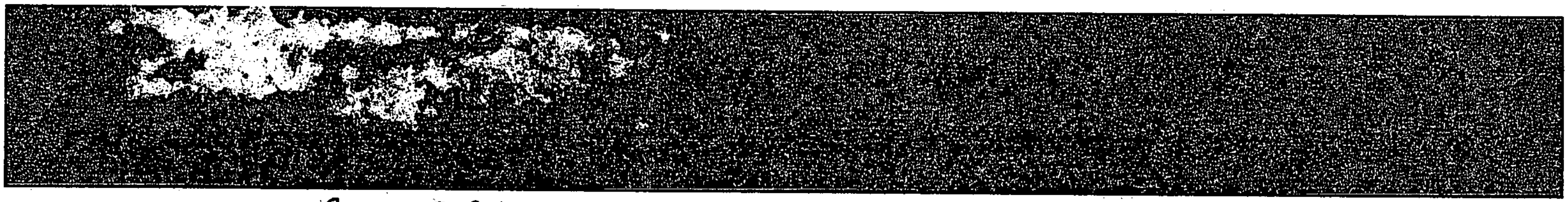

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ICE FREEZE UP AND BREAKUP IN THE LOWER THAMES RIVER: 1980-81 OBSERVATIONS

By

Inland Waters Directorate

Direction Générale des Eaux Intérieures

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ICE FREEZE UP AND BREAKUP IN THE LOWER THAMES RIVER: 1980-81 OBSERVATIONS

By

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ABSTRACT

The second year's ice observation on the lower Thames River are described and partially interpreted. Freeze-up commenced in December 1980 and breakup took place relatively early, during February 17-23, 1981. Extensive flooding occurred during the breakup period, owing to relatively large runoff and competent ice cover. Numerous ice jams formed within the study reach. Of these, the ones near the river mouth and near Louisville were the most severe. Interpretation of the season's data supported an existing theory of equilibrium jams and a recently developed conceptual model of breakup. A lack of theoretical background for non-equilibrium jams was noted and a need for studying conditions at ice jam toes was manifested.

RÉSUMÉ

Les observations des glaces du cours inférieur de la rivière Thames durant la deuxième année sont décrites et en partie expliquées. L'englacement a commencé en décembre 1980 et la débâcle s'est produite relativement tôt, du 17 au 23 février 1981. Il y a eu d'importantes crues pendant la période de la débâcle en raison de l'écoulement relativement important et de la solidité de la couverture glacielle. De nombreux embâcles se sont formés le long du tronçon d'étude. Les plus importants ont été celui près de l'embouchure de la rivière et celui près de Louisville. L'interprétation des données recueillies pendant cette saison appuie la théorie des embâcles en équilibre et est conforme au modèle conceptuel de la débâcle récemment mis au point. On a noté un manque de connaissances théoriques concernant les embâcles non en équilibre ainsi que la nécessité d'étudier les fronts des embâcles.

MANAGEMENT PERSPECTIVE

This is the second report from a continuing program of annual ice freeze-up and break-up observations aimed at developing solutions to problems related to flooding.

The data gethered in this report support a conceptual model developed at NWRI to predict the onset of break-up.

Several major ice jams were recorded and the documentation supports the use of an existing theory.

More data are needed to improve our ability to deal with ice and flooding problems.

T. Milne Dick
Chief
Hydraulics Division

March 28, 1983

PERSPECTIVE DE GESTION

Le présent rapport est le deuxième dans le cadre d'un programme en cours d'observations annuelles de l'englacement et de la débâcle visant à trouver des solutions aux problèmes associés aux crues.

Les données recueillies et présentées dans le présent rapport soutiennent un modèle conceptuel mis au point à l'INRE dans le but de prévoir le moment de la débâcle.

Plusieurs embâcles importants ont été étudiés et la documentation appuie l'application d'une théorie existante.

D'autres données sont nécessaires afin d'aider à trouver des solutions aux problèmes liés à la glace et aux crues.

T. Milne Dick
Chef, division de l'hydraulique
28 mars 1983.

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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 applied on river structures by moving ice floes, forces on ice booms, spring flooding and associated stage-frequency curves, etc.

At present, there exists a very limited capacity 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.

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 comprise complete documentations of the river regime during the entire ice season. However, manpower limitations have so far restricted the observations to mainly hydraulic aspects of breakup at only two reaches, the lower Thames R. and the upper Grand R. This report deals with the former reach, i.e. the Thames River from about Thamesvile 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 second observation season, December 1980 to February 1981. Before proceeding to describe this seasons'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. Additional hydrologic and hydraulic data pertaining to the study reach are given in an earlier report (Beltaos, 1981).

2.0 FREEZE UP AND WINTER

Figure 3 shows daily meteorological and hydrometric data as reported by Atmospheric Environment (AE) and Water Survey of Canada (WSC) at Ridgetown and Thamesville respectively. Sustained frost commenced on December 9, 1980 and WSC estimated that ice effects on stage were first experienced on December 14. The corresponding degree-days of frost and river discharge are estimated as 21.4°C-days and 44 m^3/s respectively.

Ice conditions in the lower Thames River were first documented during December 15 and 16. At Middlemiss, Willey's, Tates' and Thamesville crossings, the river was open with moving frazil ice on the surface on both December 15 and 16. There was also a small amount of border ice (see Appendix A for photos of ice conditions during freeze up and winter).

Stationary ice cover was observed from Chatham to about 2 km upstream of Louisville on December 15. The edge of the ice cover had advanced to about 1 km upstream of Kent Bridge by December 16, i.e. a distance of 7 km in 20 h ($\approx$ 0.35 km/h). At this rate, it is estimated that the edge of the cover would have arrived at Thamesville (Highway 21 crossing and WSC gauge site) at about noon of December 18. Unfortunately, the gauge malfunctioned during the period December 4 to 22 and thus the maximum stable freeze up stage[1], H_F, cannot be accurately determined. An estimate of 12.15 m was obtained from an empirical correlation (based on previous and later measurements) between water levels at Thamesville and Kent Bridge under ice covered conditions.

For Kent Bridge, the ice stage was measured manually at 1240 h on December 16. This measurement is considered a good indication of H_F, given that the edge of the ice cover was only 1 km upstream of Kent Bridge at that time. The situation is not as simple, however,

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[1] Used herein as an index of the stage at which a complete ice cover forms at a given site, as explained in a previous report (Beltaos, 1981). This stage is defined as a daily average value.

with respect to H_F at Sherman Brown Bridge where the earliest measurement was carried out at 1650 h on December 15. The WSC records for the Chatham gauge, located 3 km below Sherman Brown Bridge, indicate that the corresponding time of H_F was December 13 or 14 while the stage remained practically unchanged during December 13 to 16. Because of the proximity of this site to Sherman Brown Bridge, it is reasonable to assume similar stage behaviour for the latter location which suggests that the December 15 stage measurement should provide a fair appoximation of H_F. Table 1 summarizes H_F values for four locations within the study reach.

On December 16, the water surface elevations at several locations at and above Sherman Brown Bridge were surveyed as a means of estimating the hydraulic resistance characteristics of the ice cover. The results are summarized in Table 2, along with similar data obtained on November 10, 1980 under open water conditions. These data will be discussed later; however, it is noted at this time that the water surface slope is very small relative to values obtained further upstream and seems to depend on discharge and flow conditions. In turn, this reflects the partial control exercised by Lake St. Clair. Later in the season, the thickness of the ice cover was measured at several locations as summarized in Table 3 (includes data provided by other Agencies). The average ice thickness for the reach Middlemiss to Sherman Brown Bridge is 24.0 cm for January 6 to 8, 1981 whereas for the reach Chatham to mouth, it works out to be 29.6 cm. During the January 6 to 8 measurements, there was complete ice cover at all crossings visited, except for Tates where open water sections were observed upstream of the bridge. At Bothwell W., the appearance of the cover upstream of the bridge was visibly rough, as illustrated in photos (Appendix A). This is probably an indication of local jamming during freeze up.

3.0 BREAKUP

Figure 3 shows that 23 mm of rain fell on February 10, 1981. This caused a substantial flood wave despite the subsequent very cold weather. As the flood wave was about to peak, mild weather set in and more rain fell on February 16. This resulted in additional stage increases and led to breakup. Below is a brief description of breakup events. Photographs illustrating various aspects of the 1981 breakup are presented in Appendix B.

February 14. Ice conditions were inspected at various river crossings and access locations between Middlemiss and Chatham. The ice cover appeared competent. There was some melt water on the top of the ice near the river banks. Short open water sections were observed about 1.7 km upstream of the Highway 21 bridge.

February 17. Water levels rising throughout the reach Middlemiss to Kent Bridge, at rates of 7-9 cm/h. The ice cover remained competent but open water strips developed near the banks. There was evidence of imminent breakup near Thamesville and Fairfield Museum.

February 18. Water levels kept rising during the night but at reduced rates (3-5 cm/h). The ice cover deteriorated but remained in place except for the reach Bothwell W. to Kent Bridge. In this reach there were open water sections, minor jams and undisturbed ice cover sections. A small jam developed during the previous night near the Fairfield Museum and remained in place, despite intermittent "shoves".

At the Highway 21 crossing (gauge site), the ice cover was stationary until 0030 h but was found to be in motion at 0530 h. At that time, the moving cover comprised long, unbroken ice sheets which suggests that the movement began not long before 0530 h. The water level at the beginning of the movement (initiation of breakup) at this site is thus estimated as $H_B \approx 14.60$ m (Fig. 4). The surface speed was estimated to be between 0.5 and 1.0 m/s but it declined noticeably by 0615 h and the movement stopped at 0616. It is of interest to note in Fig. 4 that this first movement of the cover was associated with a "spike" on the stage-time record. Subsequent developments at this site are summarized in Fig. 4 and in Appendix C. The ice remained stationary for the rest of the day, except for a brief movement during 1125-1137. Figure 5 is a sketch of ice conditions in the morning of February 18, in the vicinity of Thamesville.

At Kent Bridge, an open water section had developed by 1815 h, starting about 70 m upstream and ending about 30 m downstream of the bridge.

February 19. Water levels kept rising at low rates near the downstream end of the reach (1-2 cm/h at Kent Bridge) and at high rates further upstream (5.5 cm/h at Willys and 8 cm/h at Middlemiss).

The jam near the Fairfield Museum advanced slightly during the previous night but did not release until 1637 h.

The jam at Highway 21 released at 1645 h but a new jam had formed at this site by 1910 h. The latter was probably caused by ice arriving from the Fairfield Museum.

At Kent Bridge, the ice cover began to move at 1820 h, following a rapid stage rise of 0.1 m but stopped at 1823 after brief crushing on the right bridge pier. The breakup initiation stage at Kent Bridge is thus estimated as 95.90 m (see Fig. 6a and Appendix C).

February 20. Near Thamesville, the ice had moved out during the night and open water extended to at least 3.5 km below the Highway 21 bridge. Above Highway 21, there was mostly open water with occasional minor jams. At 0815 h, the surface speed at Highway 21 was about 1.2 m/s while the water level dropped from 16.28 m at 0823 h to 16.23 m at 0830 h. This suggests that a jam downstream might have released not long ago. Noteworthy is that the head of a moving jam was observed at 0851 h about 6 km downstream of Highway 21.

At 0900 h, there was open water below the Kent Bridge crossing and an ice jam above. There were occasional open water sections from Kent Bridge to the golf course and competent ice cover below the golf course to, at least, Sherman Brown Bridge. The jam at Kent Bridge released at 1205 h (see Fig. 6b) but, by 1500 h, the ice had jammed again near the golf course. The new jam was about 5 km long; it began moving at 1730 h and advanced by about 2 km until 1800 h (Fig. 7). The ice cover below the jam remained largely intact.

At Chatham, the ice cover began breaking up at about 1700 h (water level ≃ 177.3 m, W. L. Knowles - personal communication).

February 21. During the night, the ice jam by the golf course had advanced a few km and lengthened to about 5.5 km (see Fig. 8). The water level had risen considerably near the jam's head. Despite occasional localized movements, this jam remained in place until 0750 h of February 22.

