctuations about well-defined average values of flow geometry parameters. This assumption is not uncommon in river engineering calculations (see, for example, Kellerhals et al 1972).

With the available information on the slush jam surveyed on January 15, 1980, it is not possible to directly calculate the value of n_i (=Manning roughness coefficient of the jam underside) because the jam thickness is unknown. However, one may compute a "plausible" range of n_i values using a "plausible" range of ice jam thickness values. Details of the computational procedure are outlined in Appendix A and the results are summarized in Fig. 20d (n_i versus submerged thickness, h_j', on upper graph, μ versus h_j' on lower graph); calculations were carried out for three flow conditions:

- Q=108 m^3/s, January 12, 1980; maximum ice jam effect on stage. From the gauge record, it is estimated that the ice jam was initiated during the early morning of January 12. The condition of January 12 is thus considered representative of the initial jam condition.
- Q=165 m^3/s, January 14, 1980; maximum flow discharge during ice jam, and
- Q=140 m^3/s, January 15, 1980; date of ice jam survey.

Lower limits for these three conditions are also shown in Fig. 20d; these were estimated by the procedure explained in Appendix A, based on the "narrow" jam stability criterion. An upper limit of about 1 m was set for h_j, based on measurements of the height of shear walls left on the river banks after the release of the jam.

Figure 20d indicates the following:

(i) If the jam thickness was governed by the "narrow" jam criterion, it would have been 0.3 m on January 12 and increased to 0.6 m by January 14. However, this is considered unlikely for two reasons:
  - It is difficult to visualize how the jam would thicken without internal collapse which is the formation mechanism of "wide" jams.
  - The absolute roughness of the jam on Jan. 12 would have to be larger than the jam thickness.

(ii) It is more plausible to assume that the jam thickness was stabilized shortly after its initiation (January 12) and remained unchanged afterwards; the lower limit of h_j' is then increased to 0.6 m. This is consistent with the μ-h_j' curves of Fig. 22d: for January 12, μ is higher than for the other two dates (meaning that after January 12, the jam was thicker than required and therefore stable).

(iii) Assuming that h_j did not change appreciably during the life of the jam, the hydraulic resistance of the jam underside is seen to decrease with time.

Considering that the smooth, continuous ice covers that occur in mid-winter have Manning coefficient values of about 0.01, it is reasonable to expect that the jam's coefficient, n_i, should exceed this value. Figure 20d indicates that this condition can be satisfied only if $h_j' < 0.9$ m; the range of h_j' values is thus reduced to $0.6 \text{ m} < h_j' < 0.9$ m.

(iv) In the upper graph of Fig. 20d, the dashed line represents the relationship between n_i and h_j' proposed by Nezhikhovskiy (1964) for the initial roughness of freeze up jams consisting of dense slush. If this relationship is adopted as a guide, then h_j' should be equal to 0.84 m which represents the intersection of Nezhikhovsky's line with that found for January 12, 1980. The initial value of n_i would then be 0.0375, dropping to 0.019 and 0.013 on January 14 and 15 respectively. For $h_j'=0.84$ m ($h_j=0.84/0.92=0.91$ m), the lower graph of Fig. 20d indicates an initial value of 1.0 for μ. This is somewhat less than the average value found for spring ice jams consisting of solid ice blocks ($\simeq 1.2$; Beltaos 1980b). Alternatively, if μ is fixed at 1.2, h_j' should be equal to 0.78 m ($h_j=0.85$ m) with $n_i=0.04$, 0.021 and 0.016 for January 12, 14 and 15 respectively (Fig. 20d). The above thickness values (0.85 m and 0.91 m) are close to but somewhat less than the average height (1 m) of shear walls observed on the river banks after the jam had released.

Table 4 summarizes the main results of the above discussion for convenience.

For h_j' ranging from 0.6 to 0.9 m, the channel width W at the bottom of the jam ranges from 42.3 to 40.5 m; and the overall depth of the jam ($h_T=y + h_j'$) varies from 3.84 to 3.98 m. Because these ranges are fairly limited, it is permissible to use their mid-points to compute the applicable values of η and ξ, i.e., $h_T \simeq 3.94$ m and $W \simeq 41.1$ m, which leads to $\xi=308$ and $\eta=125$. The small uncertainty introduced by this approximation is caused by the fact that W changes slightly with stage.

Slush ice jam at Bothwell W., January 1980: This jam was observed on January 14 and 15, 1980. The river was jammed as far as could be seen from the bridge. The jam stage was photographed on January 14 against the right bridge pier and later surveyed based on the photograph. For hydraulic computations, the flow was assumed to be equal to that at Thamesville for the same date (165 m^3/s). The water surface slope during the ice jam condition was assumed equal to the open-water slope, i.e. 0.000263. The bed Manning coefficient under open-water conditions is equal to 0.0423 for depths over 1.4 m but increases rapidly with decreasing depth below this value. For a plausible range of h_j=0.25 to 1.00 m, h_T is between 4.3 and 4.5 m and W varies from 58 to 55.3 m. Taking h_T=4.4 m, W=56 m and Q=165 m^3/s gives η=196 and ξ=1002.

Slush ice jam at Middlemiss, January 1980: This jam was also observed on January 14 and 15, 1980. Its stage was documented photographically much as for Bothwell. For the hydraulic computation, the flow was assumed equal to that at the gauge site near Dutton for the same date (Q≈100 m^3/s). The channel slope under the jam was again assumed equal to the open-water value of 0.0518×10^{-3}. The bed Manning coefficient varies with depth, being 0.048 at y=1.7 m and becoming a constant (=0.037) for y ≥2.8 m. The values of h_T and W are 4.8 m and 45 m while η and ξ work out to be 584 and 1766 respectively.

Ice jam near Fairfield Museum, March 18, 1980: This jam was observed in the late morning of March 18, 1980 (see Fig. 5 for its configuration and appearance). Jam stages were photographed against the river banks and the jam profile was surveyed later, using the photographs. The profile is shown in Fig. 21 along with the open-water profile of November 13, 1980. Figure 21 suggests that this jam was not in equilibrium when surveyed because its water surface does not seem parallel to the open-water surface. The discharge at the time the jam was surveyed is estimated as 130 m^3/s based on Water Survey of Canada (1981) gauge data near Thamesville. Using the water level at the head of the jam, as the most indicative value of equilibrium conditions and the local channel geometry and slope, (0.00081) gives $H_T \simeq 4.2$ m, W≃44 m and $\eta \simeq 118$, $\xi \simeq 290$. This ice jam released about 30 minutes after it was documented.

Ice jam above Sherman Brown Bridge, March 19, 1980: This jam was documented in the early afternoon of March 19. Repeated water level checks at a few locations along the jam indicated a fairly steady condition. The longitudinal profile of the jam is shown in Fig. 22. It is of interest to note that the data points corresponding to the morning documentation of the water levels are much lower than the afternoon values. This is attributed to the fact that the ice was moving in the former case.

The profile of the jam is linear except near the toe where it becomes relatively steep. This feature is not uncommon (see, for example, Doyle and Andres 1978, 1979; Beltaos 1980b). The slope of the linear portion of the jam profile is 0.00026 relative to the water level of November 19, 1980. Ordinarily, this would imply a non-equilibrium condition but does not necessarily do so in the present case because the reach of interest is subject to backwater effects from Lake St. Clair. Under open-water conditions, the flow in this reach is non-uniform and its slope is controlled by the lake level, the river discharge and the channel resistance. It can be shown that a large increase in the resistance to flow such as that imposed by the presence of an ice jam, will cause an increase in slope and reduce the degree of non-uniformity of the flow. Analysis of cross-sectional data indicated no consistent downstream trends in flow area and width under the jammed condition while computed values of $V^2/2g$ indicated that the energy slope was very nearly equal to the water surface slope. A computation for the open-water condition of November 19, 1980 was also carried out using a value of less than 0.040 for n_b* and resulted in a slope value of less than 1.5×10^{-6}. Hence, the energy slope of the ice jam can be assumed approximately equal to 0.00026. River discharge is estimated as 196 m^3/s, based on gauge data near Thamesville.

The values of η and ξ are 244 and 728, based on corresponding values of 4.7 m for h_T and 74 m for W.

Ice jam at river mouth, March 20, 1980: The water surface slope along this jam is estimated as 0.00013 based on two water level photographs taken during the aerial reconaissance of March 20, 1980. The flow condition during that time appears to have been fairly steady as illustrated in Fig. 12. Cross-sectional data indicated that the flow was mildly non-uniform while the velocity head had no significant influence on the energy slope. The flow discharge is estimated as 195 m^3/s based on gauge data near Thamesville and a travel time of 1.5 days. The average ice jam characteristics are then computed as: $h_T \simeq 4.6$ m, $W \simeq 105$ m, $\eta \simeq 337$ and $\xi \simeq 1020$.

Table 5 summarizes the present ice jam data and Fig. 23 shows a plot of η versus ξ, including previous results obtained by others and by the writer. Despite considerable scatter, the data points suggest that a well-defined relationship exists between η and ξ over a two-log cycle range of the latter. Moreover, η increases continuously with increasing ξ as predicted by the theory (Eq. 7). Also shown in Fig. 23 are predictions of Eq. 7 for different values of f_o, using $\mu=1.2$ and $f_i/f_o=1.0$ (note the latter parameter does not significantly

* Knowles and Hodgins (1980).

influence the prediction; the value f_i/f_o=1.0 was chosen because it represents the mid-point of the range of possible values, 0 to 2). Fig. 23 suggests that f_o should decrease with increasing ξ which is plausible because f_o is expected to decrease when h_j/h_T decreases and the latter occurs when ξ increases. (It should be understood, however, that a unique relationship between f_o and ξ is not likely to exist; f_o depends on ξ as well as on channel and ice jam characteristics.)

From the above, it may be concluded that Fig. 23 provides strong support for the conventional theory of ice jams. At the same time, the data of Fig. 23 do not support a recent theory (Michel 1980) that claims η=const.=41.2. For practical purposes, Fig. 23 may be utilized by drawing an "average" line through the data points and using this line to find η and h_T when Q, W and S are given.

5.0 DISCUSSION

The first year's ice observations on the lower Thames River have been described and partly interpreted in the previous sections.

Freeze up commenced in early January and breakup was completed by March 20. The ice cover began to form in the lower portion of the river where the flow is very slow and progressed upstream. Warm weather and rainfall on January 10 and 11 resulted in breakup above Kent Bridge and in formation of several slush ice jams. A new ice cover formed during the second half of January and remained in place until the spring breakup in March. The breakup progressed generally in the downstream direction; however, the ice cover through and below Chatham broke up independently of upstream ice conditions. This portion of the cover seems to have deteriorated considerably before breakup up but it is not known why.

In the river reach that is not subjected to lake effects, breakup seems to be initiated by a rise in the water level. For the vicinity of Thamesville, gauge records have been analyzed and it was possible to relate the stage required to initiate breakup to the maximum stable freeze up stage and to ice thickness. To explain this finding, a preliminary conceptual model of the breakup process was developed and shown to give some encouraging results. However, this model does not account for reductions in ice thickness, width and strength that may occur prior to breakup; its moderate success for the Thamesville data probably reflects the fact that breakup at this site usually occurs soon after a warming trend and rainfall so that there is little time for ice cover deterioration. An interesting finding of the analysis is that, other things being equal, narrow rivers require a greater stage rise above the maximum freeze up level in order to break up than do wide rivers. This is corroborated by a comparison of the present data with similar data on the Smoky River, Alberta (width $\simeq$ 250 m). Though the present model is tentative and incomplete, it has illustrated the importance of obtaining reliable data on freeze up and breakup water levels as well as on ice thickness.

During the ice season of 1979-80, no flooding occurred in the study reach. However, several ice jams were observed during both freeze up and breakup. In the latter period, five major jams are known to have occurred and four of these were documented, as may be seen in the summary of Table 6. These jams were no longer than 7 km and did not last for more than about 15 hours. On two occasions, jamming occurred at bridge sites located at or immediately downstream of river bends. The competent ice cover of Lake St. Clair, along with the local reduction of speed at the river mouth seems to have been responsible for the last jam described in Table 6.

To compare the present ice jam measurements with the existing theory of equilibrium floating jams, the latter was algebraically manipulated into a convenient form that relates observable dimensionless parameters, i.e. h_T/WS ($=\eta$) and $(q^2/gS)^{1/3}/WS$ ($=\xi$). The present data (6 cases), along with the Alberta jam data (10 cases) show that a well-defined relationship exists between η and ξ. At the same time, it appears that flows under jams with large ξ (low h_j/h_T) have a lower composite friction factor than those associated with small ξ (high h_j/h_T). The fact that the Thames River is much smaller in width than the Alberta rivers associated with the data of Fig. 27 has proved beneficial because it has enabled a significant extension of the "tested" range of ξ ; the upper limit of this range has been increased from $\xi \simeq 75$ to $\xi \simeq 1800$. Despite the encouraging results of the ice jam analysis, many more case studies are needed to develop reliable design criteria. A very important question is how to measure the thickness of an ice jam. If resolved, it will enable definitive evaluations of hydraulic roughness and internal friction characteristics of ice jams.

6.0 SUMMARY AND CONCLUSIONS

The 1979-80 ice season was not associated with damage or flooding due to ice. At the same time, several interesting events were documented, e.g. freeze up jams, beginning of breakup, spring jams.

Interpretation of the observations indicated the following:

(i) There is some merit in using the water stage as an index to forecast the beginning of breakup. The stage seems to be influenced by the maximum stable stage during the preceding winter and by ice and channel properties. Unfortunately, there is, at present, very little reliable information than can be used as a basis of developing generalized forecasting methods.

(ii) Even when the ice season is "mild" from the viewpoint of damage and flooding, significant ice jams do occur. Spring jams formed near Fairfield Museum, Kent Bridge, Louisville, Sherman Brown Bridge and river mouth. Two of these appeared to have been caused by the combined effects of bridge piers and river bends.

(iii) During the breakup period, the discharge varied from about 100 m^3/s to about 200 m^3/s and the ice thickness was, on the average, between 14 and 18 cm.

(iv) Breakup progressed in the downstream direction in the upper portion of the study reach but the ice cover through and below Chatham moved out before arrival of the upstream ice run.

(v) A convenient dimensionless expression was developed to relate the overall jam depth to hydraulic parameters, based on the conventional theory of floating equilibrium jams. The theory was then tested using the present and previous data with satisfactory outcome.

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APPENDIX A. Analysis of January 1980 Ice Jam Data

The procedure used to analyze the field data on the January 1980 ice jam above the Highway 21 bridge is explained in this appendix. With minor modifications, this procedure may also be applied to other ice jams when the water surface profile along the jam and open-water hydraulics are available.

(i) Determine value of Q at the time of the jam survey; in the present case (January 15, 1980) Q was estimated as 140 m^3/s based on data at the Byron gauge;

(ii) Assume a value of h_j and compute h_j' (=submerged portion of jam thickness) from:

$$h_j' \simeq 0.92\, h_j \qquad \text{(A.1)}$$

(iii) Determine stage of the jam bottom at the applicable cross sections (in the present case, sections 67.53 and 67.29); determine corresponding cross-sectional areas and widths and reach-average values.

(iv) Compute n_o (=composite Manning roughness coefficient) from

$$n_o = R_o^{2/3}\, S_i^{1/2}\, /V \qquad \text{(A.2)}$$

in which R_o (=average hydraulic radius of the flow under the jam) $\simeq A/2W$ (A, W = reach average area and width respectively); $V = Q/A$; and S_i=water surface slope under ice-covered conditions ($=S_o=0.767\text{x}10^{-3}$ in the present case).

(v) Compute n_i, n_b and R_i, R_b using the Sabaneev relationships

$$n_o = \left[0.5\, (n_b^{3/2} + n_i^{3/2})\right] \qquad \text{(A.3)}$$

$$R_i/R_b = (n_i/n_b)^{3/2} \qquad \text{(A.4)}$$

(in which R_i=hydraulic ratios associated with the jam underside) and the obvious relationship

$$R_i + R_b \simeq 2R_o = y \qquad \text{(1.5)}$$

in which y=average flow depth under the jam. Where n_b varies with R_b, a trial-and-error calculation may be necessary; alternatively, a site-specific analytical expression relating n_b to R_b may be developed empirically to enable a direct solution.