At Sherman Brown Bridge, the water level rose by 0.44 m during 0855 to 1106 h; dropped by 0.26 m during 1106 to 1307 h; and rose steadily after 1307 h (average rate of rise to 2208 h ≃ 5.8 cm/h, see also Fig. 9 and Appendix C). By 0845 h, a small open water section had developed just downstream of the bridge. This section lengthened during the day and by dusk there was open water downstream as far as could be seen from the bridge. By 2100 h, even the ice cover upstream of the bridge had moved out.

At 0930 h, a long section of the river through and below Chatham was open. The toe of a short jam was noticed at 1000 h about 1 km upstream of the Yacht Club (see Fig. 10). This jam kept advancing intermittently; at 1920 h, its head was observed beneath the Prairie Siding bridge.

February 22. The jam near Louisville released at 0750 h and had passed under the Sherman Brown Bridge by 1025 h. The surge due to the release of this jam resulted in peak water levels at least as far downstream as Chatham (W. L. Knowles, personal communication, see also Appendix C).

At 1250 h, there was undisturbed ice cover at the river mouth where preparations were under way to use explosives as a means of controlling the severity of anticipated jamming. The toe of an ice jam could be seen at the first bend above the river mouth. During 1300-1315 h and 1320-1344 h, the toe was observed to advance by breaking into the undisturbed ice cover, eventually coming to a halt about 600 m above the mouth. The toe appeared to be grounded and fairly high ice "rubble" could be seen in the toe area. The head of the jam was about 1.5 km below Bradley where small, scattered floes began arriving at about 1610 h, followed by heavier concentrations.

The latter was probably ice that released near Louisville in the morning and its arrival caused the head of the jam to advance upstream (see Fig. 11).

Flooding between Baptiste Creek and Bradley commenced in the afternoon, mostly because of water backing up in various inlets.

February 23. During the night of February 22 to 23, flooding became more extensive. At 0700 h, the road to the lighthouse was closed; at 0840 h, considerable flooding of the MNR dock was observed. However, during 0900-0930 h, the water level was receding at Bradley. Ice conditions near the river mouth were observed from the air shortly before noon (see Fig. 12). The ice jam released and moved out of the river at about 1430 h (W. L. Knowles, personal communication).

3.1 Summary of Breakup Observations

In general, the 1981 breakup progressed in the downstream direction. Within the reach Bothwell to mouth, breakup seems to have started near the Fairfield Museum where an ice jam formed during the night of February 17 to 18. At Thamesville (Highway 21 crossing), Kent Bridge and Sherman Brown Bridge breakup was respectively initiated at about 0530 h, February 18; 1820 h, February 19; and 1040 h, February 21.

It is noteworthy that the breakup through and below Chatham occurred independently of upstream conditions, much as happened in 1980. This is illustrated by the fact that, in Chatham, breakup was initiated at about 1700 h on February 20, well before that at Sherman Brown Bridge.

Major ice jams occurred near Fairfield Museum; Kent Bridge; golf course; Louisville and river mouth. From Chatham to the mouth, the breakup process consisted of intermittent but persistent movements of an ice jam that kept breaking through the undisturbed ice cover and advancing downstream while lengthening at the same time. This jam became threatening by February 22 and eventually resulted in considerable flooding once it was joined by broken ice from above Chatham. Selected photographs illustrating various aspects of the 1981 breakup are presented in Appendix B.

4.0 DATA ANALYSIS AND INTERPRETATION

4.1 Resistance Characteristics of Ice Cover

The data shown in Table 2 afford an opportunity to estimate the resistance characteristics of the ice cover in the reach above Sherman Brown Bridge, given that several cross sections have already been surveyed in this reach.

For ice covered conditions, the composite Manning coefficient, n_o, is calculated first and the ice coefficient, n_i, is deduced from the Sabaneev equation, i.e.

$$n_o = [\ (n_i^{3/2} + n_b^{3/2})/2\ ]^{2/3} \qquad (1)$$

As a first approximation, the river bed coefficent, n_b, was assumed to be equal to 0.027 (Table 4), though it is recognized that n_b may depend on the hydraulic radius of the bed, R_b. During the December 16 survey, the ice cover did not appear safe for access and thus its thickness at that time is not known. Measurements carried out on January 7, 1981 indicated an average thickness of 25 cm which should be close, but not necessarily equal, to that of December 16. For this reason, Table 4 gives resistance characteristics for three assumed thickness values. In Table 4, the symbols f_i, k_{si} and R_i denote the friction factor, equivalent sand roughness height and hydraulic radius associated with the ice cover. Even though the n_i values shown in Table 4 are crude, they conclusively support previously reported findings indicating that ice covers are much rougher shortly after their formation than later on in the winter when n_i is expected to be between 0.008 and 0.012 (see e.g., Carey, 1966; Nezhikhovskiy, 1964).

4.2 Initiation of Breakup

In a previous report (Beltaos, 1981), a conceptual model of the breakup process was developed which, though incomplete, resulted in some success when attempting to analyze data on breakup initiation. For convenience, this concept is outlined briefly below.

First, it is assumed that the ice cover is still fairly competent at the time breakup is initiated and that side cracks which may be caused by rising water levels are located very close to the shore relative to the river width (see also Billfalk, 1981). These two assumptions ensure that (i) the width of the ice cover at the time breakup is initiated is approximately equal to W_F (= channel width at the stage H_F); and (ii) before the ice cover loses the lateral restraint of the banks which prevents development of large stresses, the water stage must rise to at least H_F. In this manner, complications arising from various effects that may result in stages H_B lower than H_F are, for the present, eliminated. As the water level continues to increase during the pre-breakup period, the stresses in the cover will increase and eventually transverse cracks will form, as outlined by Shulyakovsky (1972). At this stage, the river will be covered by large separate ice sheets, as illustrated in Fig. 13. Breakup does not necessarily follow from this configuration because the sheets may be too long to advance for any significant distance; they may simply be re-aligned into a loose but stable arrangement (Fig. 13). With continued increase in stage, the channel width increases until some of the ice sheets can "clear" the bends or other obstacles; they subsequently pick up speed and, on impact with stationary ones, cause further breaking and fragmentation. Small ice jams begin to form causing additional stage increases, new dislodgements and so on, until the entire reach is cleared of ice. Based on this discussion, it is felt reasonable to define breakup initiation as the time when a sustained movement of the cover takes place. The reach under consideration will be cleared of ice when the last stationary ice sheet is dislodged; in all probability, this sheet will be holding back an ice jam by that time.

Dimensional Analysis. Let ℓ_i be a length representative of the longitudinal dimensions of the separate ice sheets illustrated in Fig. 13b. To initiate breakup, the channel width (W_B) must be such that it "just" permits a sufficient number of ice sheets to clear the various obstructions[2]. One could then write

$$W_B = f_3 (W_i, \ell_i; L_1, \ldots, L_K; \theta_1, \ldots, \theta_n) \tag{2}$$

in which L_K and θ_n are series of lengths and angles that define river plan geometry. The length ℓ_i may be expressed as

$$\ell_i = f_4 (\tau, \sigma_i, W_i, h_i; \ldots L_K; \ldots \theta_n) \tag{3}$$

in which τ = driving force per unit area; and σ_i = representative value of ice strength. Substituting Equation 3 in Equation 2 and performing dimensional analysis gives

$$W_B/W_i = f_5 (h_i/W_i, \sigma_i/\tau; \ldots L_K/W_i; \ldots \theta_n) \tag{4}$$

In Equation 5, W_i is the width of the cover at the time breakup is initated. On the basis of earlier discussion, W_i may be substituted by W_F. Since W_F changes from year to year, the parameters L_K/W_i do likewise. However, the variation of W_i ($\equiv W_F$) is limited in any given stream (freeze up flows); thus, as a first approximation, L_K/W_i can be considered river constants. Moreover, in most natural streams, W varies as a power of y (= average depth) so that W_B/W_F could be replaced by the more practical parameter y_B/y_F. Equation 4 may then be rewritten as

$$y_B/y_F = f_6 (h_i/W_F, \sigma_i/\tau; \text{ dimensionless river constants}) \tag{5}$$

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[2] Clearly, over a given reach with many sheets, ℓ_i will have a statistical distribution rather than being a constant. 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.

Equations 4 and 5 provide possible methods to analyze data on breakup initiation.

In earlier reports (Beltaos, 1981; 1982b), it was shown that Equation 5 could account for findings at three different river sites [i.e. Thames R. at Thamesville; Smoky R. at Watino (Alberta) and Peace R. at Peace River (Alberta)] by plotting y_B/y_F versus h_i/W_F. The possible effects of σ_i/τ and the dimensionless river constants in Equation 5 are still unknown. The parameter σ_i/τ is very difficult to assess because both σ_i and τ are partly dependent on the degree of thermal deterioration of the ice cover at the time breakup is initiated; this is a problem about which very little is known at present. The effects of dimensionless river constants can only be assessed via a quantitative theoretical analysis which has not been undertaken so far. However, because these constants describe the river planform, it is possible that they do not vary appreciably among rivers belonging to a few characteristic types.

Table 5 summarizes 1981 breakup initiation and related data for various locations within the study reach. Data for 1980 which were discussed in a previous report (Beltaos, 1981) are also included in Table 5. Figure 14 shows data for the Thamesville gauge site, plotted in the form y_B/y_F versus h_i/W_F (Fig. 14a) and $\Delta H_B/\Delta H_F$ versus h_i/W_F (Fig. 14b). Note that $\Delta H_B = H_B - H_0$ and $\Delta H_F = H_F - H_0$, with H_0 = gauge height for zero discharge = 10.25 m for Thamesville. The quantity ΔH provides a rough measure of the flow depth but is more convenient to use than the average flow depth, y. Determination of the latter must be based on a survey of several representative cross sections in the vicinity of the site of interest which may not always be available. Most of the data points in Fig. 14 (circles) are associated with an analysis of past gauge records and are thus subject to considerable uncertainty, as described earlier (Beltaos, 1981). It is of interest to note that the data points associated with in situ documentations of breakup (diamonds) are in general agreement with the historical data.

Recalling Equations 4 and 5, it may be noted that Equation 5 derives from Equation 4 via the assumption that W varies as a power of y which is valid for most natural streams (provided the stage is less than the elevation of the valley flat). However, the exponent associated with this relationship may change from one river reach to another, hence, Equation 4 is considered a more suitable basis for comparing data from different sites. This is done in Fig. 15 where it is seen that the observational data show much less scatter than the historical data while both sets exhibit the same general trends.

It was assumed earlier that side cracks are located very close to the shore relative to the river width. However, preliminary calculations (Beltaos and Wong, Unpublished Data) and field observations show that this may not be the case, depending on ice thickness and channel width. Work is under way to take this effect into account so as to improve the consistency of dimensionless plots such as those of Figs. 14 and 15.

4.3 Ice Jams

Several major jams were observed and documented during the 1981 breakup. Water levels along these jams were obtained from photographic records. Supplementary hydrometric data (e.g. cross sections, open water slope, discharge) were obtained from open water surveys and from WSC gauge records. Ice jam data obtained in this manner can be used to test the existing theory, as described by Beltaos (1981). This theory considers the jam a floating granular mass and gives the aggregate thickness, h_j, that is necessary to resist the applied forces (Pariset et al. 1966; Uzuner and Kennedy, 1976). At the same time, the flow depth under the jam, y, can be related to the flow discharge (assuming negligible flow through the jam voids) via a hydraulic resistance relationship (Beltaos, 1982a). The overall water depth, h_T (= $y + s_i h_j$; s_i = specific gravity of ice), is then given by:

$$h_T/WS\ (\equiv \eta) = \underbrace{0.63\ f_o^{1/3}}_{= y/WS}\ \xi + \frac{5.75}{\mu}\left\{1 + \sqrt{1 + \underbrace{0.11\ \mu f_o^{1/3}}_{= s_i\ h_j/WS}\ \left(\frac{f_i}{f_o}\right)\ \xi}\right\} \qquad (6)$$

in which s_i has been fixed at 0.92; μ is a coefficient that depends entirely on the internal friction of the jam; W and S are flow width and slope respectively; and f_o, f_i are the composite and ice jam friction factors respectively (note $2f_o = f_i + f_b$; f_b = channel bed friction factor). The parameter ξ is defined as:

$$\xi \equiv (q^2/gS)^{1/3} / WS \qquad (7)$$

with q = discharge intensity = Q/W.

Earlier work (Beltaos, 1982a) has indicated that the main variable on the RHS of Equation 6 is ξ. This was verified by plotting observed values of η versus ξ and obtaining a relationship with relatively little scatter (see also later discussion). It is pointed out here that the above theory applies only within the "equilibrium" reach of an ice jam. This reach is characterized by relatively uniform jam thickness and flow under the jam. Barring occurrence of severe grounded jams or other unusual circumstances, the equilibrium stage of a floating jam can be considered the maximum possible at a given site for a given discharge. Of course, an equilibrium reach may not always be present, owing to such causes as proximity of flow controls or release of an ice jam while still in evolution.

With this discussion, we now proceed to interpret the 1980-81 ice jam observations.

Jam near Fairfield Museum. This jam was first noticed at about 1100 h on February 18 and appeared to have been caused by a local constriction combined with undisturbed ice (see also Fig. 5). During 1712-1725 h on February 18, the head of the jam moved slowly downstream but the main body remained stationary. This movement was probably due to collapse and consolidation within the head area which comprised relatively small and loose ice fragments. At 0845 h on February 19, the jam appeared to have shifted slightly downstream and the water stage was noticeably higher. The jam began to move at 1637 h on February 19 and was well past the museum by 1700 h. The speed of movement was visually estimated as 1 m/s. Water level documentations (photographic) were carried out during 1500-1745 h, February 18 and 1610-1720 h, February 19. Due to prevailing foggy conditions, the quality of the photographs was poor; determinations of corresponding water levels resulted in poor consistency and large scatter which rendered accurate definition of the slope under jammed conditions impossible. Analysis of the data for this jam was based on taking average water level profiles and using the corresponding open water slope in the same reach (0.3 m/km). Selected characteristics of this and other jams are summarized in Tables 6 and 7.

Jam at Kent Bridge. This jam was initiated sometime after the ice cover began to move at 1820 h on February 19 and prior to 1900 h on February 20. Jamming was caused by the combined effects of the bridge piers and the bend located a short distance upstream. The jam released at 1205 h on February 20 and the head passed under the bridge at 1337 h. Scattered ice pieces were still coming down at 1349 h but had virtually disappeared by 1522 h.

Jam near Golf Course. This jam was initiated at about 1500 h on February 20 near the golf course (Fig. 8). The probable causes of this jam were the undisturbed ice cover, the bend not far upstream of the toe and the relatively shallow local configuration of the channel. The jam was documented during 1600-1645 h and its approximate length determined at 5 km. However, this jam must have been unstable because it released shortly afterwards (1730 h). Figure 16 shows the water level profile along this jam as determined from photographic records. The water surface slope over most of the jam's length is 0.12 m/km while it is seen to increase near the toe which appeared to be grounded (see also photo in Appendix B). The average hydraulic characteristics of this jam were estimated using three cross sections, located at 48.01, 44.59 and 43.53 km. At two of these sections, the water level was well above the banks. Possible overbank flow in either longitudinal or lateral directions has been neglected.

Jam near Louisville. This jam most likely formed during the night of February 20 to 21 and was caused by a large ice sheet lodged at a sharp bend (see Fig. 8). The jam remained in place until 0750 h on February 22 and caused flooding of considerable areas near the river. Water levels along the jam are plotted in Fig. 17 where it may be seen that stages generally rose with time. Also shown in Fig. 17 are high water marks that occurred shortly before or during the jam's release. The straight line drawn through the data points is representative of conditions at about 1430 h on February 21 and has a slope of 0.32 m/km. Because of the relative proximity of Lake St. Clair, it is difficult to establish whether or not this jam had an equilibrium reach. At sites that are not subject to water level controls, this question can be resolved by comparing the longitudinal water surface profiles under jammed and open water conditions. If there is a section where such profiles are approximately parallel (i.e. they have equal slopes), this is an indication that equilibrium had been attained by the jam (see also Beltaos, 1982a). However, where control influences are present, the open water slope changes with discharge and control conditions. In principle, one could consider the channel bed slope by plotting minimum bed elevations versus river distance but this too is a very difficult task because channel irregularities "mask" the consistent elevation trend that is sought. However, because of the large resistance to flow under an ice jam, it is expected that uniform flow conditions should be established within a relatively short distance. Thus, an indication of equilibrium may be sought in (a) checking for consistent trends in flow areas of the available cross secions and (b) comparing the measured water surface slope with those obtained for past ice jams in the same reach. For the present jam, no consistent cross-sectional area variation was detected; at the same time, the measured slope (0.32 m/km in the nearby reach 39.2 - 44.2 km) compares favourably with a slope of 0.26 m/km obtained for an ice jam on March 19, 1980 in the nearby reach 35 km to 39.2 km (Beltaos, 1981). With this evidence and in lack of a more advanced theory that would take into account non-uniform flow and jam thickness conditions, the data for this jam have been analyzed according to the equilibrium theory, using six cross sections, located at 43.53, 42.77, 41.59, 40.69, 39.19 and 38.56 km. Moreover, using a value of $n_b = 0.027$, as discussed earlier, a more detailed analysis was performed (see Beltaos, 1982a) which is based on a relationship between ice jam thickness and resistance characteristics. This resulted in $h_j = 1.1$ m, $\mu = 1.6$, $f_i = 0.14$ and $f_o = 0.093$. The value of μ is higher than the average value of

1.2 found by Beltaos (1982a) but relatively close to it. In the same report, a trend for f_0 to decrease with increasing ξ (see Equation 7) was detected as shown in Fig. 18; the present value of f_0 is also plotted in this figure and seems to be consistent with the other data points.

Jam near Yacht Club. This jam was first noticed in the morning of February 21 and documented during 1000-1100 h. The stage profile of this jam is shown in Fig. 19. The straight line drawn through the data points has a slope of 0.35 m/km. This value may be in considerable error because the jammed reach was relatively short and the elevation differences involved are small. Only mild steepening near the toe of the jam is indicated in Fig. 19 which may be indicative of a floating toe (see also photo in Appendix B). Data analysis was based on three cross sections located at 17.45, 18.80 and 20.00 km, but it should be understood that this jam was unlikely to have attained equilibrium. Shortly after it was documented, the jam released and kept advancing intermittently.

Jams near the Mouth. A major jam had formed near the river mouth by the afternoon of February 22 (see also Fig. 11 and photos in Appendix B). By the morning of February 23, the toe of this jam had advanced well into Lake St. Clair. Water level profiles along these jams are shown in Fig. 20. For the February 22 jam, the extreme steepness of the profile near the toe (at least 4 m/km) suggests local grounding which is in agreement with the appearance of the toe (see photos in Appendix B). From the two points located at 1.0 and 2.3 km respectively, the water surface slope is estimated as 0.27 m/km. At the time of observation the jam appeared to be stable, as it remained in place until (at least) the evening of February 22. However, there is little evidence to indicate whether or not the jam had an equilibrium reach. Over the main portion of the February 23 jam, the data points indicate a slope of 0.41 m/km but again it is not known whether an equilibrium condition had been attained. There is also some uncertainty regarding the flow discharges applicable to these two jams. Though estimates can be made using data at Thamesville and applying suitable travel times, there was considerable overbank flooding on both occasions. It is thus possible that a part of the flow had been escaping towards the sides. Thus, the corresponding values of ξ in Table 7 are shown as upper limits. The cross sections used for this analysis were located at 0.02, 0.82 and 1.41 km.

Discussion. Figure 21 shows the present data from Table 7 plotted in the form of η versus ξ along with the data range established earlier (Beltaos, 1982a). The two data points representing cases where an equilibrium condition was likely, plot inside the range. Of the three data points which represent cases where equilibrium was unlikely, two plot below the range and one falls inside the range. For the two jams near the river mouth, the points plot somewhat low but the limitation on ξ indicated by the arrows seems to be in the right direction.

4.4 Peak Stages

Predicting the peak stage during breakup is one of the chief objectives of ice hydraulics. Unfortunately, accurate prediction of this stage is only a hope for the future. At present, the best that can be done is to obtain estimates of stage values that are not expected to be exceeded. Two possible approaches and their implications are outlined below.

Equilibrium Jam Stage. It was argued earlier that, barring unusual circumstances, the highest stage that can occur, at a given site and for a given discharge, is that which is caused by a floating jam that has attained equilibrium. The condition of equilibrium requires that the jam contains within its length a reach in which the jam thickness and flow depth are approximately uniform. For reaches that are not subject to control influences, the equilibrium condition implies that the corresponding water surface slope is approximately equal to the channel slope. Under open water conditions, the latter does not depend on discharge, i.e. it is uniquely defined for a given reach[3]. Where this is the case, as for example near Thamesville, the

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[3] That is, a reach that is long enough to permit meaningful averaging of channel characteristics.

equilibrium jam stage can be computed as a function of discharge in two ways: (a) detailed method and (b) simplified method, as explained in Beltaos (1982a). The simplified method makes use of the relationship shown in Fig. 21, after first drawing an "average" line. The detailed method is more laborious. As an example, these methods have been applied to the reach near the Thamesville gauge. The results are shown in Fig. 22, along with pertinent data obtained from Water Survey of Canada gauge records. Also shown in Fig. 22 are three data points applicable to the 1981 breakup. Four types of stage-discharge pairs are depicted in Fig. 22. "Max. stage" denotes instances when the maximum breakup stages occurred. "Max. backwater" denotes instances associated with the maximum ice effect on stage or "backwater"; such instances do not necessarily coincide with those associated with max. stage. "Discharge Measurement" denotes instances when both discharge and gauge height have been measured during the breakup. The corresponding data points are the most accurate but do not generally represent max. stage or backwater. "Freeze up" indicates peaks occuring during freeze up. Though freeze up jams do not necessarily behave in the same manner as do breakup jams[4], these data points have been included in Fig. 22 for comparison purposes. Figure 22 shows that the theoretical curves lie generally above the data points, as postulated. At the same time, the discrepancy between theory and observation seems to increase with increasing discharge. This is reasonable because the high discharges are probably associated with unstable jams that release before attaining equilibrium or with significant overbank flows that limit the peak attainable stage. Figure 22 could be used to approximately forecast the potential severity of an anticipated breakup if the peak discharge during the breakup can be estimated.

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[4] Because of possible cohesion effects introduced by negative air temperatures. Cohesion has been neglected in the present analysis because this is a fair assumption for breakup jams and on the safe side for freeze up jams.