The above calculation can also be carried out in terms of the corresponding friction factors, f_i, f_b and f_o which have the advantage of being dimensionless; however, in the present case, it was found that n_b was much less variable than f_b, hence use of the Manning coefficients was adopted.

After step (v), the following auxiliary parameters can be calculated:

(vi) A measure of the absolute roughness height of the jam underside, $d_{i,84}$, which is analogous to the particle diameter exceeding 84 percent of the particle sizes present on a river bed; the following equation is "borrowed" from Limerinos' (1970) study on gravel streams:

$$\sqrt{f_i} = 8.86\, n_i/R_i^{1/6} = \left[1.16 + 2 \log (R_i/d_{i,84})\right]^{-1} \qquad \text{(A.6)}$$

which may be used to calculate $d_{i,84}$ once n_i and R_i have been determined.

(vii) For an equilibrium jam considered a granular mass, a dimensionless coefficient μ that depends on the jam's internal friction, may be calculated from (Pariset et al 1966; Uzuner and Kennedy 1976; Beltaos 1978, 1979).

$$\mu = 11.5 \frac{W\, S_i}{h_j'} \left(\frac{R_i}{h_j'} + 1 \right) \qquad \text{(A.7)}$$

Equation A.7 reflects the balance between the forces applied on the jam and the jam's ability to resist these forces. The jam is assumed to have no cohesion. Pariset et al (1966) reported a value of 1.3 for μ; subsequent analysis of several case studies has indicated an average value of 1.2 for spring ice jams consisting of solid ice blocks (Beltaos 1980b).

A lower limit for h_j may be estimated using the non-submergence criterion of Pariset et al (1966) which governs in the case of "narrow" jams, i.e.

$$\sqrt{2g\,(1 - s_i)\, h_j} \geq V \qquad \text{(A.8)}$$

If μ is not very much larger than 1.2, it can be shown that ice jam thickness is governed by the internal friction criterion (Eq. A.7) for most natural streams, i.e. the value of h_j obtained from Eq. A.8 would be less than that obtained from Eq. A.7.

APPENDIX B. Derivation of Eq. 7

In Eq. 5 of the text, the shear stress τ_i may be expressed as:

$$\tau_i = \rho g R_i S \qquad (B.1)$$

in which ρ=density of water and R_i = hydraulic radius associated with the ice cover. Using the conventional two-layer analysis of hydraulic resistance of ice-covered flow, Eq. B.1 may be modified to (see, for example, Beltaos 1980b):

$$\tau_i = \frac{f_i}{2f_o} \rho g y S \qquad (B.2)$$

Substituting Eq. B.2 in Eq. 5 and re-arranging gives:

$$\mu s_i (1 - s_i) h_j^2 = WS \left(\frac{f_i}{2f_o} y + s_i h_j\right) \qquad (B.3)$$

which shows that the effects of channel width and slope on h_j are combined in the product WS. It is thus convenient to non-dimensionalize Eq. B.3 using this product as a length parameter. Dividing both sides of Eq. B.3 by $(WS)^2$ and solving for h_j/WS gives

$$h_j/WS = 2\mu (1 - s_i)^{-1} \left\{ 1 + \sqrt{1 + [2\mu (1 - s_i) f_i/s_i f_o] (y/WS)} \right\} \qquad (B.4)$$

To determine y and thence y/WS, one may use the composite resistance equation:

$$f_o = 8 \frac{g(y/2)\, S}{(q/y)^2} \qquad (B.5)$$

in which q=Q/W. Solving Eq. B.5 for y and dividing by WS gives:

$$y/WS = 0.63\, f_o^{1/3} \left\{ \frac{(q^2/gS)^{1/3}}{WS} \right\} \qquad (B.6)$$

Denoting the bracketted term on the RHS of Eq. B.6 by ξ and substituting Eqs. B.4 and B.6 in Eq. 6 of the text gives, after some algebra:

$$h_T/WS = 0.63\, f_o^{1/3}\, \xi + \frac{S_i}{2\mu\,(1-S_i)} \left\{ 1 + \sqrt{1 + \frac{1.26\,\mu\,(1-S_i)}{S_i}\, f_o^{1/3} \left(\frac{f_i}{f_o}\right) \xi} \right\} \tag{B.7}$$

which, with S_i=0.92, reduces to Eq. 7 of the text. Had the theory not been available, a qualitative understanding of the problem along with dimensional analysis, would have shown that

$$h_T/W = f\left[(q^2/g)^{1/3}/W,\ S,\ f_o,\ f_i/f_o,\ \mu,\ S_i\right] \tag{B.8}$$

It may be noticed that Eq. B.7 is a specific version of Eq. B.8. Moreover, the theory greatly facilitates the task of evaluating the function f that appears in Eq. B.8 by providing a specific functional form which shows how the variables involved are to be combined.

Tables

TABLE 1 AVERAGE RIVER SLOPES BETWEEN CONTOUR INTERSECTIONS

Contour Elevation (m)	Distance of Intersection With River Banks (km from river mouth)	Average River Slope to Next Downstream Contour (m/km)
195.072	155.90	0.115
192.024	129.32	0.167
188.976	111.03	0.218
185.928	97.03	0.208
182.880	82.40	0.095
179.832	50.23	0.236
176.784	37.32	N.A.

TABLE 2 MINIMUM, MAXIMUM AND AVERAGE FLOWS (m^3/s) DURING 1970-79*

Gauge / Year	Thames R. at Byron Drain.Area=3100 km^2 Location: 202.68 km Upstream of Mouth			Thames R. near Dutton Drain.Area=3760 km^2 Location: 128.22 km Upstream of Mouth			Thames R. at Thamesville Drain.Area=4300 km^2 Location: 65.55 km Upstream of Mouth		
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
1970	5.2 Sep 13	29.2 -	317 Apr 9	Insufficient Data			5.3 Aug 25	35.7 -	289 Apr 5
1971	2.9 May 21	28.0 -	388 Apr 3	Insufficient Data			4.9 Jul 6	36.8 -	328 Apr 4
1972	2.6 Oct 6	37.1 -	408 Mar 23	4.9 Oct 8	44.7 -	368 Apr 18	5.6 Oct 9	49.6 -	351 Apr 19
1973	4.7 Sep 9	42.5 -	521 Mar 12	5.4 Sep 11	51.8 -	453 Mar 14	6.3 Sep 13	57.5 -	498 Mar 15
1974	5.9 Sep 27	40.8 -	566 Mar 5	6.4 Sep 7	49.8 -	513 Mar 7	8.2 Aug 21	57.5 -	515 Mar 8
1975	6.2 Jul 6	40.8 -	564 Apr 20	7.8 Jul 10	48.1 -	467 Apr 21	9.2 Aug 20	55.8 -	453 Apr 22
1976	8.3 Jun 13	50.7 -	663 Mar 6	10.6 Sep 8	61.2 -	524 Mar 8	10.2 Sep 8	68.8 -	592 Mar 8
1977	5.2 Jun 15	46.7 -	915 Mar 14	8.0 Jun 16	59.5 -	895 Mar 15	7.5 Jun 17	69.7 -	946 Mar 16
1978	5.2 Aug 27	40.8 -	583 Apr 2	6.4 Sept 3	46.4 -	501 Apr 9	7.2 Sep 9	53.5 -	530 Apr 9
1979	5.6 Jul 22	49.7 -	695 Apr 14	5.1 Jul 27	57.6 -	580 Mar 6	5.5 Jul 27	67.2 -	678 Apr 17
Average	5.2	40.6	562	6.8	52.4	538	7.0	55.2	518

* Data from Water Survey of Canada annual publications "Surface Water Data - Ontario"; discharge values quoted are daily averages.

TABLE 3 ICE THICKNESS DATA

Date (1980)	Location (Thames R.)	Average Ice Thickness (m)
Feb. 6	Thamesville (Highway 21)	0.12
Feb. 7	Kent Bridge	0.15
Feb. 5	Near Mouth of Jeannettes Ck. (MNR Dock)	0.23
Feb. 5	Mouth	0.23

TABLE 4 RESULTS OF ANALYSIS; JANUARY 1980 JAM NEAR THAMESVILLE

Assumed Criterion	h_j' (m)	h_j (m)	Value of n_i on:			Coefficient μ
			Jan. 12	Jan. 14	Jan. 15	
"Narrow" jam stability; lower limit of thickness	0.60	0.65	0.047	0.027	0.024	2.35
"Wide" jam stability; μ=1.2	0.78	0.85	0.040	0.021	0.016	1.20
Nezhikhovskiy's n_i - thickness relationship	0.84	0.91	0.038	0.019	0.013	1.00
Upper limit of thickness; n_i = 0.01	0.90	0.98	0.035	0.017	0.010	0.85

TABLE 5 SELECTED ICE JAM CHARACTERISTICS; THAMES RIVER, 1980

Location	Time (1980)	Q (m^3/s)	S m/km	h_T (m)	W (m)	$\eta = h_T/WS$	$\xi = \frac{(q^2/gS)^{1/3}}{WS}$	Probable Condition
Middlemiss	Jan. 14	100	0.052	4.8	45	584	1766	Equilibrium
Bothwell W.	Jan. 14	165	0.263	4.4	56	296	1002	Equilibrium
Thamesville	Jan. 12	108	0.767	3.9	41	125	308	Equilibrium
Fairfield Museum	Mar. 18	130	0.808	4.2	44	118	290	Evolving
Sherman Brown Bridge	Mar. 19	196	0.260	4.7	74	244	728	Equilibrium
River Mouth	Mar. 20	195	0.130	4.6	105	337	1020	Equilibrium

TABLE 6 MAJOR ICE JAMS DURING SPRING BREAKUP OF 1980

Location		Approx. Time of Formation	Approx. Time of Release	Approx. Flow Discharge	Probable Causes
Toe	Head				
Unknown	By Fairfield Museum, 75.9 km above mouth	Before 1100 h, Mar. 18	1210 h, Mar. 18	130 m^3/s, shortly before release	Unknown
Kent Bridge, 50 km above mouth	≃51.5 km above mouth, est'd from speed and time of run at bridge	1640 h, Mar. 18	1730 h, Mar. 18	150 m^3/s at 1700 h, Mar. 18	River bend and bridge piers
Unknown; est'd between 38 and 44 km above mouth, i.e. near Louisville	Unknown; est'd between 45 and 51 km above mouth	Unknown; night of Mar. 18 to 19 most likely	Unknown; est'd between 0800 and 1000 h, Mar. 19	180 m^3/s at 0800 h, Mar. 19	Unknown
Sherman Brown Bridge, 33.8 km above mouth	≃40.5 km above mouth	1115 h, Mar. 19	1430 h, Mar. 19	196 m^3/s at 1300 h, Mar. 19	River bend and bridge piers
Past river mouth in Lake St. Clair	1.4 km above mouth	Unknown; night of Mar. 19 to 20 most likely	1100 h, Mar. 20	195 m^3/s at 1020 h, Mar. 20	Lake ice and slow flow

Figures

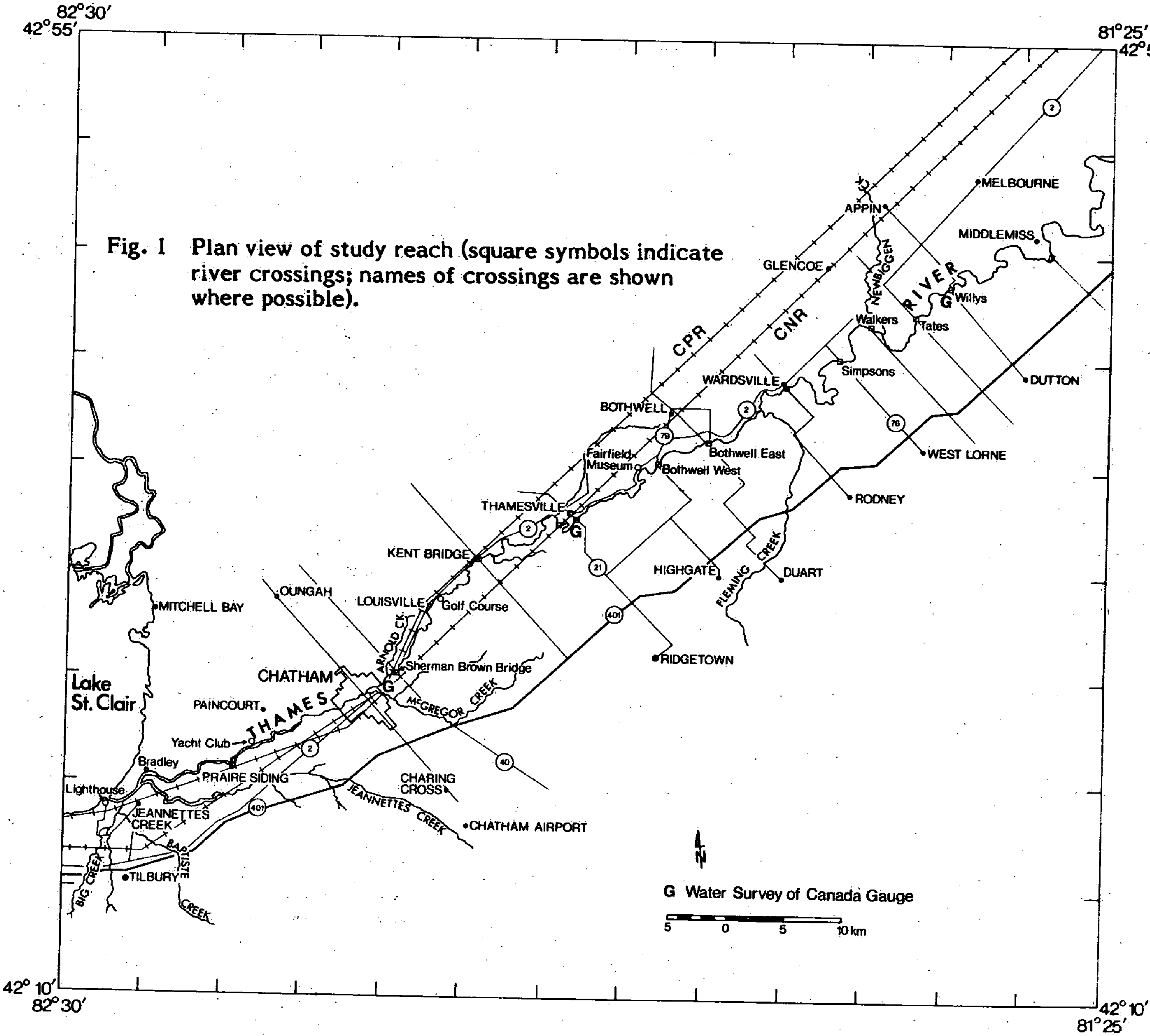


Fig. 1 Plan view of study reach (square symbols indicate river crossings; names of crossings are shown where possible).