"Ice-Clearing" Discharge. The conceptual model of breakup described earlier has an interesting consequence regarding the maximum breakup stage, as described below. It has been postulated that, just prior to breakup, the river is covered by large separate ice sheets and that breakup is initiated when a certain percentage of these sheets are able to clear the corresponding obstructions and begin to move. Pursuing this concept further, it is reasonable to expect that a reach will be cleared of ice when that ice sheet which is least amenable to dislodgement is finally able to move downstream. Let y_C and H_C be the average flow depth and stage respectively, at which this ice sheet can be dislodged. Then by similar reasoning as before, one could write:

$$y_C/y_F \quad \text{or} \quad \Delta H_C/\Delta H_F \leq f_7 \text{ or } f_8 \quad (h_i/W_F,\ \sigma_i/\tau,\ \ldots\ ) \qquad (8)$$

The inequality sign accounts for the fact that, during the breakup period, the ice sheet will be subjected to reductions in competence and dimensions owing to thermal and mechanical deterioration. The discharge, Q_C, which corresponds to y_C may be viewed as the "ice clearing" discharge since it is responsible for the final clearance of the ice from the reach of interest. Letting q_C denote the corresponding discharge intensity (= Q_C/W_C) and f_C the composite friction factor of the flow under the ice sheet, gives:

$$q_C = \sqrt{4g\ S/f_C}\ (y_C - s_i h_i)^{3/2} \qquad (9)$$

for which it has been implicitly assumed that the flow is uniform. Simultaneous consideration of Equations 8 and 9 suggests that q_C has an upper limit dictated by y_F, h_i, W_F, σ_i, τ, f_C and channel geometry and slope. Equation 9 may be rearranged to read:

$$(y_C - s_i h_i)/y_F = (f_C/4)^{1/3}\ [(q_C{}^2/gS)^{1/3}/y_F] \qquad (10)$$

For the Thamesville gauge data, $s_i h_i$ does not exceed ten percent of y_c so that Equation 10 could be simplified to:

$$y_c/y_F \approx (f_c/4)^{1/3}\,[(q_c{}^2/gS)^{1/3}\,/y_F] \tag{11}$$

Substituting Equation 11 in Equation 8 gives:

$$\frac{(q_c{}^2/gS)^{1/3}}{y_F} \leq \left(\frac{4}{f_c}\right)^{1/3} f_7\left(\frac{h_i}{W_F}, \frac{\sigma_i}{\tau}, \ldots\right) \tag{12}$$

which affords a means for testing the concept of the "ice clearing" discharge. The latter can be obtained from the gauge records as the maximum discharge attained prior to the disappearance of ice effects on stage. To find the discharge intensity, q_c, an estimate of W_c, the channel width at the depth y_c is also needed. Considering that y_c is between y_B and y_{max} (= flow depth at max. breakup stage)[5], one could, as a first approximation, take the average of the corresponding widths. This approach, however, is not practical from the viewpoint of forecasting because it utilizes information pertaining to what is to be forecast (i.e. W at $y = y_{max}$). Considering that W is a weak function of stage (so long as the latter is less than the valley top level), it would seem a fair assumption to use W_B in place of W_c. With this assumption, the available data are plotted in Fig. 23, in the form suggested by Equation 12. Figure 23 shows consistency of the Thames River data with those of the Smoky and Peace Rivers. At the same time, the upper envelope of the data points increases with h_i/W_F, at least to the value h_i/W_F = 0.01. Beyond this value of h_i/W_F, the data points are too few to enable extrapolation. With regard to the legend of Fig. 23,

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[5] It is assumed that the maximum stage is caused by an ice jam that, in all probability, forms behind the ice sheet that is dislodged last.

"uncertain" values of Q_c are those that are based entirely on estimates. "Satisfactory" values are those that have been based on discharge measurements taken shortly before or after the time of occurrence of Q_c.

Figure 23 can be utilized to estimate an upper limit of Q_c when H_F and h_i are known. This value may then be used in conjunction with Fig. 22 to determine the corresponding maximum stage, H_{max}, which is thus shown to depend on H_F and h_i. This is illustrated in the dimensional plots of Figs. 24 and 25. It should be emphasized that H_F and h_i only define a "potential" H_{max}. Whether this potential will be realized during breakup depends on runoff and weather conditions. As an example, let us assume that H_F and h_i are given as 12.0 m and 25 cm respectively. From cross-sectional data it can be found that W_F = 37.9 m and y_F = 2.1 m. Hence, $100\ h_i/W_F = 25/37.9 = 0.66$ which in Fig. 14b gives $\Delta H_B/\Delta H_F \simeq 2.05$. The stage at zero discharge is 10.25 m, therefore $H_B \simeq 10.25 + 2.05\ (12-10.25) \simeq 13.84$ m and thence $W_B \simeq 46.4$ m. Moreover, Fig. 23 gives $(q_c^2/gS)^{1/3}/y_F \simeq 13.8$. The slope at Thamesville is 0.23 m/km, hence, $q_c \simeq [(13.6 \times 2.1)^3 \times 9.8 \times 0.00023]^{1/2} = 7.4\ m^2/s$ and $Q_c = 7.4 \times 46.4 = 344\ m^3/s$. If runoff estimates for the event leading to breakup give a peak discharge exceeding 344 m^3/s, the ice will clear at the latter value. Hence, the upper limit of H_{max} is estimated as 18.2 m using Fig. 22. However, if the expected runoff peak is less than 344 m^3/s, say 250 m^3/s, then Fig. 22 would indicate that H_{max} should not exceed 17.5 m.

5.0 DISCUSSION

The second year's ice observations in the lower Thames River have been described and partly analysed in the previous sections. Interpretation of the data has focused on two major aspects. The effects of freeze up and winter conditions on the initiation and severity of the breakup; and testing of the existing theory of river ice jams using quantitative field data. Below is a detailed discussion of the present findings.

5.1 Conceptual Model of the Breakup Process

A conceptual model of the breakup process has been proposed and used with fair success to interpret pertinent data for the gauge site near Thamesville. Briefly, this model indicates that cracking of the ice cover begins when the stage H_F is exceeded. This results in the formation of large separate ice sheets which are initially stationary owing to various obstacles. With increasing water stage and thence channel width, some of the sheets can eventually move downstream. Subsequently, they impact with channel boundaries and stationary sheets which result in additional fragmentation and formation of small ice jams. This causes additional stage increases, more dislodgements and fragmentation and so on. A reach is cleared of ice when the ice sheet that is least amenable to dislodgement is finally able to move. Using this conceptual framework, it was possible to derive dimensionless relationships and identify some of the parameters that govern the initiation and severity of breakup. It is emphasized that the postulated breakup mechanism is not unique. For example, it cannot be expected to apply in cases of:

(a) Mature breakups, i.e. breakups associated with warm weather and little runoff. In such instances, the ice cover can disintegrate even at stages lower than H_F because of intense thermal deterioration. It is perhaps significant that application of the present concept had some success for the lower Thames River where breakup is usually "premature", i.e. it is associated with intense runoff under cloudy conditions.

(b) Presence of significant controls on water stage which may inhibit stage increases that normally result from increased runoff. A good example is the reach near the mouth of the Thames River where the stage is controlled by that of Lake St. Clair. Here, a "premature" breakup involves mechanical destruction of the ice cover by advancing ice jams that comprise broken ice from upstream reaches. It is plausible to expect that breakup characteristics depend on flow discharge, ice thickness and strength and possibly on H_F, however, it is not known in what manner. The stability of ice jam toes is a central question in this case but the writer is not aware of any pertinent studies.

Moreover, even in cases where the present breakup concept can be expected to apply, there are several additional factors which may complicate the general picture, i.e.:

(a) Formation of side cracks at distances from the shore that are not negligible relative to the ice cover width. The width of the ice cover, W_i, is then significantly different from W_F.

(b) Tributaries that break up prior to the main channel can cause local deterioration and breakage of the main channel ice cover.

(c) Localized distintegration of the ice cover, as is often observed when holes in the cover appear at seemingly random locations.

(d) Intense fragmentation of the ice cover caused by sudden releases of upstream ice jams, prior to the formation of large, separate ice sheets.

Some of the above effects can, at least in principle, be quantified (see Billfalk, 1981; 1982), others would seem unpredictable at present. It follows that what has been done so far is but a first step towards understanding the mechanisms of river ice breakup. At the same time, some interesting findings have become evident for reaches not subjected to stage controls, i.e.:

(a) Other things being equal, the stage required to initiate breakup and the peak breakup stage increase when H_F and h_i increase but decrease when W_F increases.

(b) To reduce ice jamming frequency and severity, an efficient channel cross section would be as sketched in Fig. 26a where it is assumed that H_F does not exceed H_1 and flooding occurs only when the stage exceeds H_2. Though this type of geometry does not usually occur in nature, it might be worth considering when designing flood protection dykes. It is also noteworthy that trees growing on river banks can effectively limit the channel width that is available for ice passage. This can be a significant detriment. For example, at river bends (frequently sites of ice jams) where the topography usually affords ample width with moderate stage increases, trees may act in a detrimental manner (Fig. 26b).

(c) Other obvious control measures include reduction of the dimensions of the pre-breakup large ice sheets by thermal or mechanical means; reduction of ice thickness and strength; and reduction of H_F where possible.

5.2 Ice Jams

Our findings so far support the existing theory of equilibrium jams. However, measurement of jam thickness is still not possible. It is felt that, unless a method to overcome this problem is devised, further accumulation of data on equilibrium jams in the Thames River should be a matter of lessened priority.

A question that has become evident in earlier discussion is how to deal with ice jams in reaches subjected to stage control, such as the reach of the Thames River near the mouth. As it has already been pointed out, equilibrium may or may not occur even where steady state conditions have been established. Unfortunately, no satisfactory theoretical formulation of this problem is available at present. Uzuner and Kennedy (1976) have presented the governing differential equations assuming the jam to be a granular mass but solution is hampered by the lack of knowledge concerning the downstream boundary condition, i.e. conditions at the toe of the jam. For the Thames River near the mouth, a first approximation for now would be to use Fig. 21 in conjunction with slope values similar to those that have been measured already. It should be understood that this approach has only empirical justification.

6.0 SUMMARY AND CONCLUSIONS

The 1980-81 ice season was associated with considerable flooding that took place during the breakup. The latter occurred relatively early and could be considered "premature". This fact combined with the fairly thick ice cover that formed during the winter and the relatively large runoff to cause the flooding. Several major ice jams formed during the breakup. Of these, the ones near Louisville and river mouth were the most severe. The flow discharge during the breakup period varied from about 100 m^3/s to about 550 m^3/s and the ice thickness was, on the average, between 31 cm (Thamesville) and 45 cm (river mouth).

Interpretation of the season's data indicated the following:

(a) The data provided additional support to a conceptual model, developed earlier to predict the onset of breakup.

(b) This model was extended to define an upper limit for the maximum breakup stage by introducing the concept of the "ice clearing" discharge. Past and present data were used to test this concept and the outcome was favourable.

(c) Documentations of the various ice jams supported the existing theory of equilibrium floating, wide-channel type jams. At the same time, a lack of theoretical background for non-equilibrium jams was noted and a need for studying conditions at jam toes was manifested.

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TABLES

TABLE 1. VALUES OF H_F FOR THE 1980-81 ICE SEASON

Location	Time of H_F	H_F (m)	Remarks
Thamesville Gauge - Highway 21 Bridge	Dec. 18	12.15	Time of H_F estimated from rate of advance of ice edge. H_F estimated from stage correlation with Kent Bridge. Value of H_F denotes gauge height; add 167.558 m to find geodetic elevation (geodetic H_F=179.71 m).
Kent Bridge	Dec. 16	93.30	Measured. Value of H_F denotes arbitrary elevation referred to local temporary benchmark; add 82.975 m to find geodetic elevation (geod. H_F=176.28 m).
Sherman Brown Bridge	Dec. 13-14	92.32	Estimated from stage measurements on Dec. 15 and 16 plus WSC records at Chatham. Value of H_F denotes arbitrary elevation referred to local temporary benchmark; add 83.067 m to find <u>approximate</u> geodetic elevation (geod. H_F=175.39 m).
Chatham Gauge	Dec. 13-14	175.37	Estimated from WSC records. Value of H_F denotes geodetic elevation.

TABLE 2. HYDRAULIC CONDITIONS NEAR SHERMAN BROWN BRIDGE UNDER OPEN WATER AND ICE COVERED CONDITIONS

Location (River Kilometres above Mouth)	Nov. 10, 1980; Discharge ≈ 59.7 m^3/s		Dec. 16, 1980; Discharge ≈ 35 m^3/s	
	Water Surface Elevation (m)	Slope to Previous Survey Location	Water Surface Elevation (m)	Slope to Previous Survey Location
Sherman Brown Bridge-33.79	-	-	92.29	N.A.
34.99	-	-	92.32	0.025×10^{-3}
35.82	-	-	92.34	0.024×10^{-3}
40.18	92.480	N.A.	-	-
40.69	92.486	0.012×10^{-3}	-	-
41.59	92.512	0.029×10^{-3}	92.51	0.029×10^{-3}
44.16	92.577	0.025×10^{-3}	-	-

Note: Elevations are arbitrary but all are referred to a local temporary benchmark; add 83.067 m to find approximate geodetic elevation.