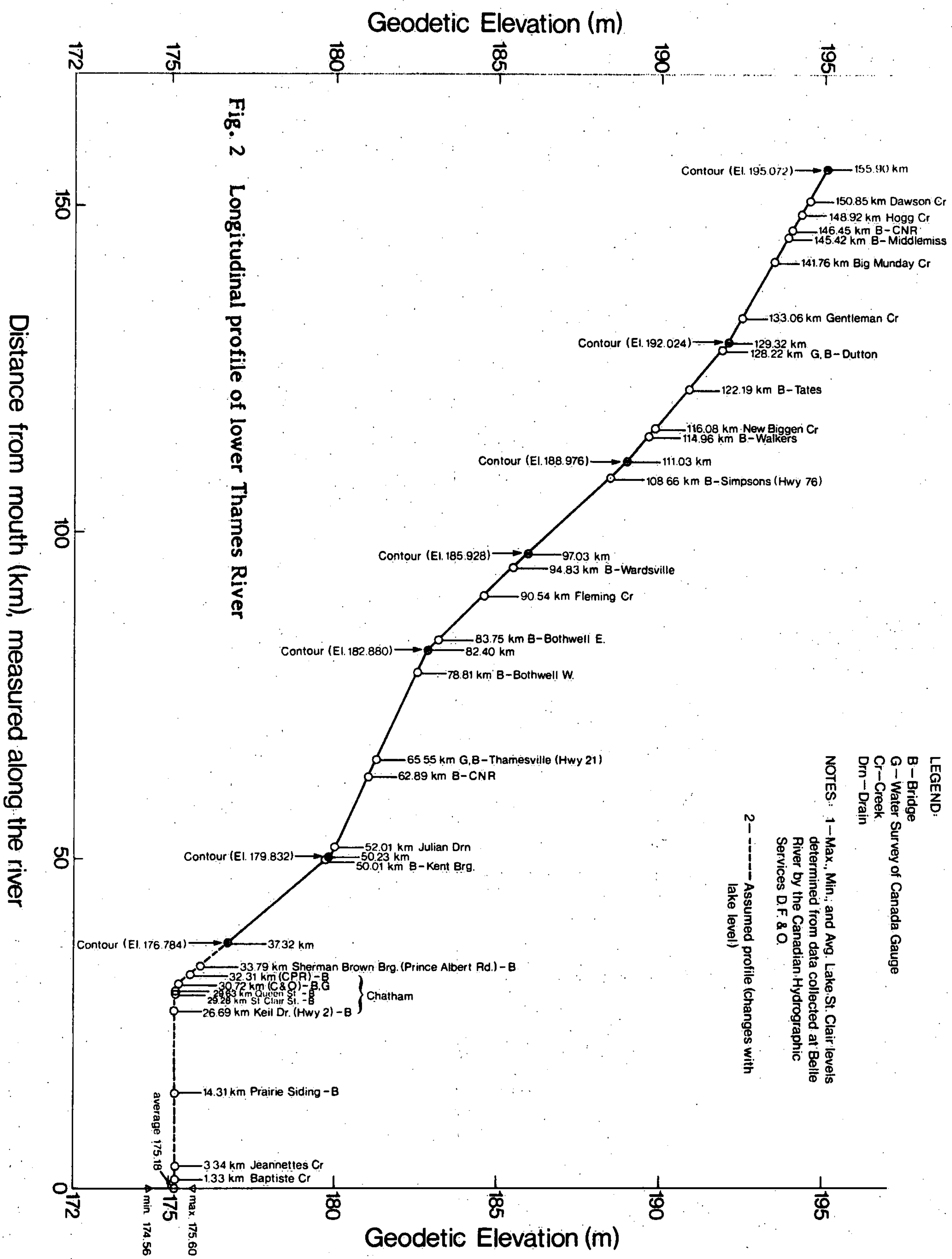


Fig. 2 Longitudinal profile of lower Thames River

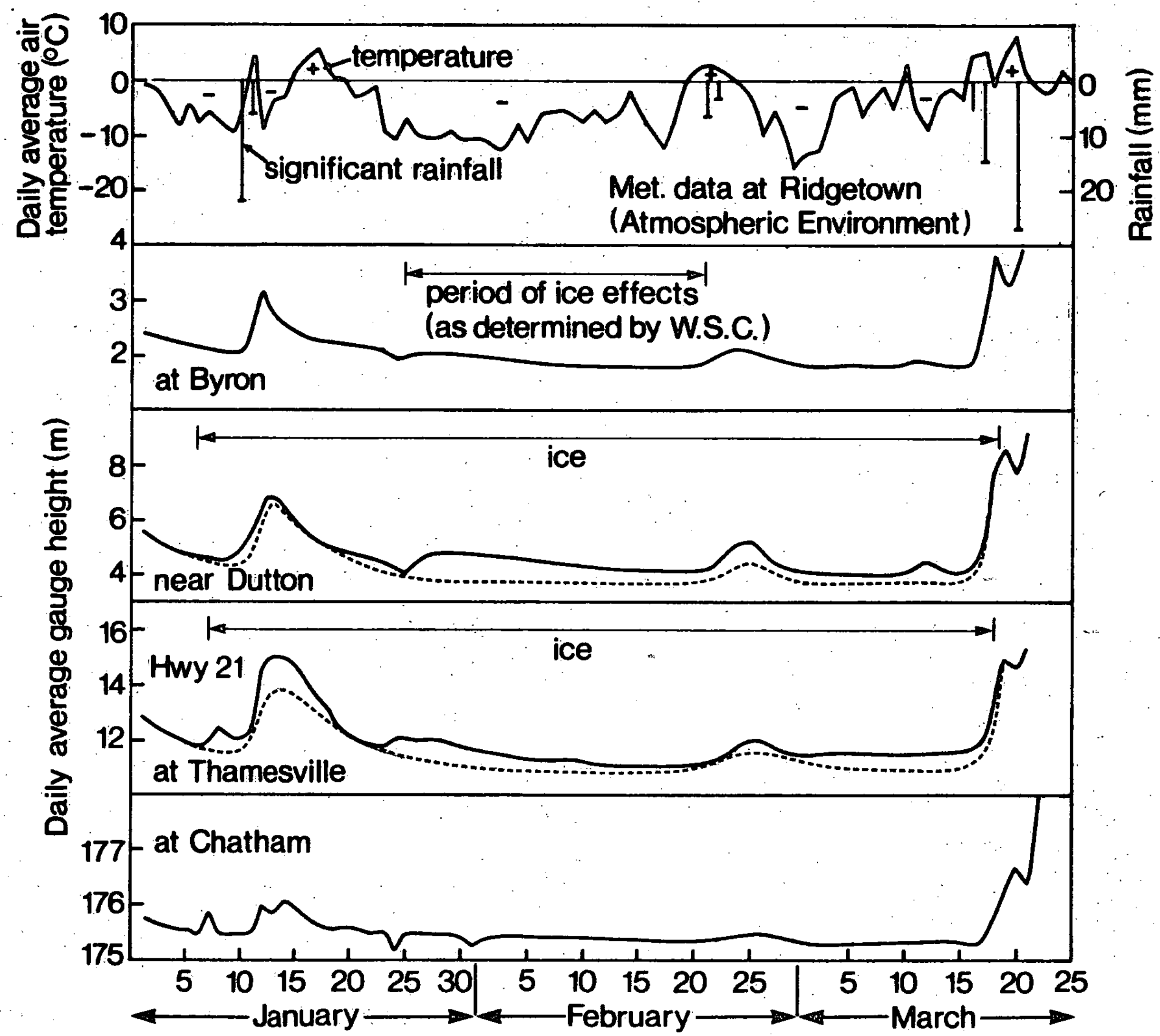
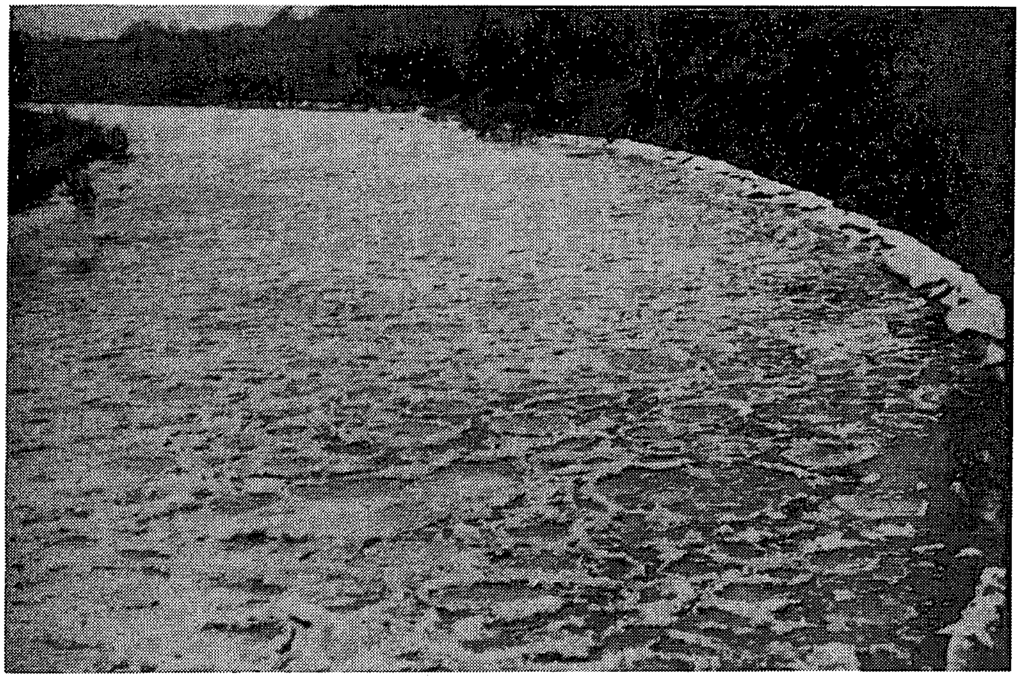


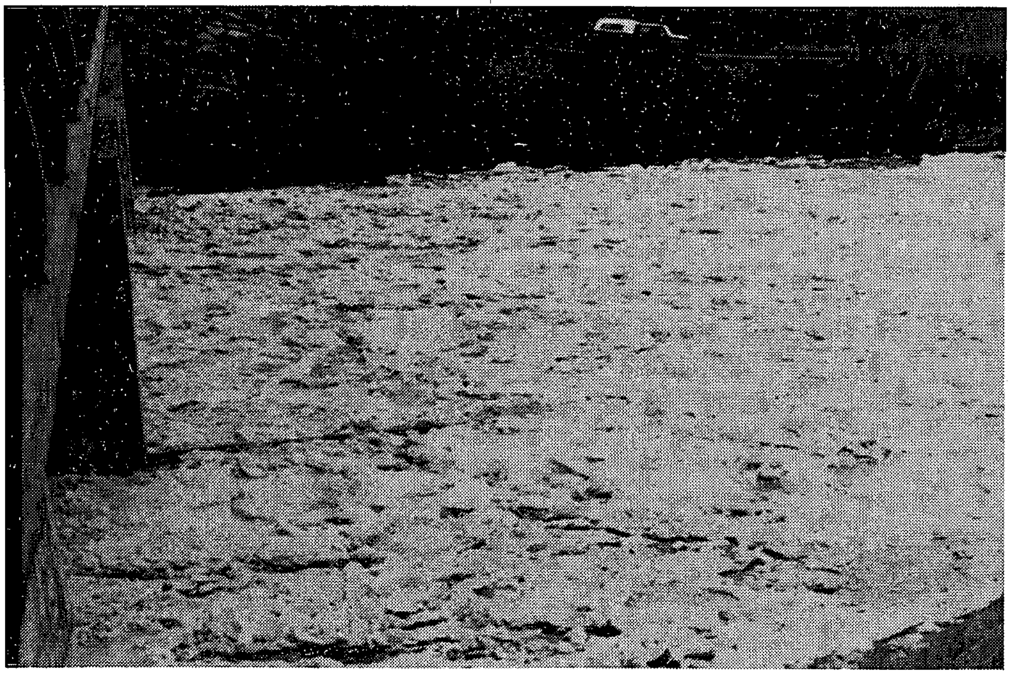
Fig. 3 Daily meteorological data and water levels in lower Thames R.; 1979-80 ice season



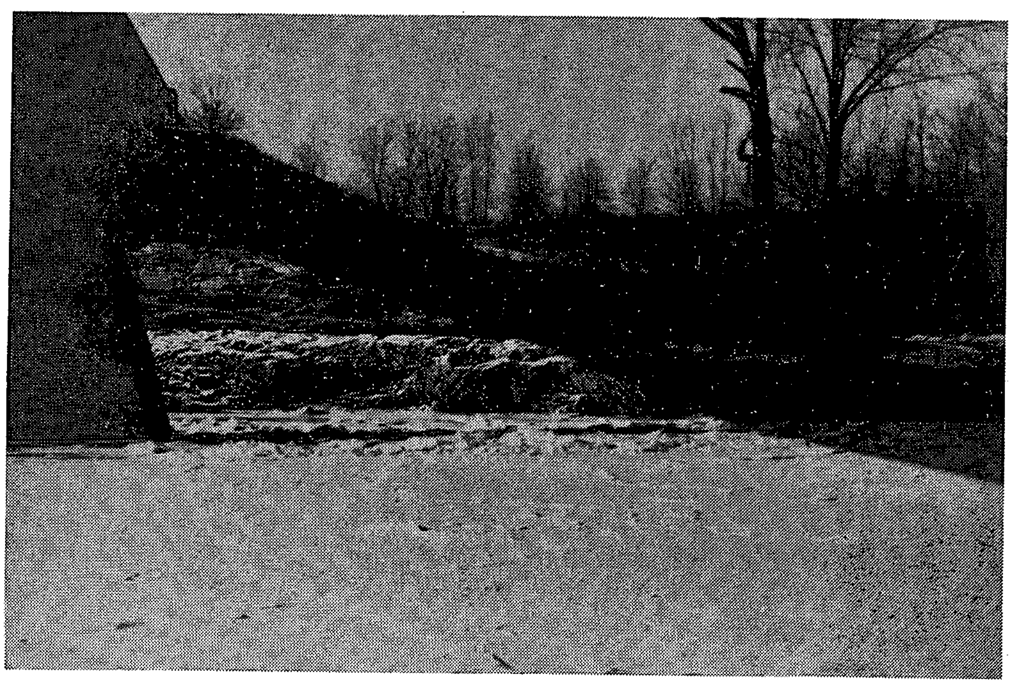
(a) Looking upstream from crossing near Middlemiss; 1040h, 14 Jan. 1980; note jammed pancake ice

(b) Looking towards left bank at crossing near Middlemiss; 1230h, 29 Jan. 1980; note remnants of ice jam near the pier and new ice cover.

Fig. 4 Photographs of slush ice jams observed during Jan. 14 and 15, 1980; left-right convention is for an observer facing downstream.



(c) Looking towards left bank at Bothwell W. crossing; 1230h, 14 Jan. 1980; note jammed ice.



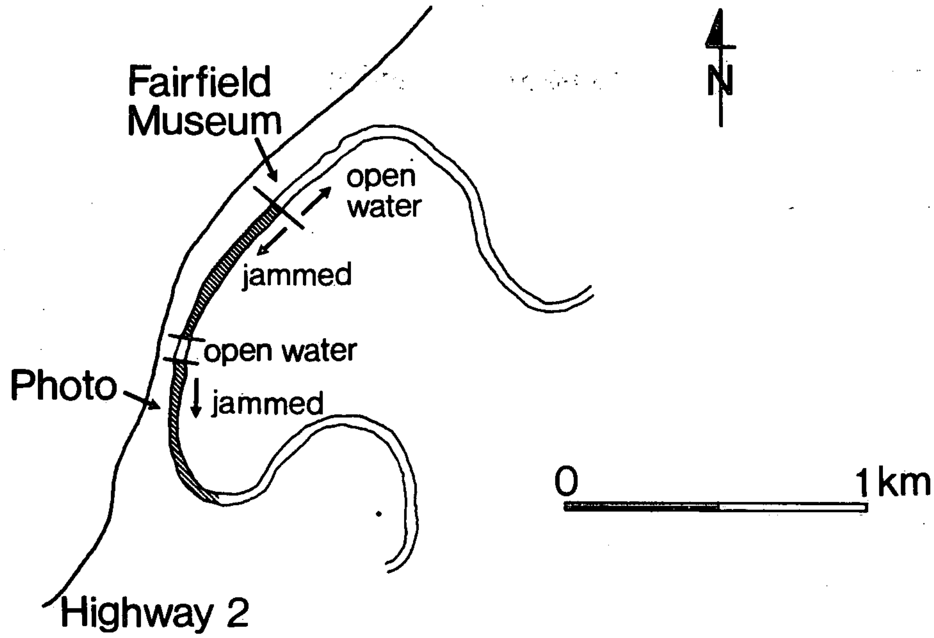
(d) Looking towards right bank at Bothwell W. crossing; 1500h, 29 Jan. 1980; note remnants of jam on river bank and new ice cover.

Fig. 4 continued

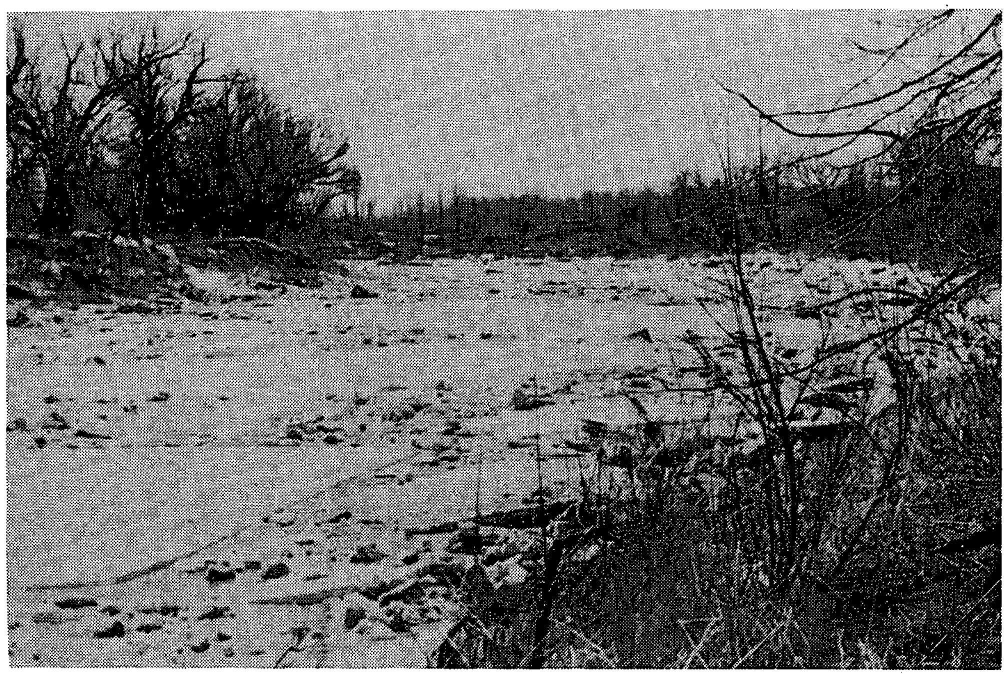
(e) Looking towards right bank about 2 km upstream of Hwy 21 crossing; 1320h, 14 Jan. 1980; note head of ice jam.

(f) Looking towards right bank about 1-2 km upstream of the Hwy 21 crossing; 1310h, 14 Jan. 1980; note toe of jam.

Fig. 4 concluded



(a) River plan at about 1130h, 18 Mar. 1980.



(b) Photograph taken at 1110h, 18 Mar. 1980; see (a) for location.

Fig. 5 Plan view of Thames River near Fairfield Museum and ice conditions on March 18, 1980.

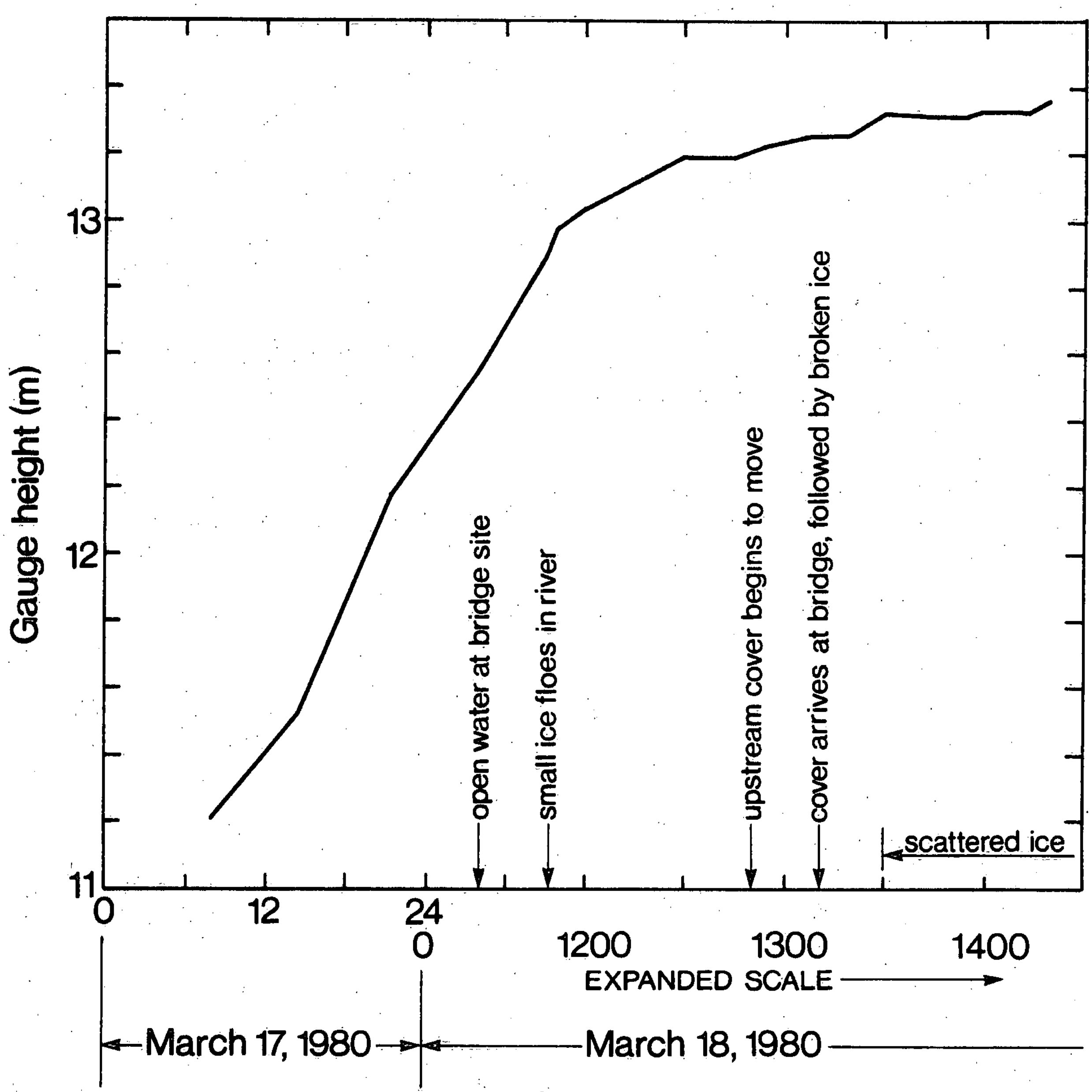


Fig. 6 Water level variation with time at the Highway 21 bridge (Thamesville gauge)

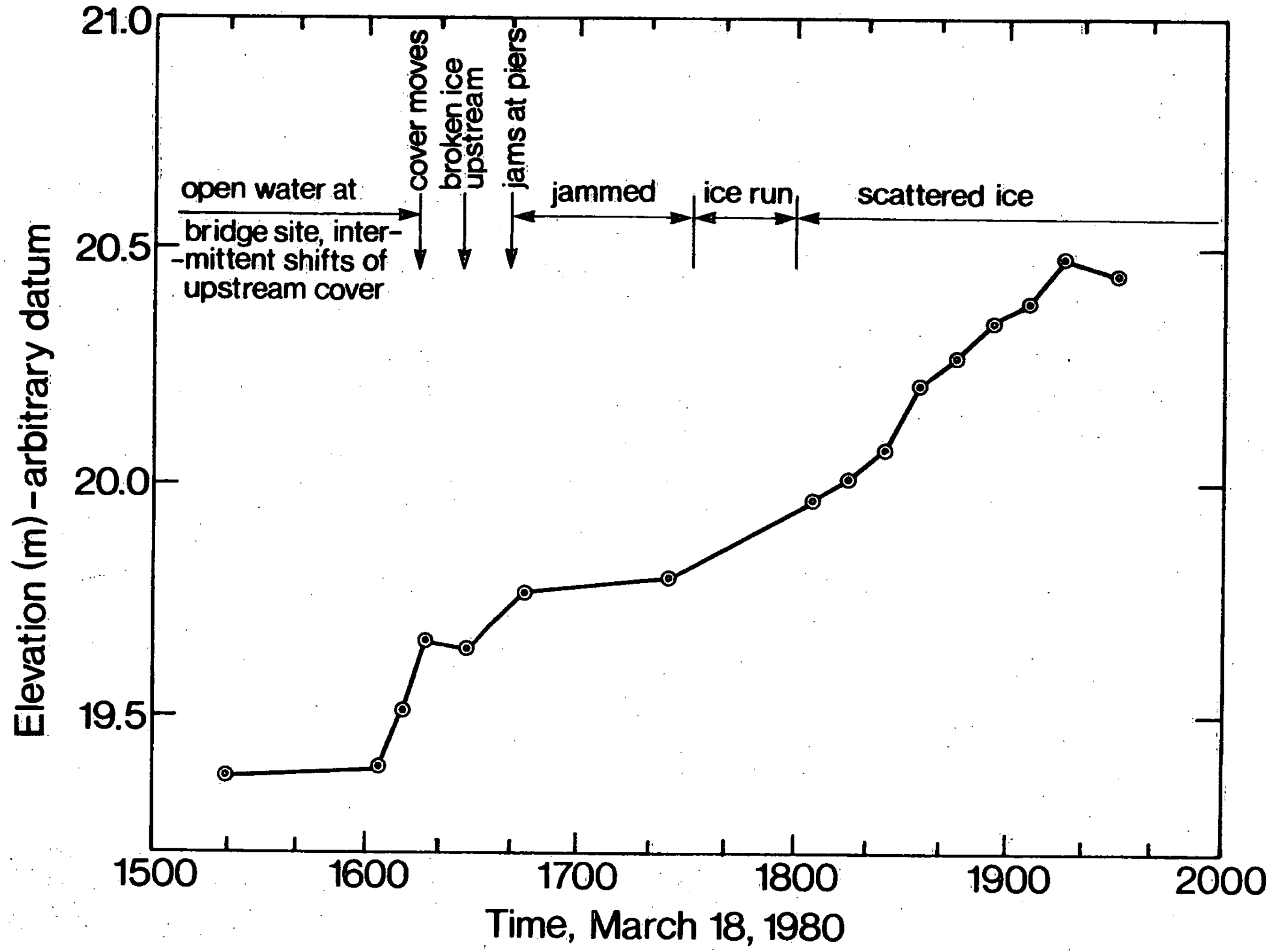


Fig. 7 Water level variation with time at Kent Bridge, Mar. 18, 1980
(Manual readings using tape and weight; some error caused by moving ice).

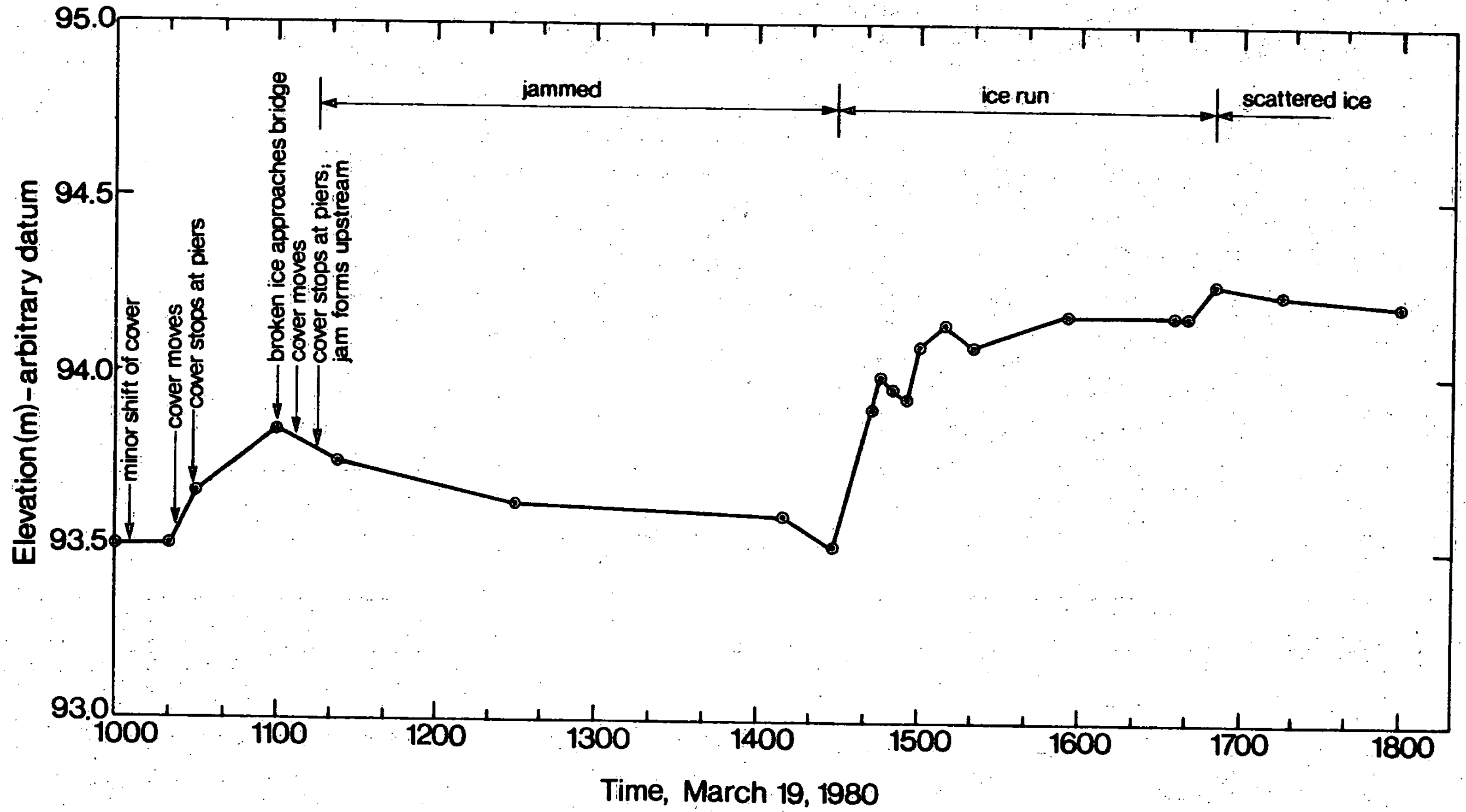


Fig. 8 Water level variation with time at Sherman Brown Bridge, Mar. 19, 1980 (Manual readings using tape and weight; some error caused by moving ice).