TABLE 3. SUMMARY OF ICE THICKNESS MEASUREMENTS

Location	Date 1981	Average Ice Thickness (cm)	Range of Ice Thickness (cm)	Date 1981	Average Ice Thickness (cm)	Range of Ice Thickness (cm)	Date 1981	Average Ice Thickness (cm)	Range of Ice Thickness (cm)
Middlemiss Br.	Jan. 6	24.5	16-32						
Willy's Br.	Jan. 6	23.9	19-36						
Walker's Br.	Jan. 6	22.5	17-33						
Simpson's Br.	Jan. 6	23.5	18-28						
Wardsville Br.	Jan. 8	24.1	17-29						
Bothwell W. Br.	Jan. 8	28.6	25-33						
Thamesville Br.	Jan. 8	22.3	18-30	Jan.22**	26.2	22-30			
Kent Bridge (1)	Jan. 7	21.8	18-27						
Kent Bridge (2)	Jan. 7	22.3	20-25						
Sherman Brown Br.	Jan. 7	23.7	22-27						
Chatham(4th St.)*	Jan. 12	25.6	23-28				Feb. 6	33.5	31-36
Prairie Siding Br.*	Jan. 12	27.8	24-33				Feb. 6	37.5	34-41
Gov't. Dock*	Jan. 12	29.3	24-34	Jan. 28	31.0	25-41	Feb. 6	38.3	33-45
Lighthouse Dock*	Jan. 12	32.4	31-35	Jan. 28	37.3	36-41	Feb. 6	44.8	43-48
Mouth*	Jan. 12	33.0	29-35	Jan. 28	37.7	36-42	Feb. 6	44.5	37-47

* Data for these locations have been provided by Lower Thames Valley Conservation Authority.

**From data provided by Water Survey of Canada, Guelph Office; free flotation of the ice cover has been assumed, i.e. the quoted values ("water surface to bottom of ice") have been divided by 0.92 (= specific gravity of ice).

TABLE 4. HYDRAULIC RESISTANCE CHARACTERISTICS OF THAMES RIVER ABOVE SHERMAN BROWN BRIDGE UNDER OPEN WATER AND ICE COVERED CONDITIONS

Condition	n_o	n_b	n_i	f_i	k_{si} (m)	R_b (m)	R_i (m)
Nov. 10, 1980; open water	N.A.	0.027	N.A.	N.A.	N.A.	2.60	N.A.
Dec. 16, 1980; ice cover; thickness = 15 cm	0.034	0.027 (assumed)	0.041	0.106	0.69	1.04	1.96
Dec. 16, 1980; ice cover; thickness = 25 cm	0.033	0.027 (assumed)	0.038	0.092	0.49	1.09	1.82
Dec. 16, 1980; ice cover; thickness = 40 cm	0.030	0.027 (assumed)	0.033	0.073	0.27	1.18	1.59

TABLE 5. BREAKUP INITIATION STAGES AND RELATED PARAMETERS AT FOUR SITES WITHIN THE STUDY REACH

Location	Season	H_F (m)	h_i (cm)	H_B (m)	Remarks
Thamesville (WSC Gauge)	1980-81	12.15	31	14.60	See corresponding column of Table 1.
Kent Bridge	1979-80	93.20	20	94.25	See corresponding column of Table 1.
	1980-81	93.30	32	95.90	See corresponding column of Table 1.
Sherman Brown Bridge	1980-81	92.32	35	95.30	See corresponding column of Table 1.
Chatham (WSC Gauge)	1980-81	175.37	35	177.30	See corresponding column of Table 1.

TABLE 6. MAJOR ICE JAMS DURING THE 1981 BREAKUP

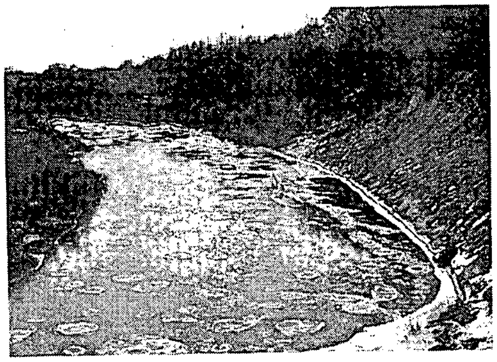
Location Distances are km above river mouth		Time of Formation	Time of Release	Approximate Flow Discharge	Probable Causes
Toe	Head				
Approx. 75.4 km	Near Fairfield Museum, 76.0 km	After 1630 h, Feb. 17 and before 1100 h, Feb. 18.	1637 h, Feb. 19	200 m^3/s at the time of release.	Channel constriction and continuous ice cover.
Kent Bridge, approx. 50.0 km	≈53.2 km, est'd. from speed and duration of run at bridge	After 1830 h, Feb. 19 and before 0900 h, Feb. 20.	1205 h, Feb. 20	260 m^3/s at the time of release.	Bend and bridge piers.
Near golf course, approx. 43.5 km	Approx. 48.5 km	About 1500 h, Feb. 20	1730 h, Feb. 20	300 m^3/s at the time of release.	Continuous ice cover and bend nearby.
Near Louisville, approx. 38.7 km	Approx. 44.4 km	During the night of Feb. 20 to 21.	0750 h, Feb. 22	540 m^3/s at the time of release.	Large ice sheet at a sharp bend.
Near Yacht Club, approx. 17.5 km	Approx. 19.4 km	Before 1000 h, Feb. 21	Before 1200 h, Feb. 21	350 m^3/s at 1130 h, Feb. 21.	Continuous ice cover; toe located in a relatively straight channel reach.
Approx. 0.6 km	Near Bradley, approx. 4.5 km	About 1330 h, Feb. 22	During the night of Feb. 22 to 23	450 m^3/s at 1430 h, Feb. 22	Continuous ice cover; toe located within mild bend.
Past mouth, in Lake St. Clair	Approx. 1.9 km	During the night of Feb. 22 to 23	Approx. 1430 h, Feb. 23	Unknown; some flow escaping laterally on flood plain.	Continuous ice cover in Lake St. Clair.

TABLE 7. SELECTED ICE JAM CHARACTERISTICS; THAMES RIVER 1981

Approximate Location	Time	Q (m^3/s)	S m/km	h_T (m)	W (m)	ξ	η	Probable	Accuracy of Jam Stage Profile
Fairfield Museum	p.m., Feb. 18	145	0.30	4.9	45	1140	365	Equilibrium	Poor
Fairfield Museum	p.m., Feb. 19	200	0.30	5.1	46	1340	367	Imminent Release	Poor
Gold Course	p.m., Feb. 20	300	0.12	6.0	86	2090	580	Imminent Release	Fair
Louisville	p.m., Feb. 21	425	0.32	6.8	83	765	256	Equilibrium	Good
Yacht Club	a.m., Feb. 21	345	0.35	4.9	100	430	140	Evolving	Fair
Lighthouse	p.m., Feb. 22	$\leq$450	0.27	5.4	109	$\leq$632	182	Unknown	Fair
Mouth	a.m., Feb. 23	$\leq$550	0.47	5.6	113	$\leq$325	105	Unknown	Good

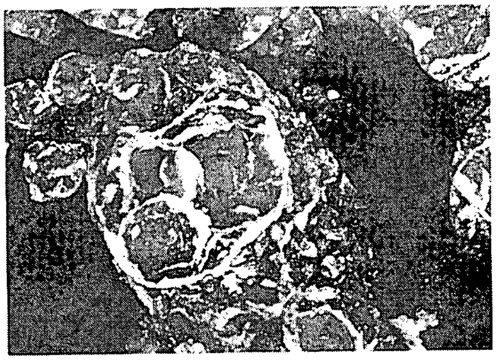
APPENDICES

APPENDIX A. Photographs - Freeze Up and Winter

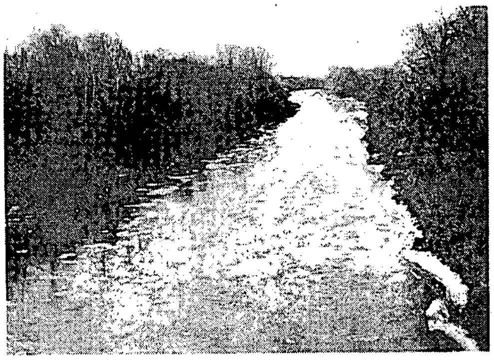


Looking u/s of Middlemiss Bridge;
1340 h, Dec. 15, 1980

u/s side of Middlemiss Bridge;
1340 h, Dec. 15, 1980

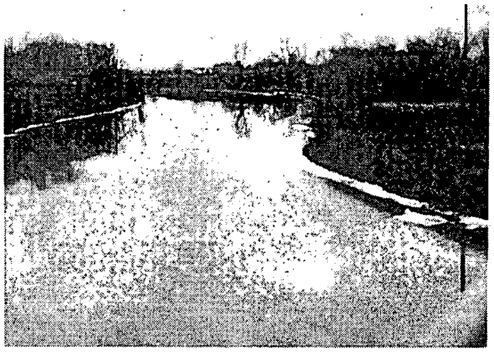


Frazil slush under Middlemiss
Bridge, 1340 h, Dec. 15, 1980



Looking u/s of Hwy 21 bridge;
1540 h, Dec. 15, 1980

Looking u/s of Sher. Brown
Bridge; 1645 h, Dec. 15, 1980.
Ice cover is stationary.



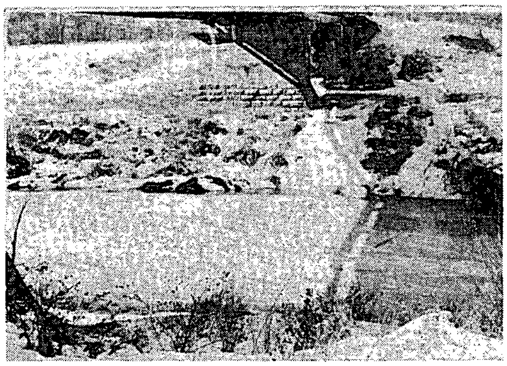
Looking d/s of Sher. Brown Bridge;
1645 h, Dec. 15, 1980.
Ice cover is stationary.

Looking d/s, a few km above Sher. Brown Bridge; 1700 h, Dec. 15, 1980.

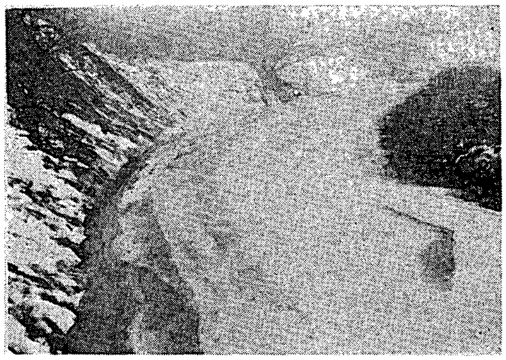
u/s side of Bothwell W. Bridge, looking toward Right Bank; 0900 h, Jan. 8, 1981. Note rough surface of ice cover.

APPENDIX B. Photographs - Breakup

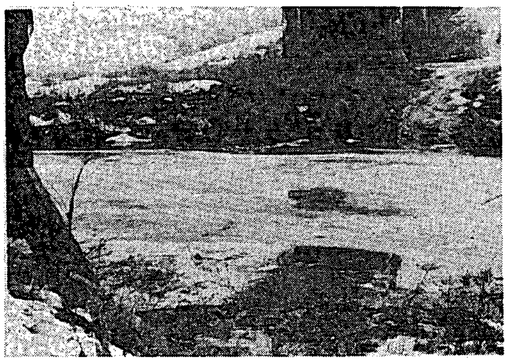
1230 h, Feb. 14, 1981



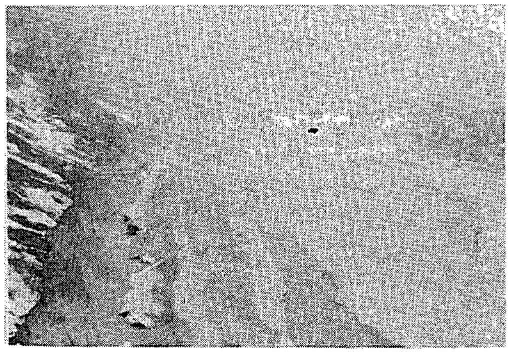
1230 h, Feb. 14, 1981



1140 h, Feb. 17, 1981



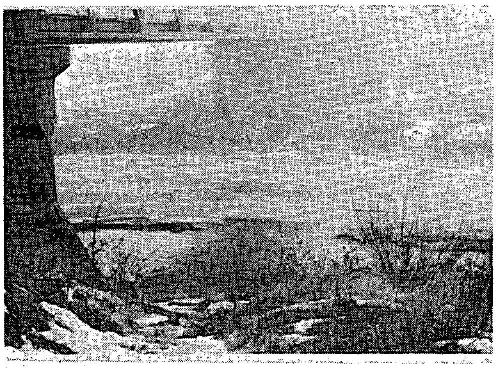
1140 h, Feb. 17, 1981



1330 h, Feb. 18, 1981

↑

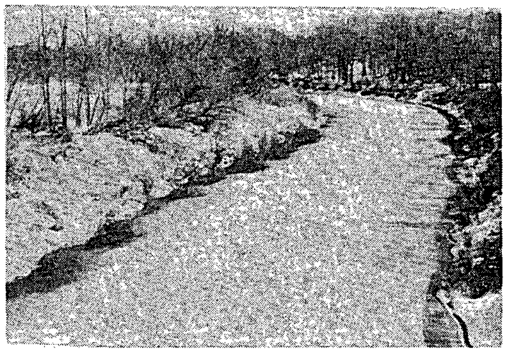
Looking d/s of Middlemiss Bridge at different times.