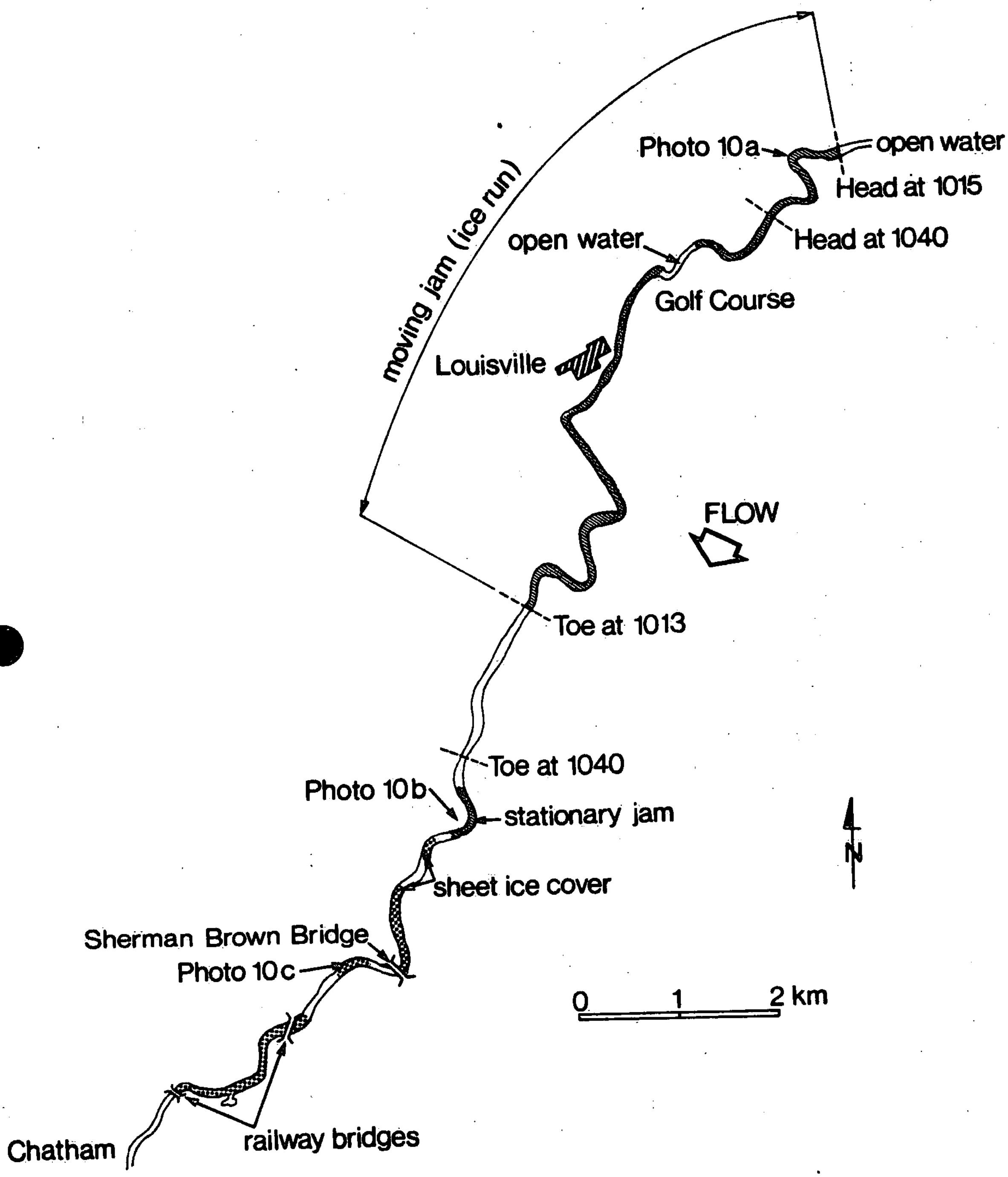
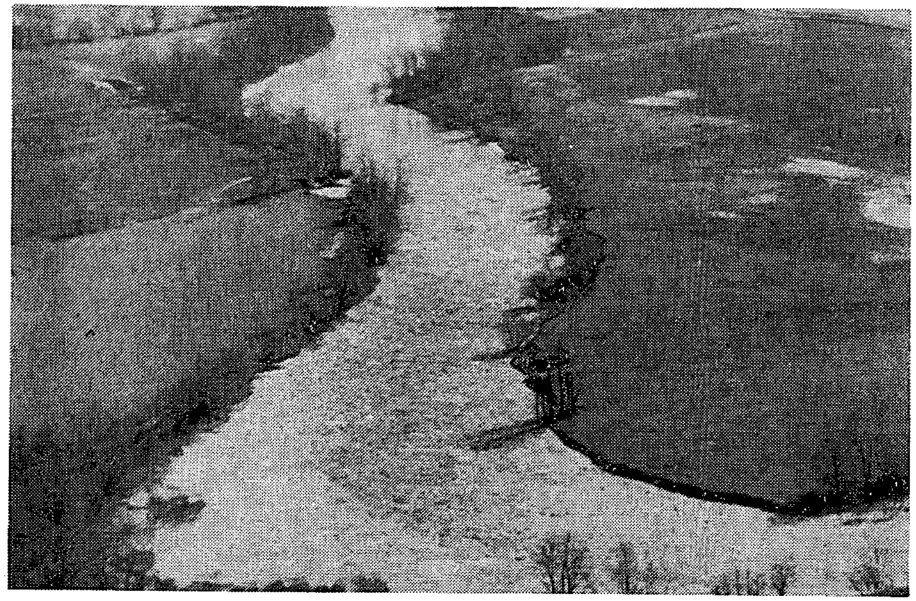
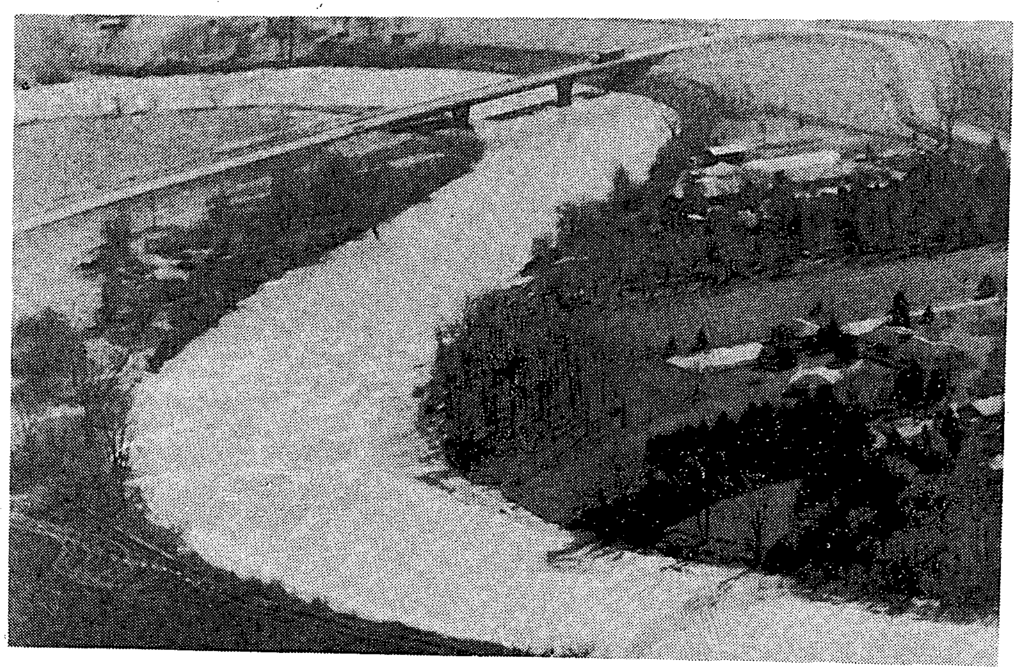


Fig. 9 Ice conditions above Chatham, morning of Mar. 19, 1980



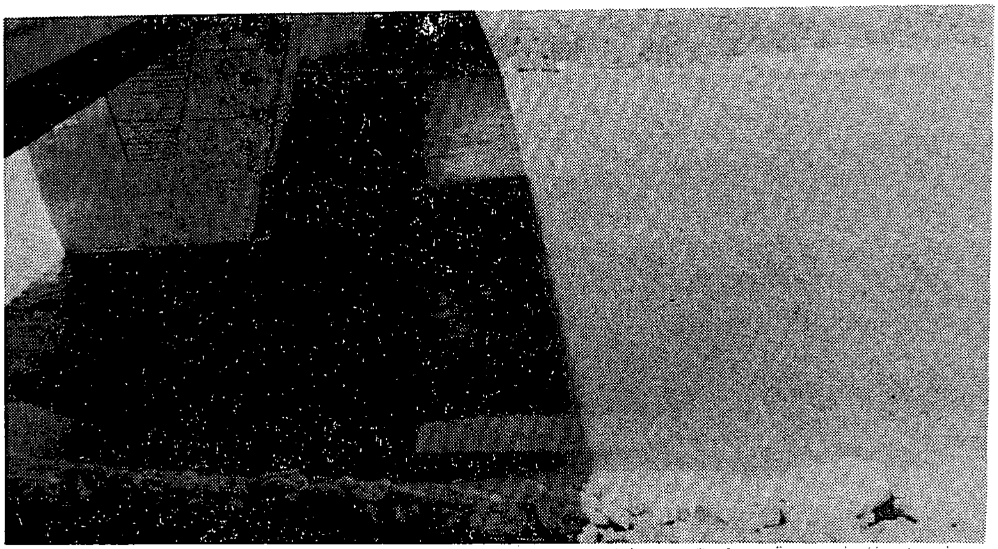
(a) Looking upstream; ice run at 1015h

(b) Looking downstream; minor jam at 1010h



(c) Looking upstream at 1010h; note Sherman Brown bridge at upper end of photo.

Fig. 10 Photographs taken in the morning of Mar. 19 1980 upstream of Chatham; see Fig. 9 for locations.



(a) 1210h; note large ice sheet wedged between bridge pier and left bank.

(b) 1432h, 2 min. after release of jam.

(c) 1440h, 10 min. after release of jam. Note increase in stage against the piers.

Fig. 11 Looking toward right bank before and after release of ice jam of Mar. 19, 1980 (Sherman Brown bridge).

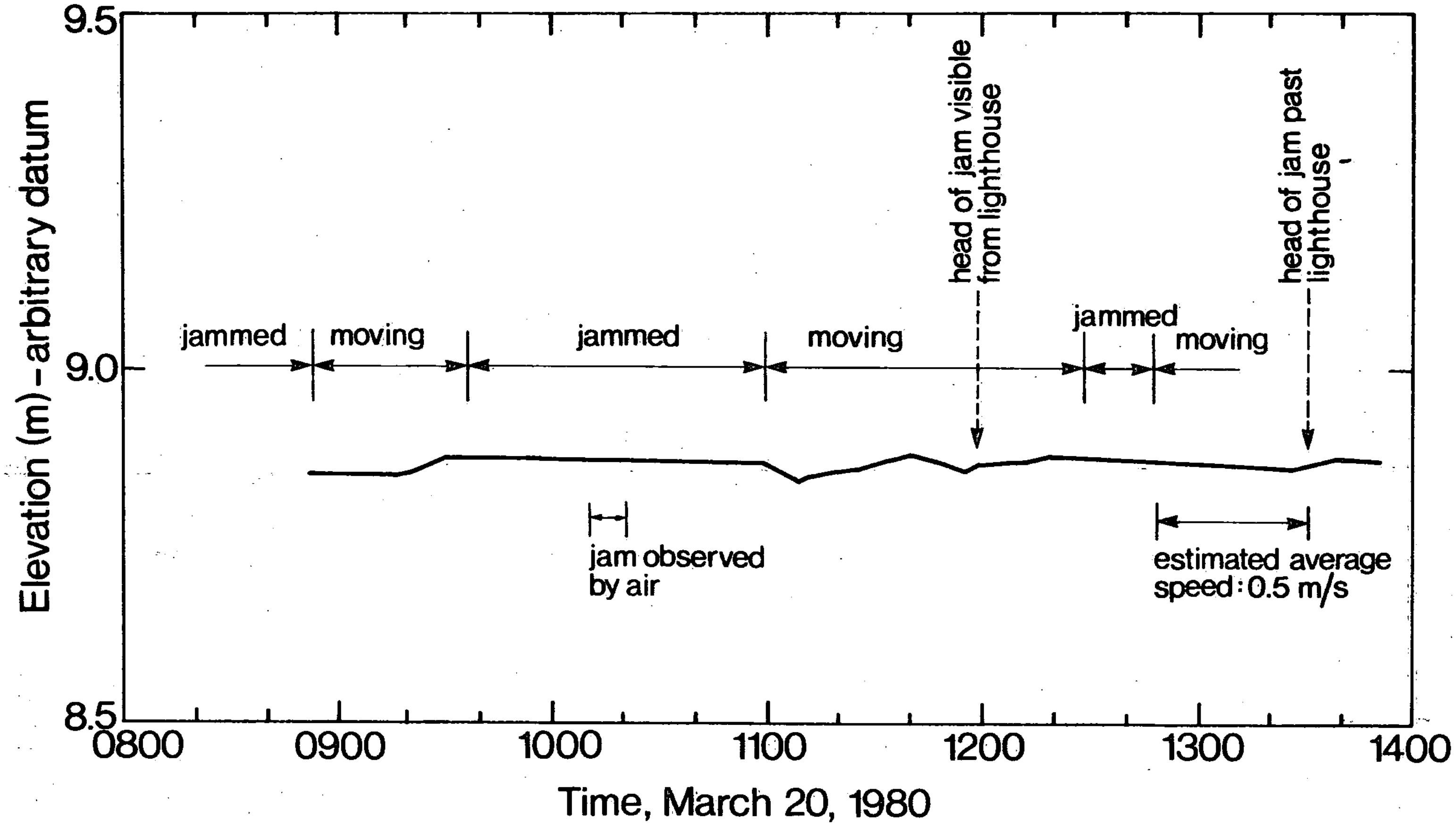


Fig. 12 Water level variation with time near the river mouth, Mar. 20, 1980 (Manual readings using tape and weight).

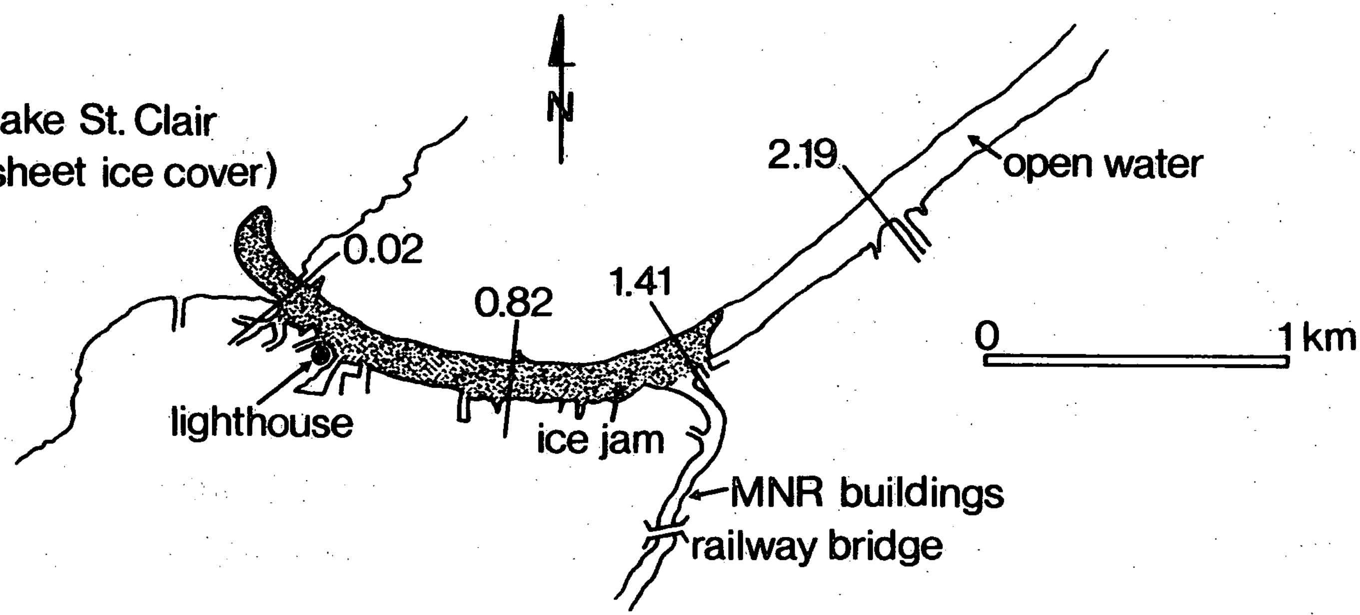
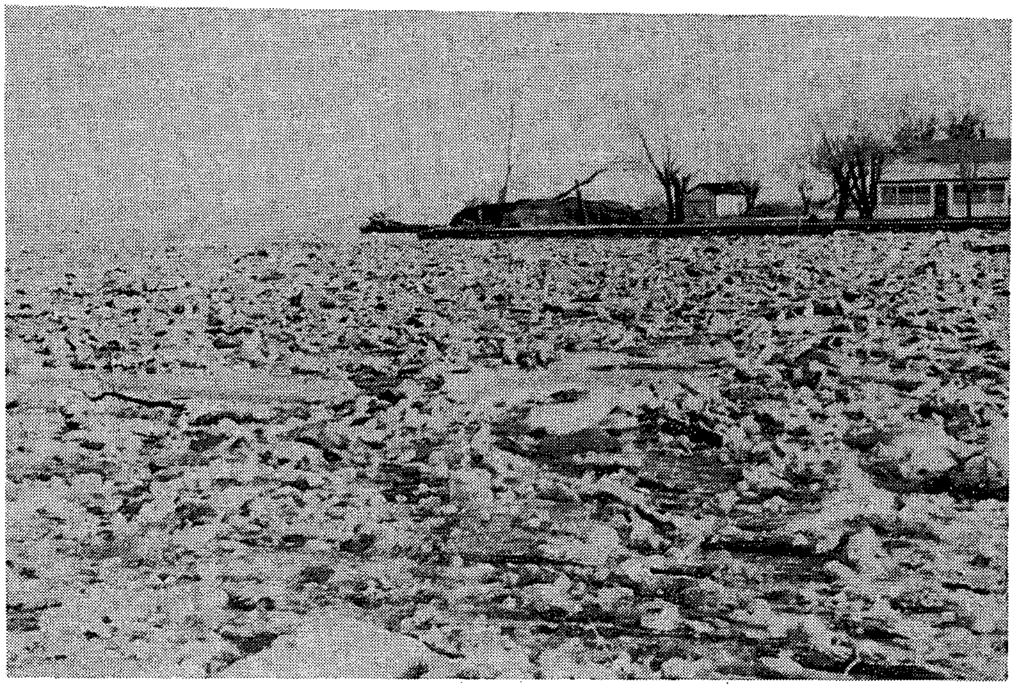
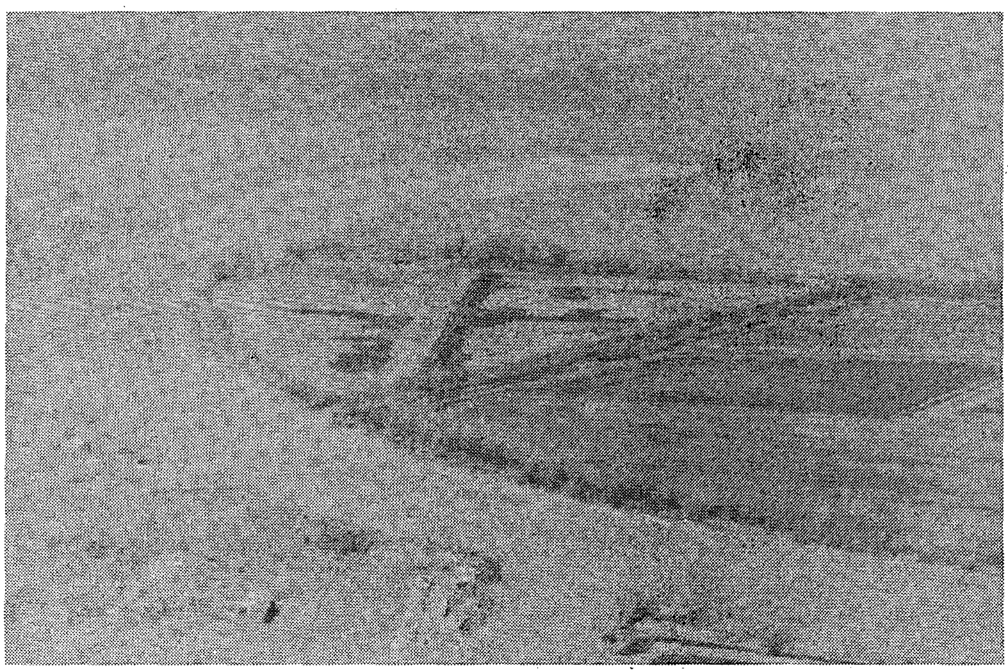