1330 h, Feb. 18, 1981

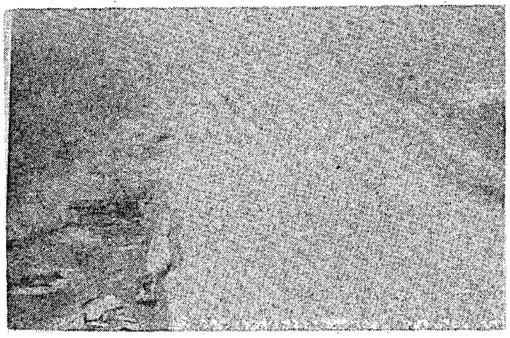
↑

Middlemiss Bridge. Looking towards Right Bank at different times.

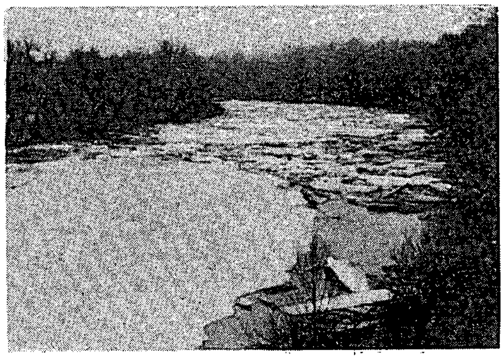


1300 h, Feb. 14, 1981

1720 h, Feb. 17, 1981



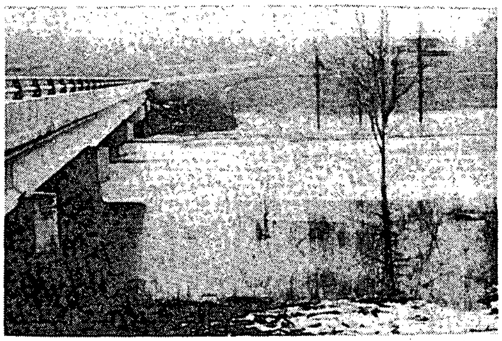
1520 h, Feb. 18, 1981



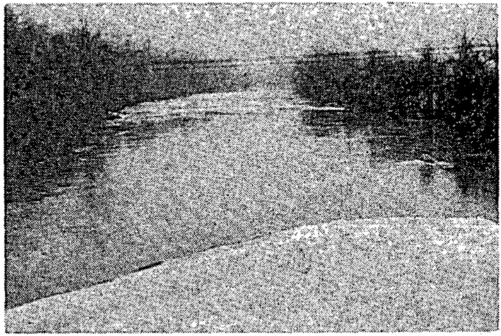
1410 h, Feb. 20, 1981

↑

Looking u/s of Willy's Bridge
at different times.



u/s side of Willy's Bridge
1410 h, Feb. 20, 1981.



Looking d/s of Willy's Bridge;
1410 h, FEb. 20, 1981.

Ice beginning to break up near Fairfield Museum. Looking u/s, 1620 h, Feb. 17, 1981.

Ice jam at 1730 h, Feb. 17, 1981 at same location as above.

Surface texture of ice jam near Fairfield Museum. Looking towards Left Bank at 1650 h, Feb. 18, 1981

Head of ice jam near Fairfield Museum at 1710 h, Feb. 18, 1981.

1530 h, Feb. 14, 1981

1400 h, Feb. 17, 1981

0820 h, Feb. 20, 1981

↑

Looking u/s of Hwy 21 bridge.

1600 h, Feb. 14, 1981

1240 h, Feb. 20, 1981
(moving ice)

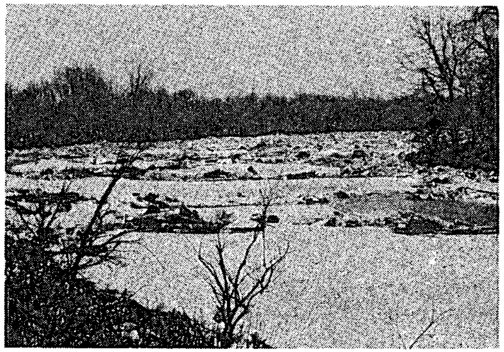
1540 h, Feb. 20, 1981

u/s side of Kent Bridge at
different times

Toe of jam at Kent Bridge at
0935 h, Feb. 20, 1981
(looking u/s).

Toe of ice jam at Kent Bridge at 0900 h, Feb. 20, 1981
(looking u/s).

Ice Jam near Golf Course; 1620 h, Feb. 20, 1981

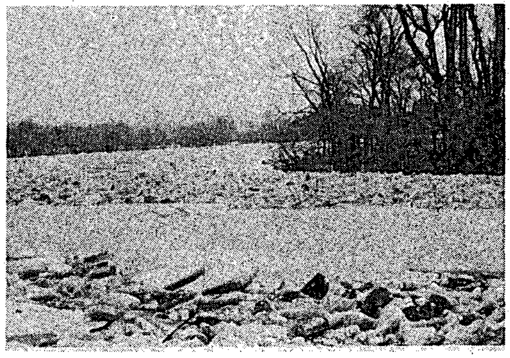


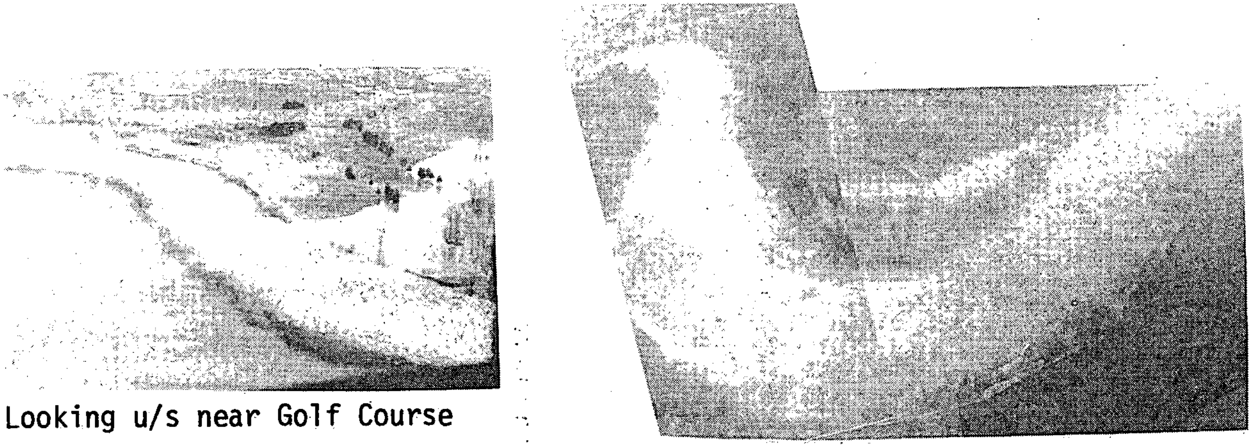
Looking u/s from toe.

Looking towards Left Bank at toe.

Looking d/s from Right Bank at toe.

Ice Jam near Louisville; 0830 h, Feb. 21, 1981. Corresponding photos were taken at same locations as above to illustrate rise in water level.





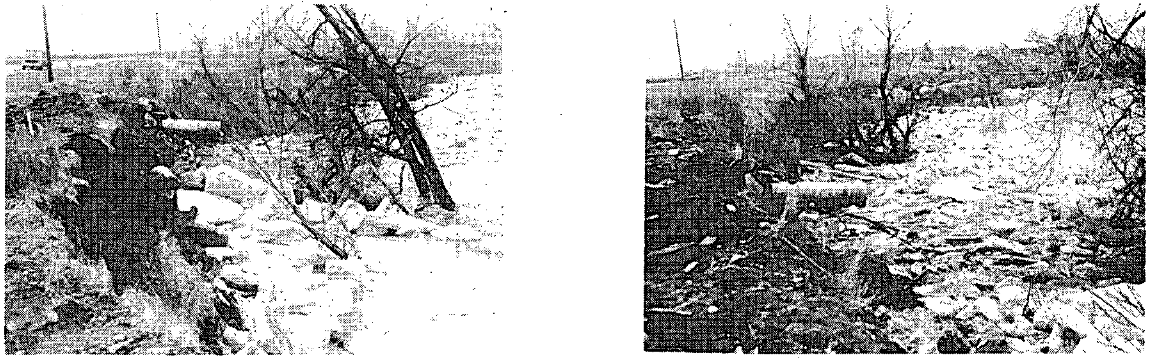
Looking u/s near Golf Course

Toe

Two views of ice jam near Louisville at about 1600 h, Feb. 21, 1981. (Courtesy of W.L. Knowles).

Surface texture of ice jam. Looking towards Right Bank near Golf Course, at 1727 h, Feb. 21, 1981.

Flooding of river road near Golf Course at 1000 h, Feb. 22, 1981.

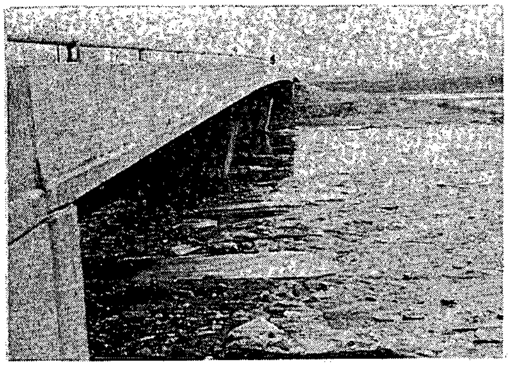


1220 h, Feb. 21, 1981
(ice jam)

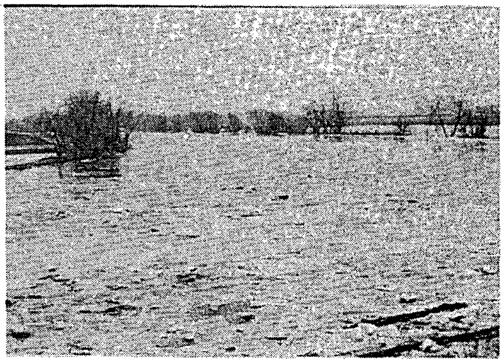
0950 h, Feb. 22, 1981
(ice run)

Looking d/s at first bend above Louisville jam toe location. Note change in water level.

1100 h, Feb. 20, 1981



u/s side of Sherman Brown Bridge at 1038 h, Feb. 22, 1981; ice run.

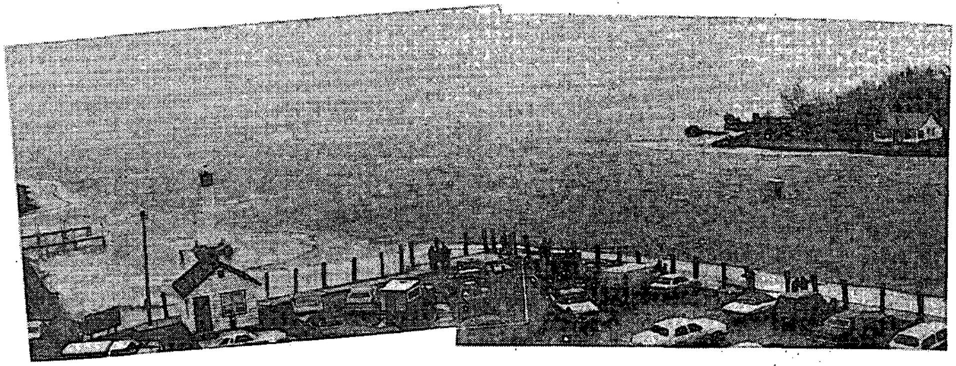


1038 h, Feb. 22, 1981

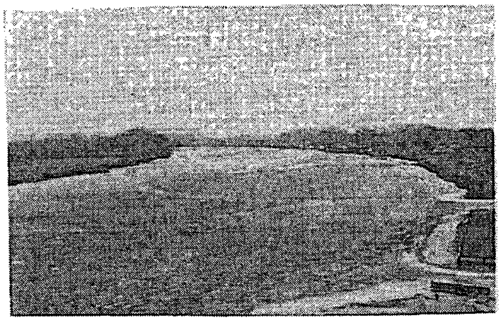
↑

Looking u/s of Sherman Brown Bridge at different times.