Fig. 13 Ice conditions near the river mouth, morning of Mar. 20, 1980

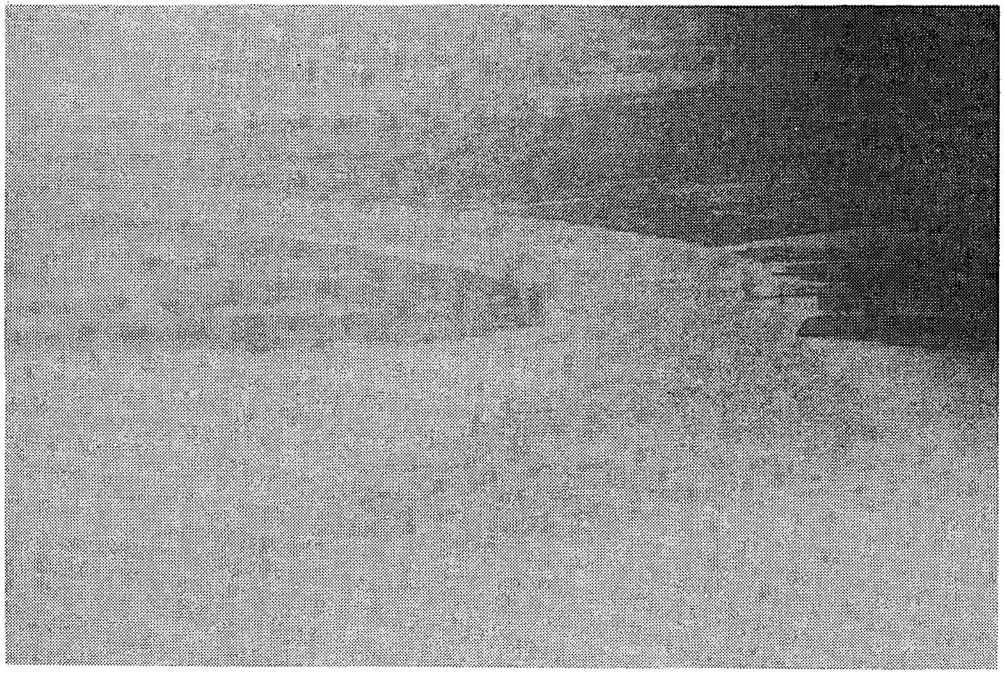


(a) Surface texture of ice jam; looking toward right bank at river mouth; 0750h.

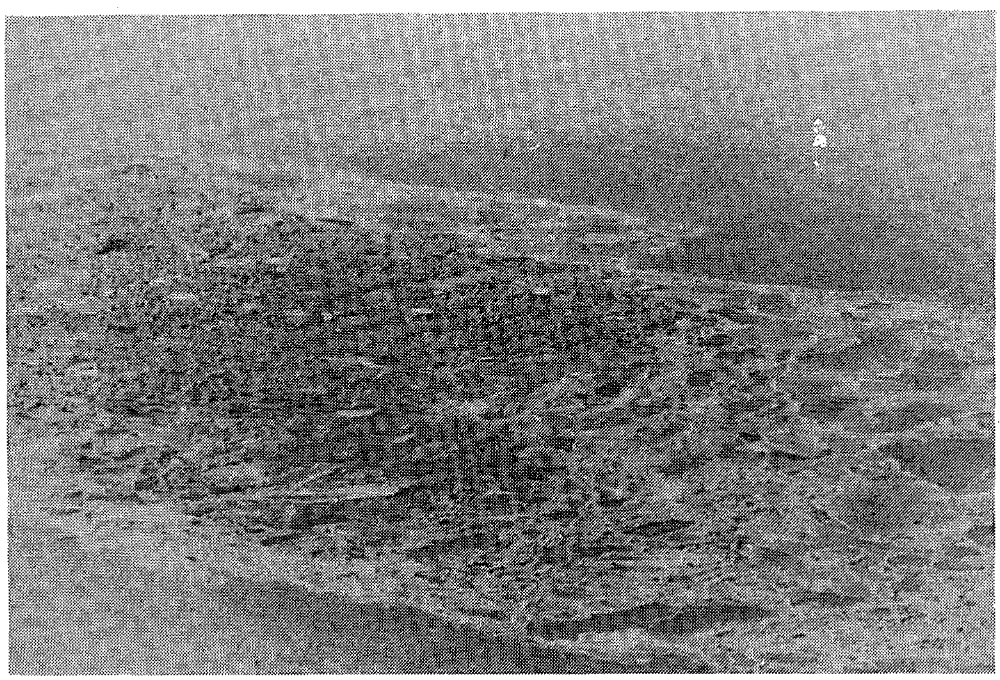


(b) Oblique view of jam at 1010h

Fig. 14 Photographs of ice jam near river mouth; morning of Mar. 20, 1980

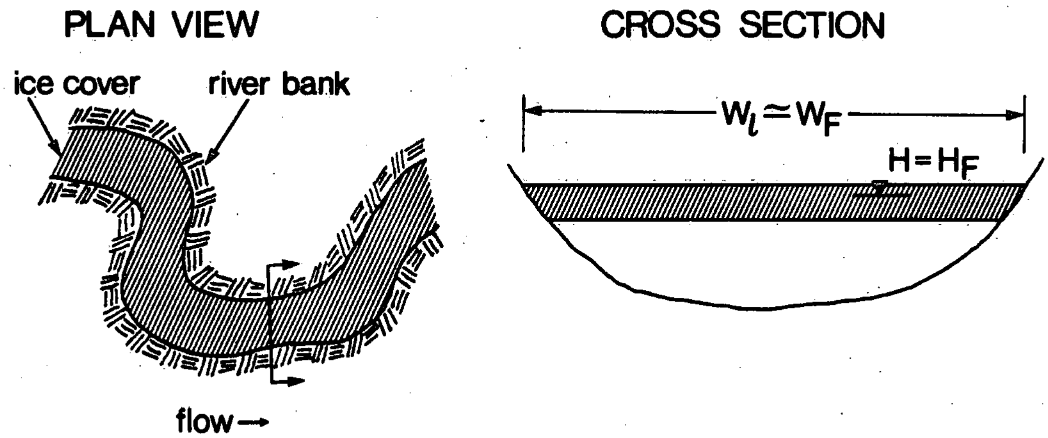


(c) Looking upstream at 1010h; note undisturbed lake ice and advance of jam in Lake St. Clair.

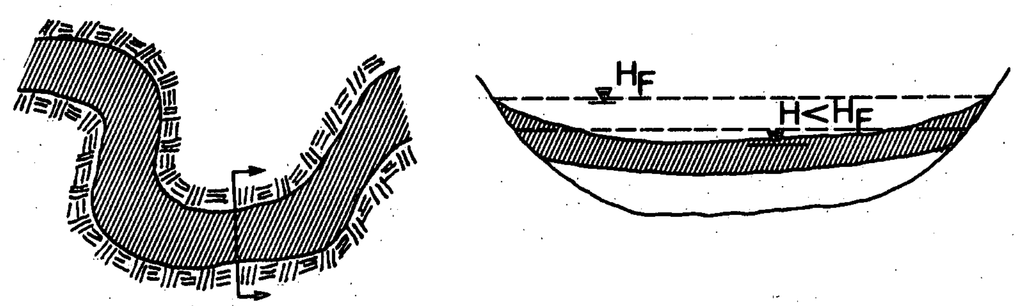


(d) Closer view of toe at 1010h; flow is from left to right.

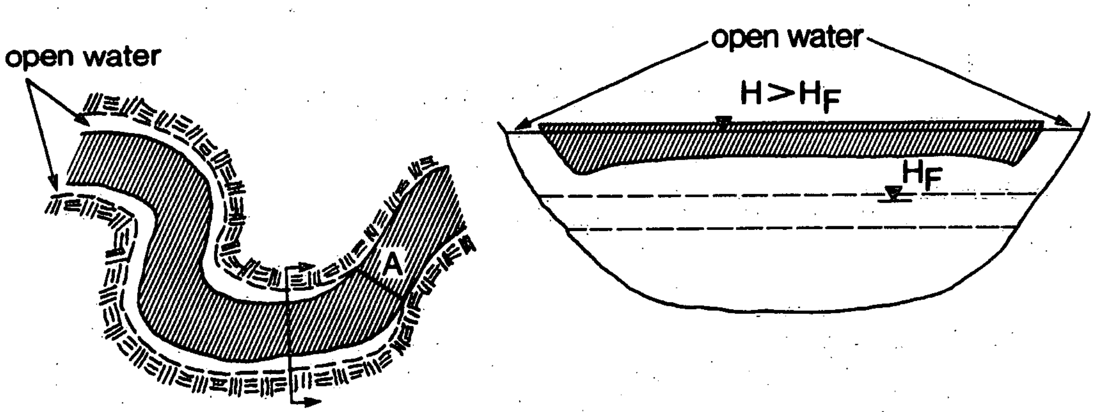
Fig. 14 Concluded



(a) Early winter, maximum stable freeze up stage



(b) Late winter, low stage



(c) Pre-breakup condition, advancing flood and increasing stage

Fig. 15. Schematic illustration of ice conditions during winter season

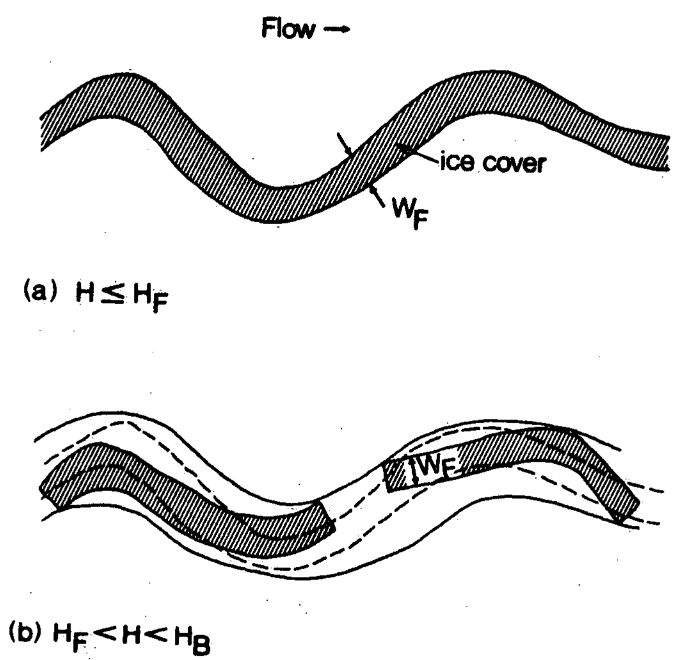


Fig. 16 Schematic illustration of pre-breakup ice conditions

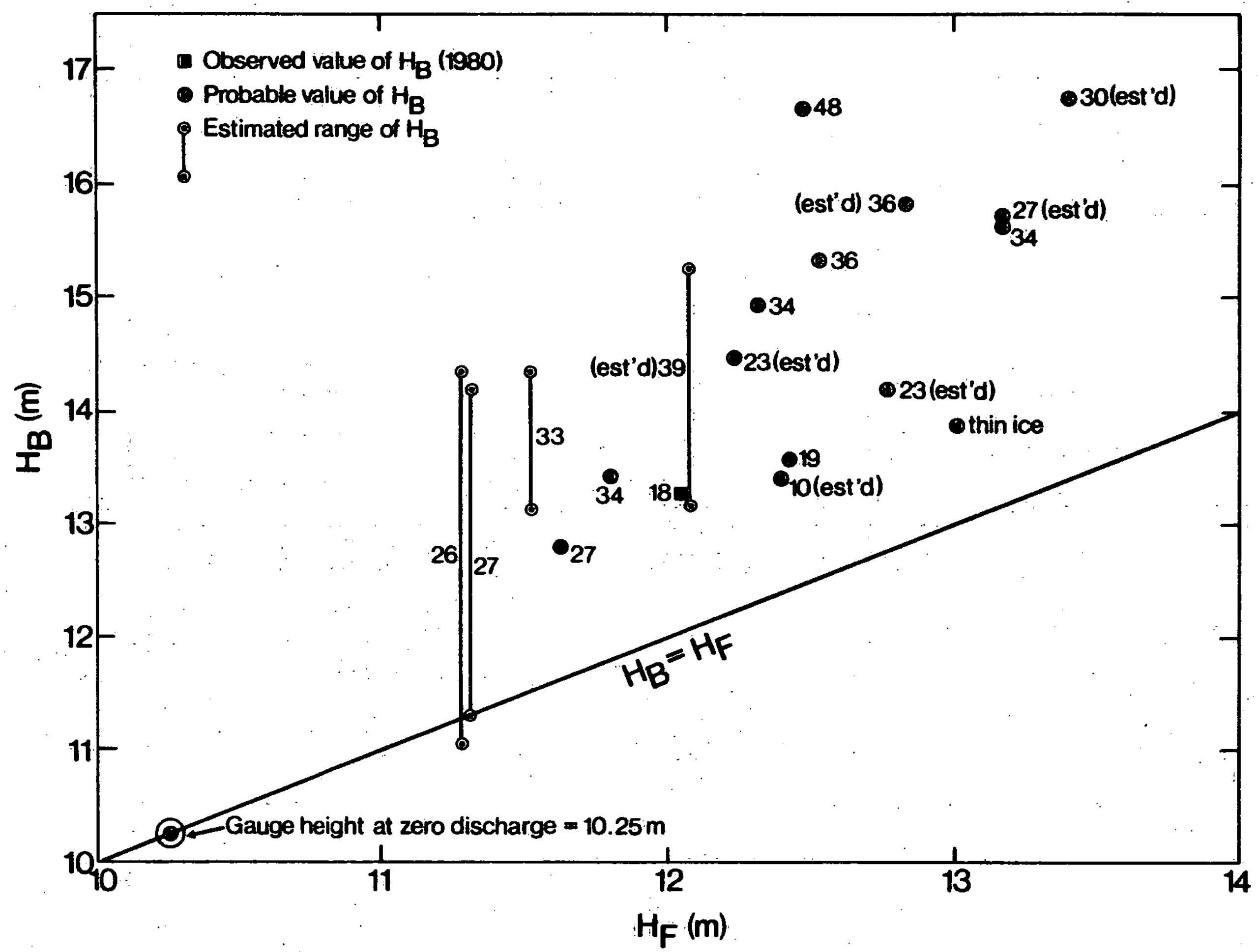


Fig. 17 Historical data on breakup initiation; Thames R. at Thamesville (Gauge records provided by Water Survey of Canada).

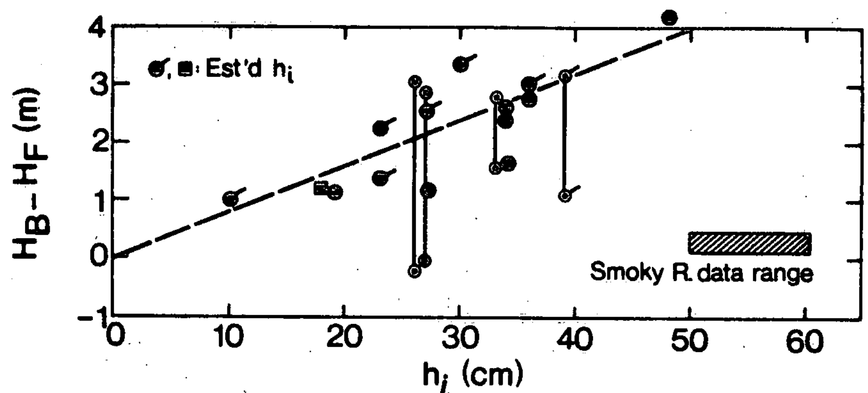


Fig. 18 Stage rise above H_F needed to initiate breakup; legend same as for Fig. 17

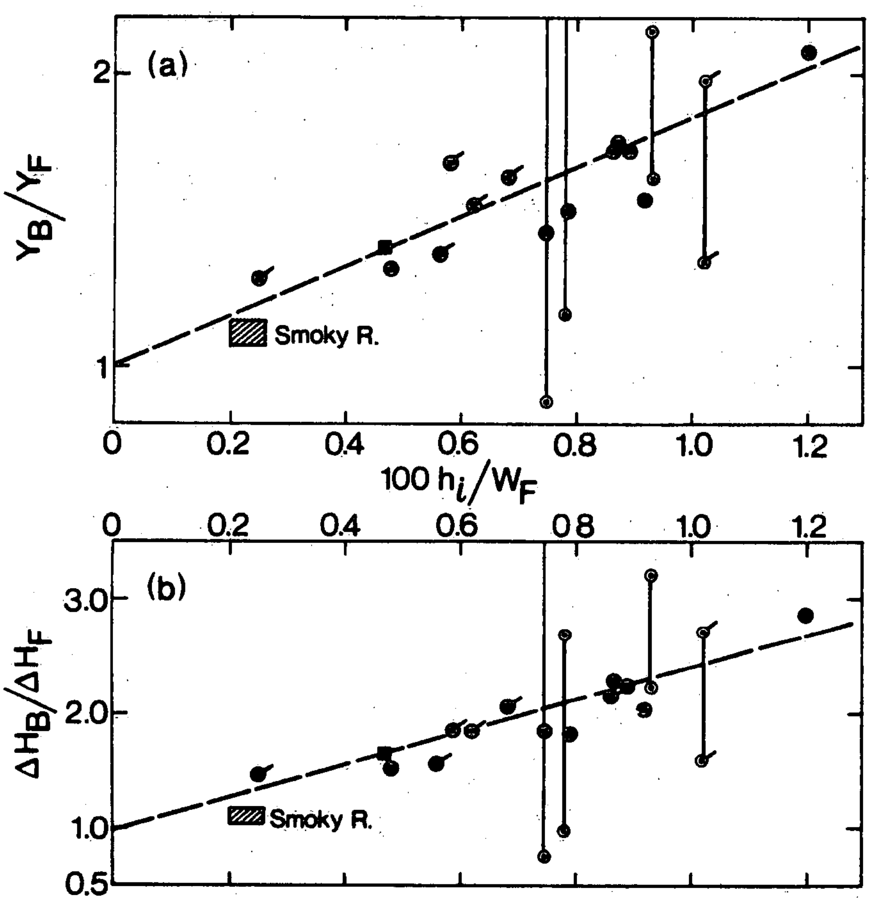


Fig. 19 Dimensionless breakup depth and net stage versus h_i/W_F; legend same as for Fig. 17

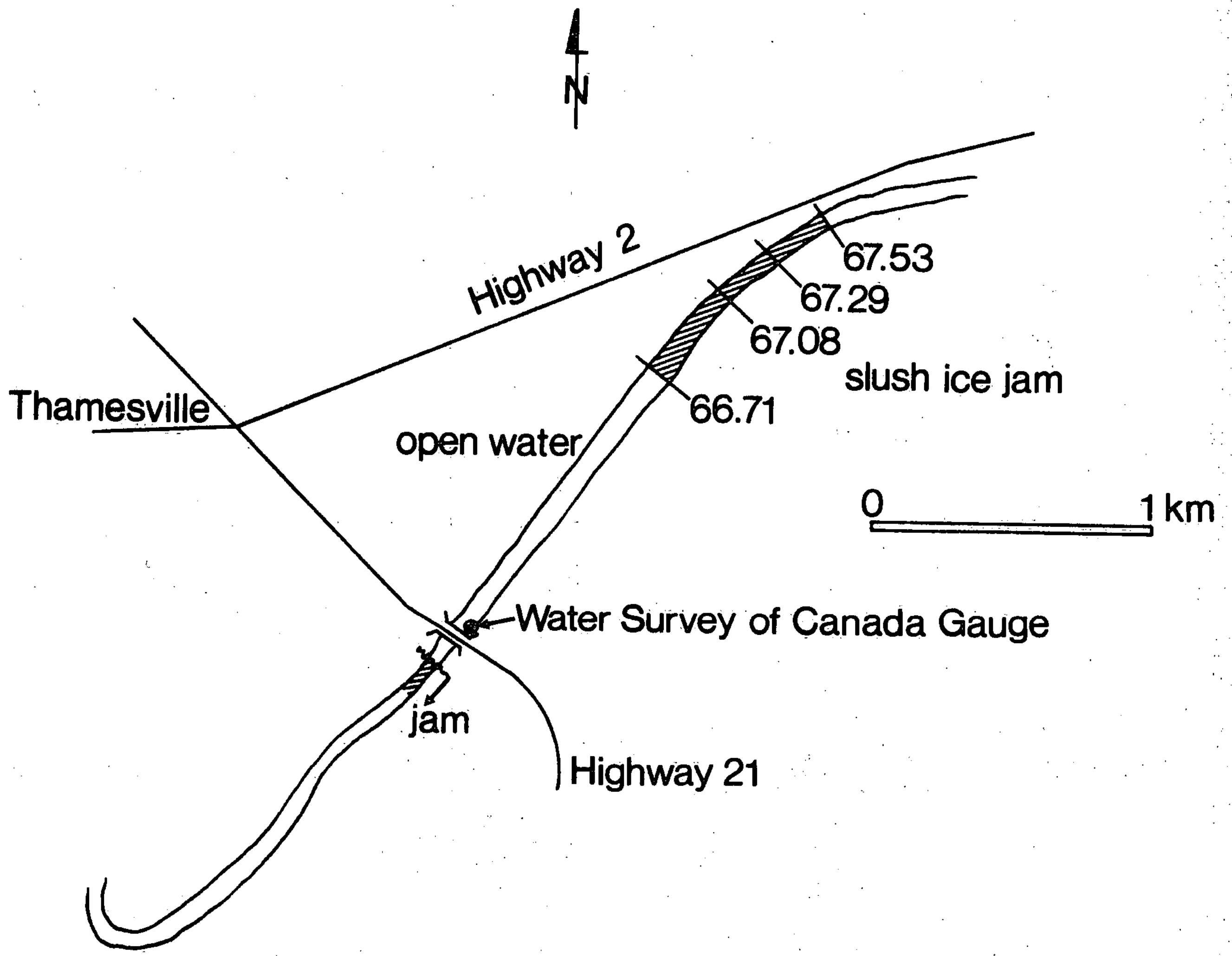


Fig. 20a Plan view of Thames R. near Thamesville and ice conditions on Jan. 15, 1980

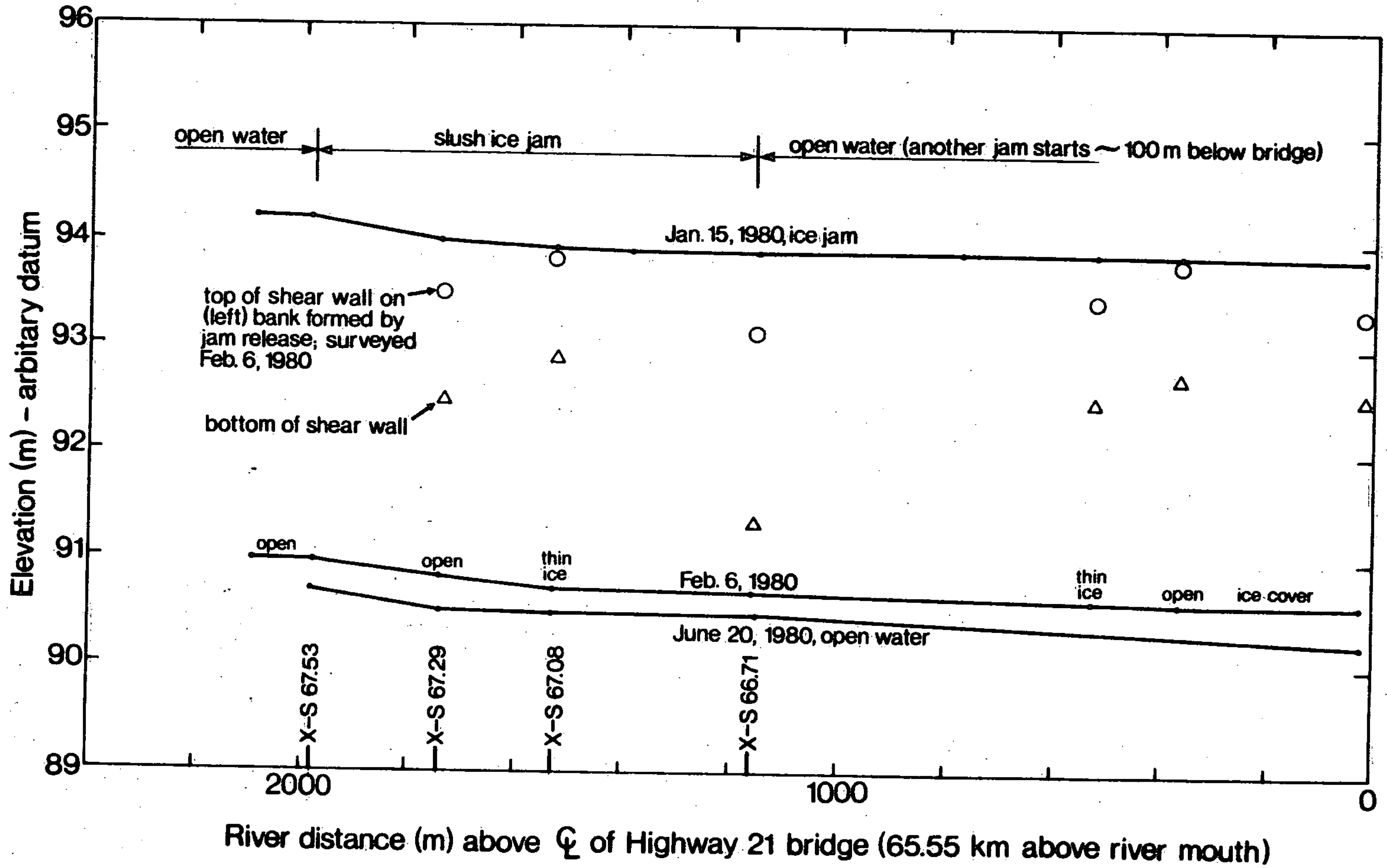


Fig. 20b Water level profiles near Thamesville during different flow conditions

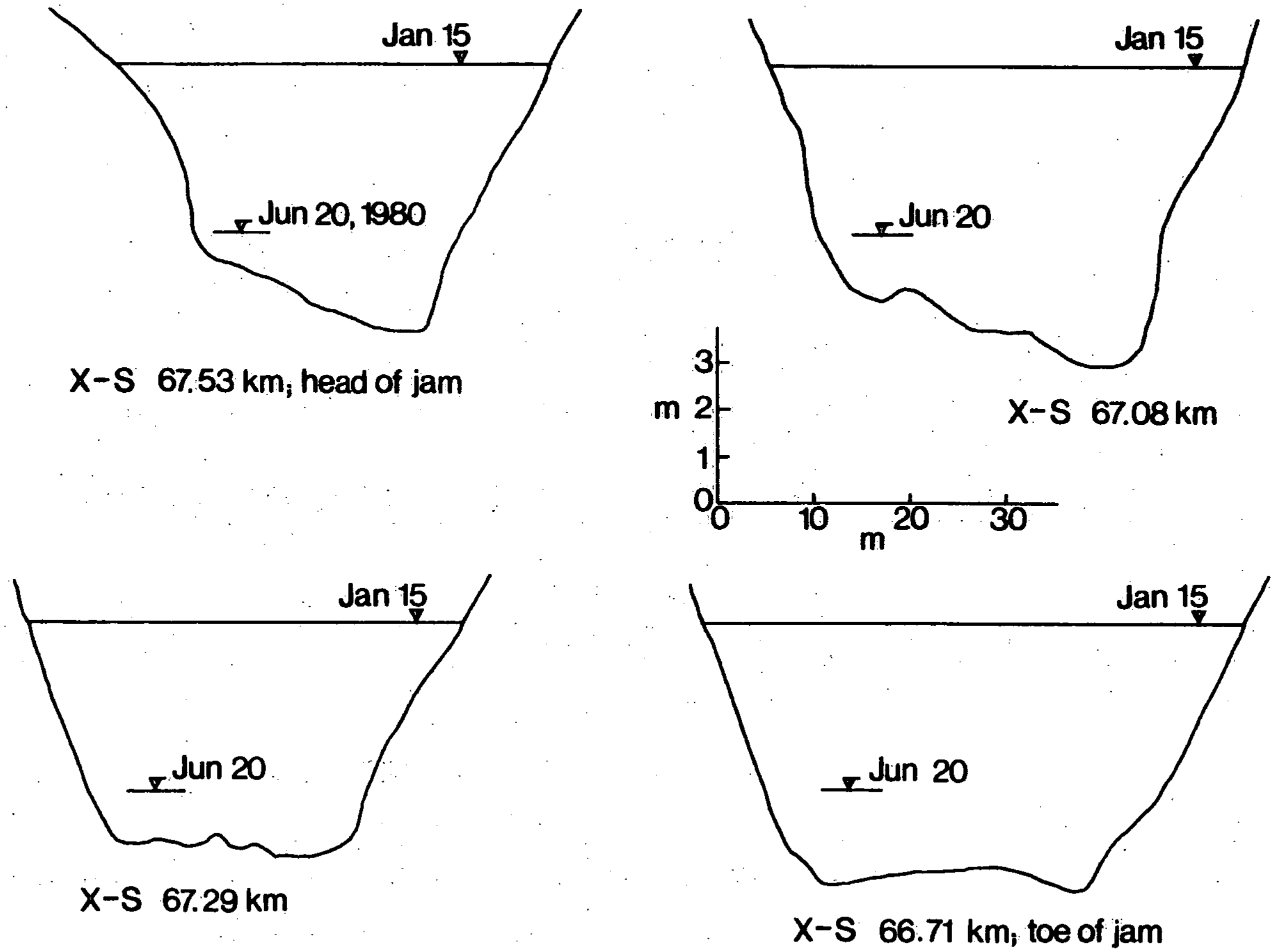


Fig. 20c River cross sections along jammed reach of Jan. 15, 1980 near Thamesville