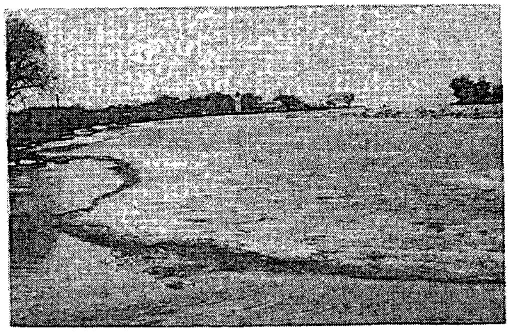
Yacht Club. Flooding of parking lot at 1206 h, Feb. 22, 1981.



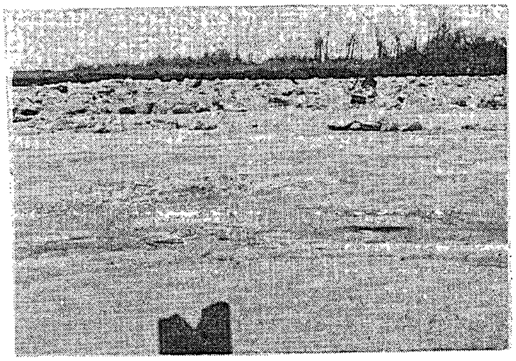
River mouth at 1342 h, Feb. 22, 1981. Preparations under way to apply explosives.



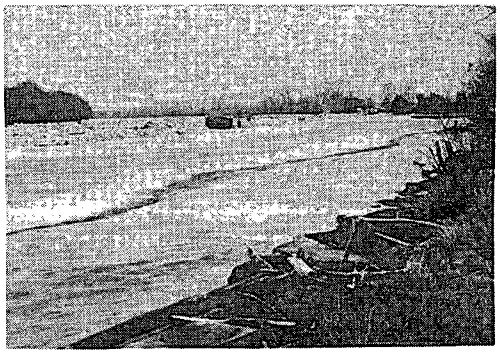
Looking u/s from Lighthouse at 1342 h, Feb. 22, 1981. Toe of jam at bend.



Toe of jam at 1400, Feb. 22, 1981. Looking d/s. Note relief of "rubble".

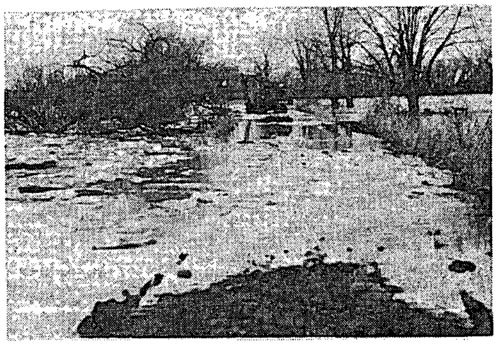


Toe of jam at 1400 h, Feb. 22, 1981. Looking toward Right Bank.

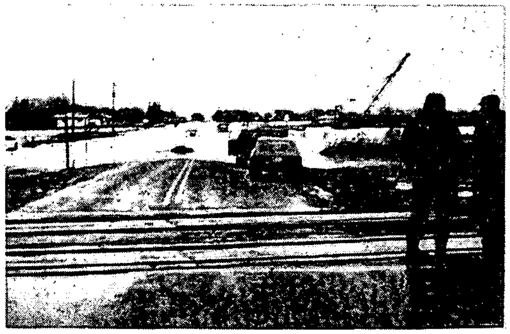


Looking u/s of toe at 1400 h, Feb. 22, 1981.

Ice piles on Left Bank; 1415 h, Feb. 22, 1981.

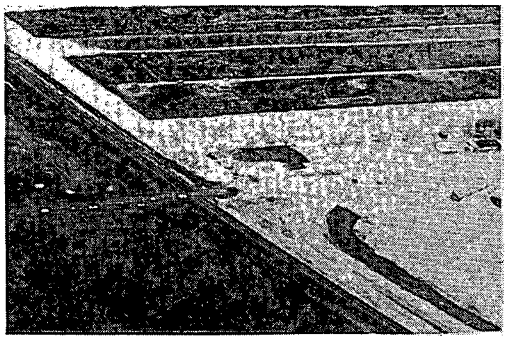


Overtopping of dyke at Bradley. Looking d/s at 1720 h, Feb. 22, 1981.



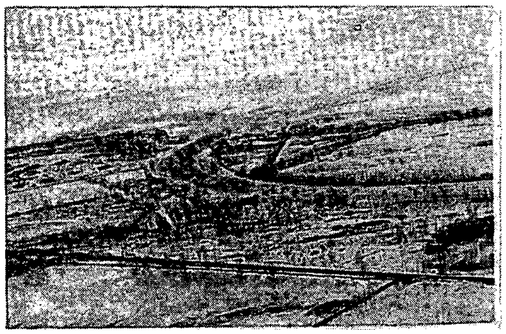
Road access to river mouth flooded; 0730 h, Feb. 23, 1981.

Flooding at MNR dock; 0840 h, Feb. 23, 1981.

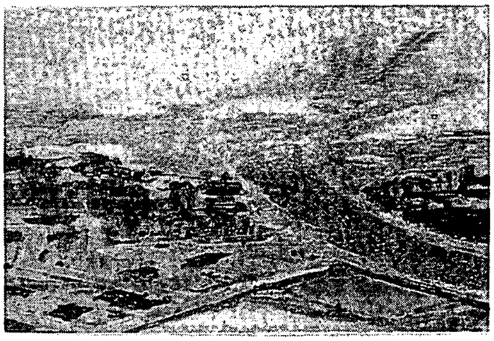


Aerial view of flooded area shown above; 1125 h, Feb. 23, 1981.

Head of ice jam at 1125 h, Feb. 23, 1981. Note flooding.



Ice jam and flooding near river mouth at 1125 h, Feb. 23, 1981.

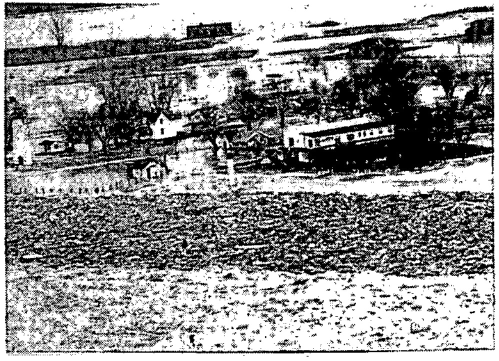


River mouth at 1125 h, Feb. 23, 1981. Note three rows of holes blasted on the previous day to weaken the L. St. Clair ice cover and facilitate passage of jam.

↓

← Closer view.

River mouth, looking u/s at 1125 h, Feb. 23, 1981.



Ice jam and flooding near Lighthouse. Looking toward Left Bank at 1130 h, Feb. 23, 1981.

Flooding on Left Bank above the mouth, 1130 h, Feb. 23, 1981.

APPENDIX C
TABLE C.1. WATER LEVELS AND ICE CONDITIONS AT HIGHWAY 21

Date Feb'81	Time	Tape Reading (m)	Corresponding Gauge Height (m)	Remarks
17	1412	10.302	13.491	Continuous ice cover u/s of bridge; open water at sides ≈1-5 m wide. Single narrow crack on each side of ice sheets ~3-6 m in from edge. Open water sections d/s (1) of bridge.
	1506	10.226	13.567	Tape readings every 10-15 minutes throughout this period indicate steady water level rise of 9 cm/h. Occasional ice piece breaks off edges.
	1718	10.066	13.727	
	1928	9.921	13.872	Air temperature = 8°C; foggy.
	2000	9.853	13.940	
	2030	9.838	13.955	
	2135	9.762	14.031	
	2225	9.701	14.092	
	2327	9.640	14.153	
18	0020	9.579	14.214	No movement of ice so far.
	0530	-	-	Large ice sheets moving downstream; possibly very close to beginning of ice movement.
	0540	9.152	14.641	
	0555	9.091	14.702	
	0600	-	-	Still moving - large ice sheets.
	0604	9.045	14.748	Surface speed steady at 0.6-0.9 m/s.
	0609	-	-	Large sheet arrives; slowing down somewhat.
	0612	9.030	14.763	Sheet still moving; noticeable slowdown at 0615; stopped at 0616; ice under bridge.
	0618	8.969	14.824	(Reading taken on top of ice.)
	0623	9.061	14.732	Same condition; ice cover ≈1/2 of water surface width.
	0628	9.091	14.702	Same condition; ice cover ≈1/2 of water surface width.
	0645	9.091	14.702	Same condition; ice cover ≈1/2 of water

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(1) d/s = downstream; u/s = upstream.

APPENDIX C

TABLE C.1. WATER LEVELS AND ICE CONDITIONS AT HIGHWAY 21

Continued

Date Feb'81	Time	Tape Reading (m)	Corresponding Gauge Height (m)	Remarks
18	0700	9.091	14.702	Same condition; ice cover ≈1/2 of water surface width.
	0715	9.061	14.732	Same condition; ice cover ≈1/2 of water surface width.
	0731	9.000	14.793	Same condition; ice cover ≈1/2 of water surface width.
	0740	9.000	14.793	Same condition; ice cover ≈1/2 of water surface width.
	0824	8.931	14.862	Same condition; air temperature=6°C.
	0856	8.893	14.900	Same condition; foggy, air temperature=6°C
	1100	8.801	14.992	Same condition; foggy, air temperature=6°C
	1125	8.687	15.106	Ice moving after rise of 0.1 m.
	1135	8.641	15.152	
	1137	-	-	Jammed again. River filled with large ice floes but these are beginning to break up. Largest floes 30 m wide x 100 m long.
	1148	8.656	15.137	Water level increases slowly but steadily.
	1622	8.565	15.228	Water level increases slowly but steadily.
	1625	-	-	Head of jam ≈800 m u/s bridge.
	1654	8.580	15.213	Slow drop in water level; maximum air temperature=11°C at 1600 h.
	1828	8.588	15.205	
19	0802	8.489	15.234	Air temperature=9°C, foggy. No apparent change in ice conditions since 18/02/81. Water levels rose very slowly during this period, then stable.
	1306	8.397	15.396	Head of jam visible ≈300 m u/s bridge. Water level rising steadily about 5 cm/h.
	1620	8.260	15.533	Discharge measured by WSC staff.
	1645	-	-	Jam moving.
	1656	8.184	15.609	Major part of jam passed under bridge (average speed ≈300/11x60=.45 m/s).
	1725	8.001	15.792	Open water; water level stable; small ice pieces moving d/s.
	1910	7.925	15.868	Jammed.

APPENDIX C

TABLE C.1. WATER LEVELS AND ICE CONDITIONS AT HIGHWAY 21

Continued

Date Feb'81	Time	Tape Reading (m)	Corresponding Gauge Height (m)	Remarks
20	0823	7.510	16.283	Open water; surface speed ≈1.3 m/s.
	1300	7.550	16.243	Open water; surface speed ≈1.3 m/s.
21	0805	6.650	17.143	Open water; surface speed ≈1.3 m/s.
	1500		17.401	From LTVCA staff.
23	1350		18.180	From WSC staff.