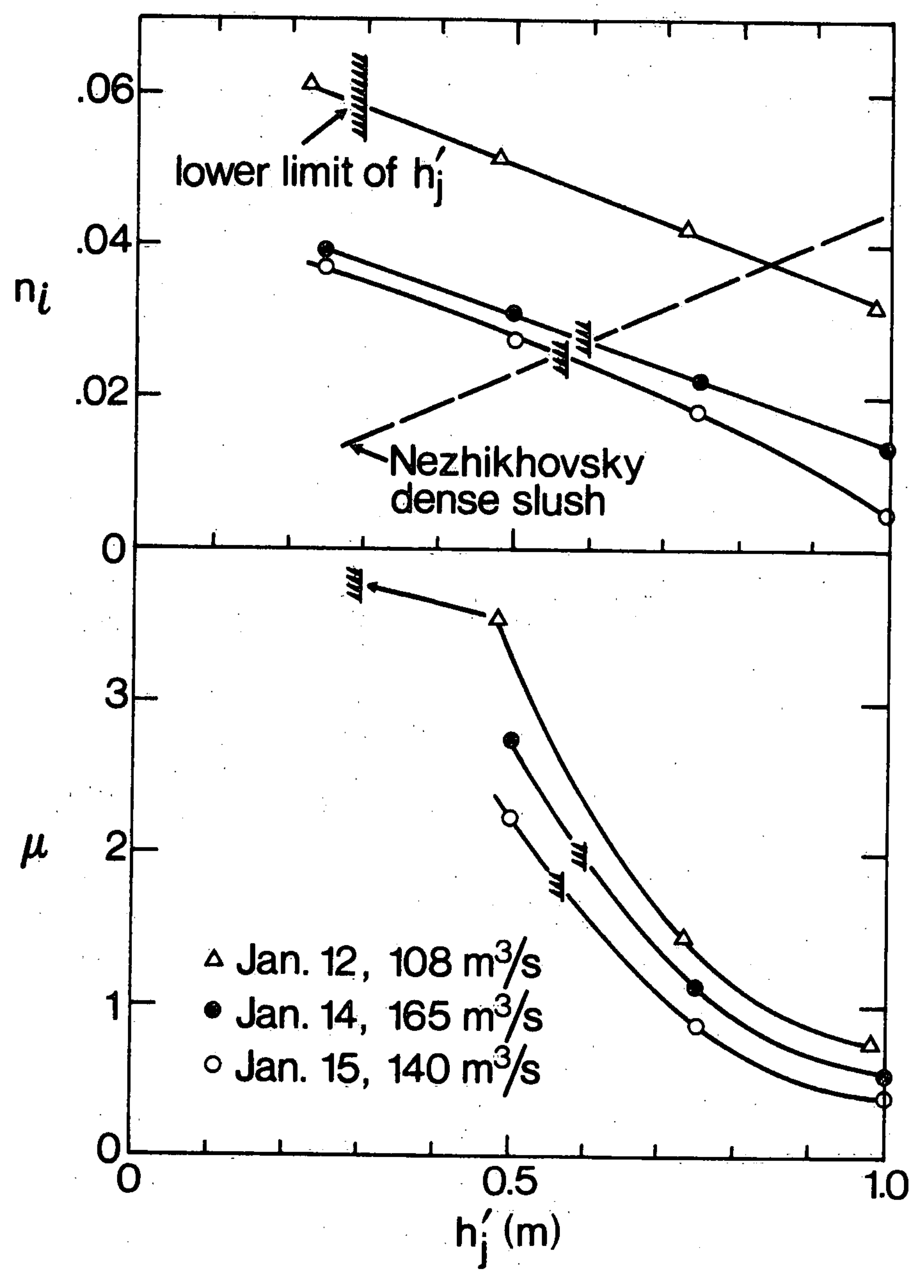


Fig. 20d Calculated values of n_i and μ versus assumed values of submerged ice jam thickness (note $h'_j=0.92\,h_j$). Jan. 1980 jam near Thamesville.

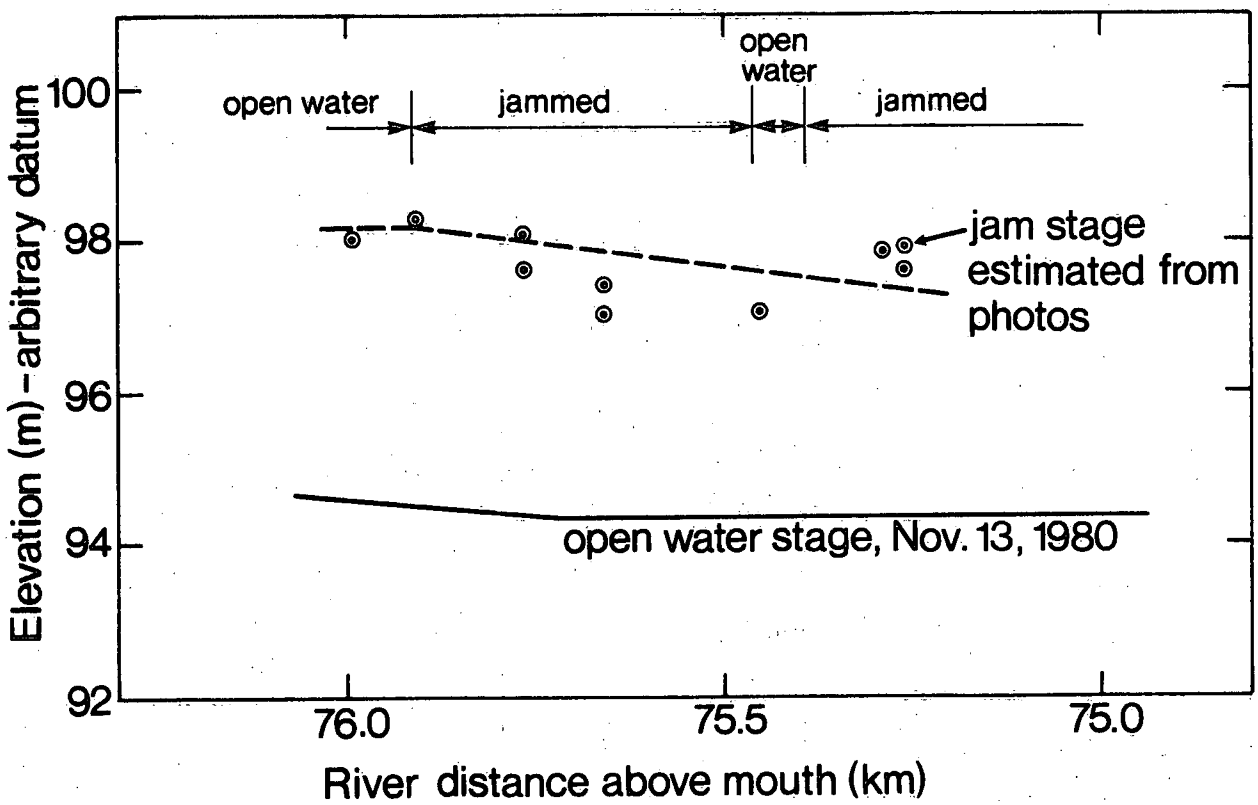


Fig. 21 Water level profiles along jammed reach of March 18, 1980 near Fairfield Museum

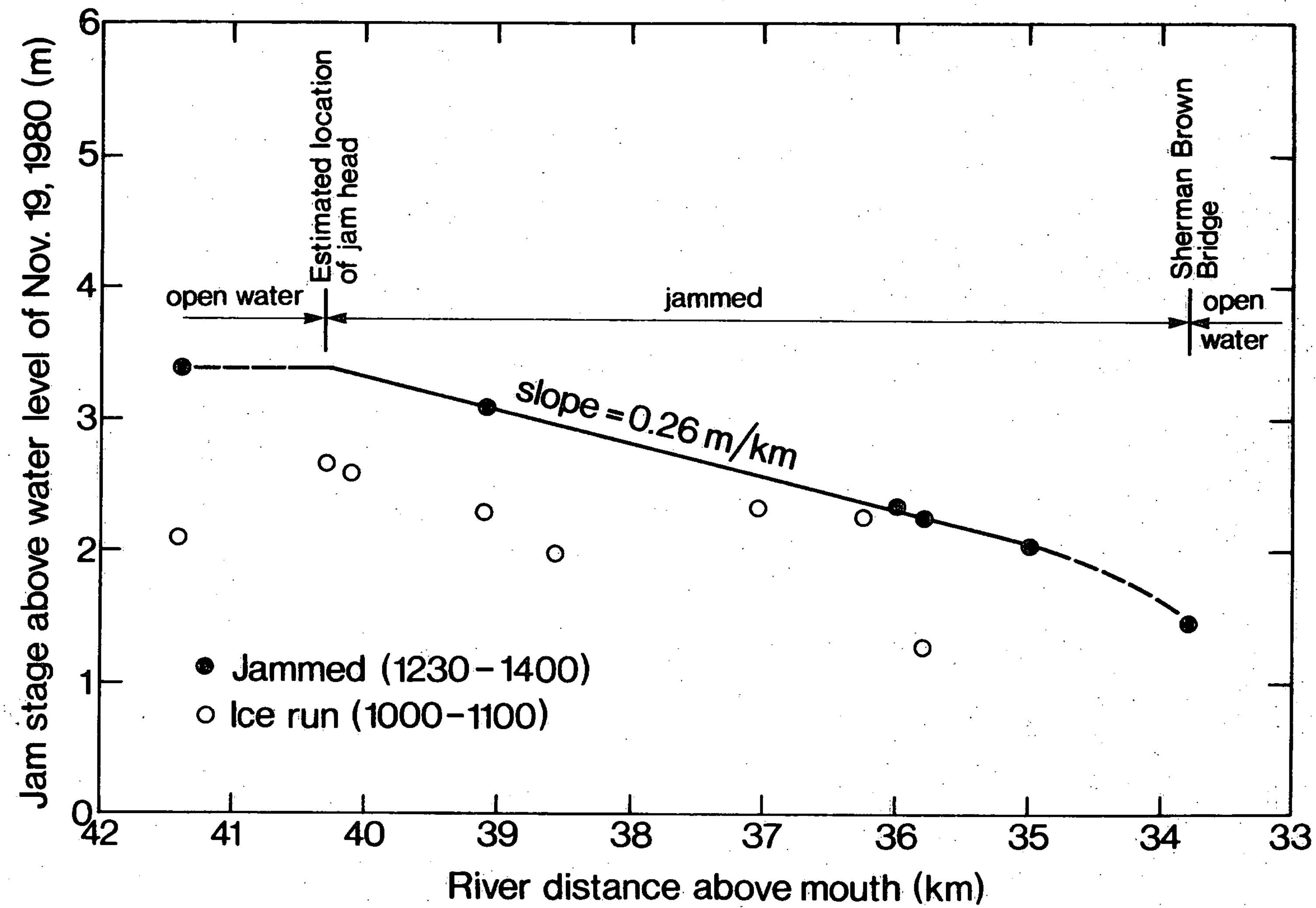


Fig. 22 Water level profiles above Sherman Brown bridge; Mar. 19, 1980

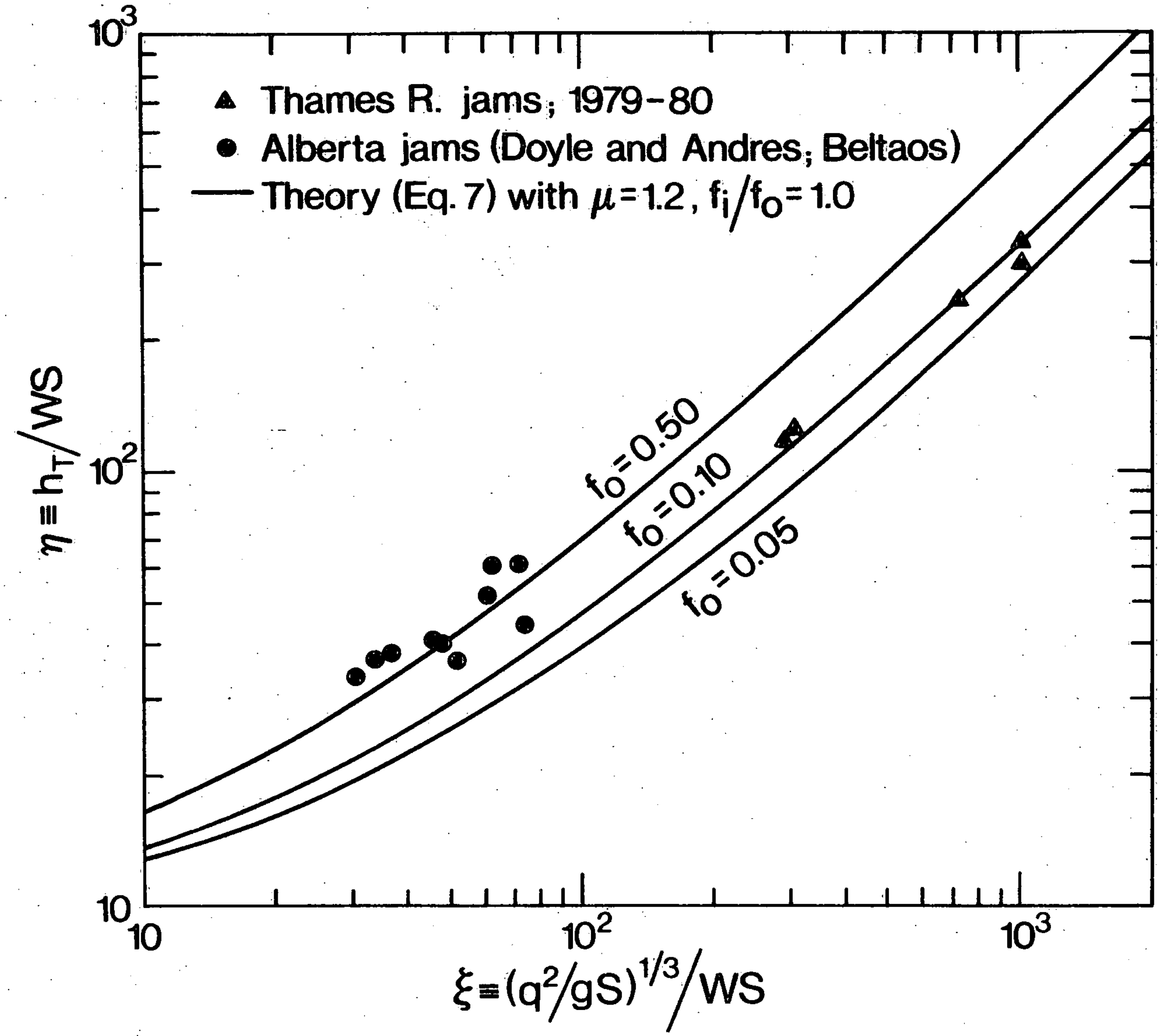


Fig. 23 Dimensionless presentation of ice jam data

Date Due