APPENDIX C

TABLE C.2. WATER LEVELS AND ICE CONDITIONS AT KENT BRIDGE

Date Feb'81	Time	Stage-Arbitrary (m)	Stage-Geodetic (m)	Remarks
17	1445	94.08	177.06	Competent ice cover with strips of open water at sides.
	1512	94.11	177.09	No change in ice conditions.
18	0832	94.83	177.81	No change in ice conditions.
	0925	94.85	177.83	No change in ice conditions.
	1815	95.22	178.20	Small open water lead starts 70 m u/s and ends 30 m d/s of bridge.
19	0815	95.47	178.45	Small open water lead starts 70 m u/s and ends 30 m d/s of bridge.
	1440	95.55	178.53	Open water 30 m u/s and as far as can be seen d/s of bridge.
	1815	95.85	178.83	Open water 30 m u/s and as far as can be seen d/s of bridge.
	1820			U/s ice cover begins to move.
	1823			Stops against right pier.
	1824	95.95	178.93	Approximate stages.
	1837	95.95	178.93	Approximate stages.
	1847	95.97	178.95	Approximate stages.
20	0900			Open water d/s of bridge; ice jam u/s; floating toe.
	0930	96.971	179.946	No change in ice conditions.
	0940	96.986	179.961	No change in ice conditions.
	1120	96.758	179.763	No change in ice conditions.
	1137	96.788	179.763	No change in ice conditions.
	1149	96.806	179.781	No change in ice conditions.
	1200	96.819	179.794	No change in ice conditions.
	1205			Jam begins to move
	1207	97.215	180.190	Ice run, approximate stages
	1208	97.184	180.159	Ice run, approximate stages
	1210	97.291	180.266	Ice run, approximate stages

APPENDIX C

TABLE C.2. WATER LEVELS AND ICE CONDITIONS AT KENT BRIDGE

continued

Date Feb'81	Time	Stage-Arbitrary (m)	Stage-Geodetic (m)	Remarks
20	1211	97.276	180.251	Ice run, approximate stages.
	1214	97.245	180.220	Ice run, approximate stages.
	1217	97.276	180.251	Ice run, approximate stages.
	1220	97.337	180.312	Ice run, approximate stages.
	1225	97.367	180.342	Ice fragments noticeably smaller
	1228	97.337	180.312	Stages more accurate from this time on.
	1232	97.398	180.373	
	1235	97.398	180.373	
	1243	97.520	180.495	
	1248	97.550	180.525	
	1254	97.550	180.525	
	1300	97.581	180.556	
	1306	97.550	180.525	
	1313	97.581	180.556	
	1320	97.611	180.586	
	1328	97.642	180.617	
	1333	97.642	180.617	Surface concentration of ice begins to decrease.
	1336	97.642	180.617	
	1339	97.672	180.647	Jam head under bridge at 1337 h
	1343	97.672	180.647	
	1349	97.672	180.647	Scattered ice fragments
	1354	97.703	180.678	
	1400	97.733	180.708	
	1406	97.733	180.708	
	1412	97.733	180.708	
	1426	97.824	180.799	
	1437	97.855	180.830	
	1522	97.946	180.921	Surface concentration of ice ≃ 0
21	0820	99.013	181.988	
	1345	98.922	181.897	

APPENDIX C

TABLE C.3. WATER LEVELS AND ICE CONDITIONS AT SHERMAN BROWN BRIDGE

Date Feb'81	Time	Stage-Arbitrary (m)	Stage-Approx. Geodetic (m)	Remarks
21	0855	95.116	178.183	Competent ice cover; a few signs of deterioration; small open lead d/s of bridge.
	0915	95.147	178.214	
	0930	95.177	178.244	
	0947	95.192	178.259	
	1003	95.208	178.275	
	1018	95.238	178.305	
	1037	95.284	178.351	
	1040			A part of the cover begins to move.
	1043	95.391	178.458	
	1046	95.452	178.519	
	1049			Movement stops.
	1051	95.482	178.549	No change in ice conditions, 1051 to 1850h.
	1058	95.528	178.595	
	1106	95.558	178.625	
	1114	95.512	178.579	
	1125	95.482	178.549	
	1143	95.421	178.488	
	1204	95.360	178.427	
	1225	95.299	178.366	
	1307	95.299	178.366	
	1405	95.345	178.412	
	1430	95.360	178.427	
	1515	95.406	178.473	
	1528	95.421	178.488	
	1546	95.436	178.503	
	1606	95.452	178.519	
	1623	95.467	178.534	
	1653	95.482	178.549	
	1743	95.512	178.579	
	1757	95.512	178.579	

TABLE C.3. WATER LEVELS AND ICE CONDITIONS AT SHERMAN BROWN BRIDGE

continued

Date Feb'81	Time	Stage-Arbitrary (m)	Stage-Approx. Geodetic (m)	Remarks
	1812	95.543	178.610	
	1826	95.543	178.610	
	1840	95.573	178.640	
	1850	95.573	178.640	
	2100			Ice cover u/s of bridge has moved out.
	2120			Large ice sheets moving in Chatham.
	2140	95.787	178.854	
	2208	95.817	178.884	
22	0700	95.863	178.930	[Ice jam near Louisville released at ≈ 0750 h]
	0836	96.244	179.311	Ice sheets moving d/s
	0843	96.335	179.402	
	0848	96.366	179.433	
	0852	96.396	179.463	Surface speed ≈ 1.5 m/s
	0857	96.427	179.494	Heavy flux of ice fragments - toe of jam
	0904	96.427	179.494	
	0918	96.427	179.494	
	0925	96.427	179.494	Surface speed ≈ 1.7 m/s
	0931	96.457	179.524	
	0947	96.549	179.616	Heavier flux of ice fragments
	0957	96.579	179.646	
	1009	96.610	179.677	
	1021	96.640	179.677	Ice flux begins to decrease
	1026	96.671	179.738	Head of jam under bridge
	1034	96.671	179.738	Scattered ice fragments
	1040	96.671	179.738	
	1045	96.671	179.738	Surface speed ≈ 1.7 m/s
	1052	96.671	179.738	

APPENDIX C

TABLE C.3. WATER LEVELS AND ICE CONDITIONS AT SHERMAN BROWN BRIDGE

continued

Date Feb'81	Time	Stage-Arbitrary (m)	Stage-Approx. Geodetic (m)	Remarks
22	1100	96.671	179.738	
	1115	96.655	179.722	
	1129	96.640	179.707	
	1145	96.625	179.692	Surface speed ≃ 1.7 m/s

APPENDIX C

TABLE C.4. WATER LEVELS AND ICE CONDITIONS AT 34.99 km (1.20 km UPSTREAM OF SHERMAN BROWN BRIDGE)

Date Feb'81	Time	Stage-Arbitrary (m)	Stage-Approx. Geodetic (m)	Remarks
21	1145	95.597	178.664	Competent ice cover; open lead u/s
	1440	95.557	178.624	No change,Surface water speed=0.6-0.9 m/s
	1537	95.617	178.684	No change,Surface water speed=0.6-0.9 m/s
	1606	95.687	178.754	No change,Surface water speed=0.6-0.9 m/s
	1800	95.707	178.774	No change,Surface water speed=0.6-0.9 m/s
22	0820	96.497	179.564	Ice cover moving; surface speed ≈ 1.5 m/s
	0839	96.557	179.624	[Ice jam near Louisville released at ≈ 0750 h]
	0846	96.617	179.684	
	0853	96.647	179.714	Heavy flux of ice fragments - toe of jam
	0920	96.747	179.814	
	0927	96.757	179.824	Surface speed ≈ 1.2 m/s
	0938	96.807	179.874	Surface speed ≈ 1.2 m/s
	0944	96.837	179.904	
	1020	≈ 96.947	180.014	Head of jam arrives
	1025	96.917	179.984	
	1032	96.897	179.964	Mostly open water, scattered ice fragments
	1138	96.847	179.914	

TABLE C.5. WATER LEVELS AND ICE CONDITIONS AT RIVER MOUTH (BY LIGHTHOUSE)

Date Feb'81	Time	Stage-Arbitrary (m)	Stage-Approx. Geodetic (m)	Remarks
22	1300		175.41	Competent ice cover; toe of jam moving in at bend u/s.
	1315			Stopped
	1320			Moving again
	1335		175.40	
	1344			Stopped
	1357		175.40	
	1415		175.40	
	1435		175.40	
	1505		175.41	
	1530		175.43	Open lead at right side of jam toe
	1602		175.43	
	1642		175.43	Open lead starts to develop ~200 m d/s jam toe and lengthens.

FIGURES

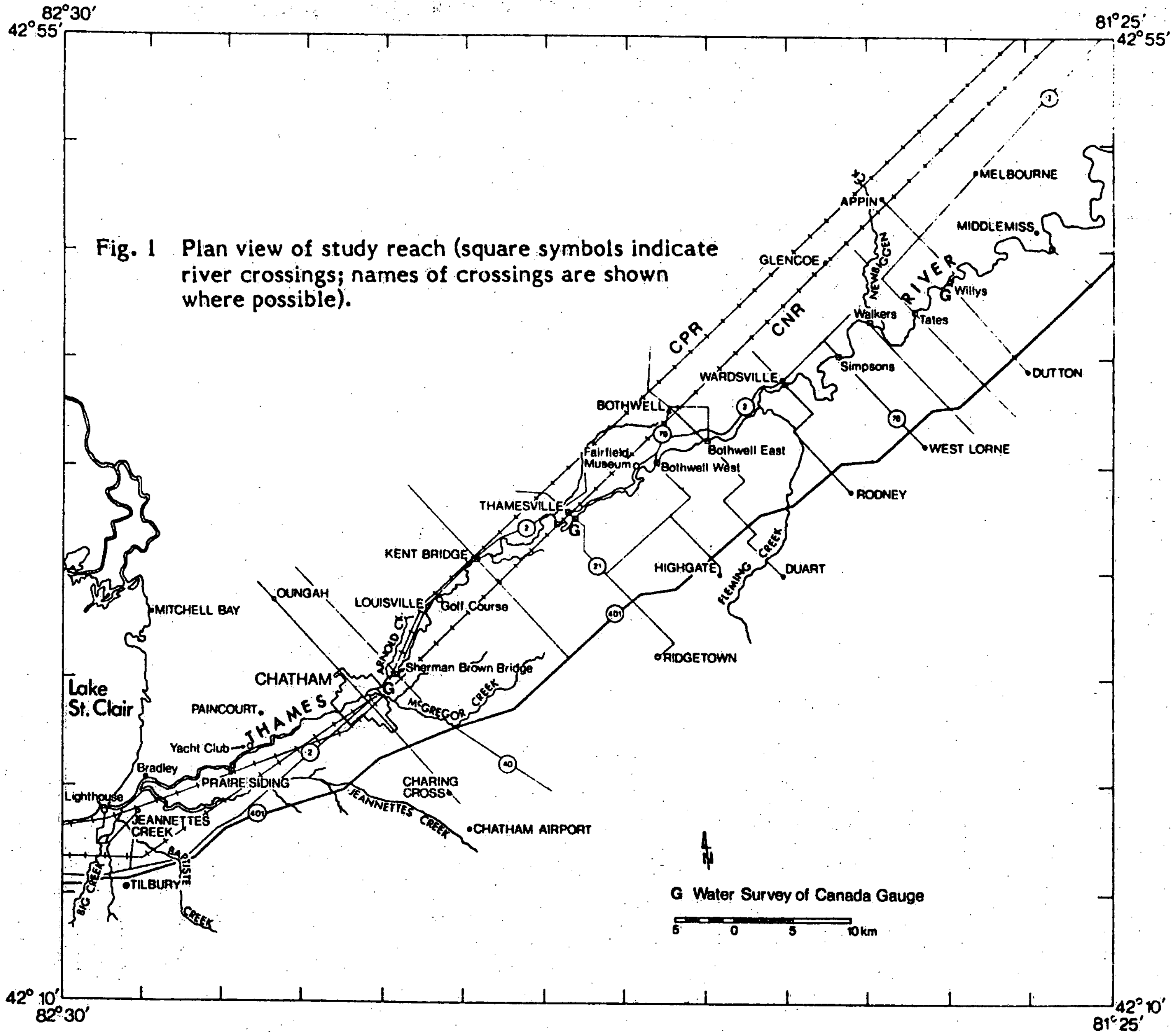


Fig. 1 Plan view of study reach (square symbols indicate river crossings; names of crossings are shown where possible).

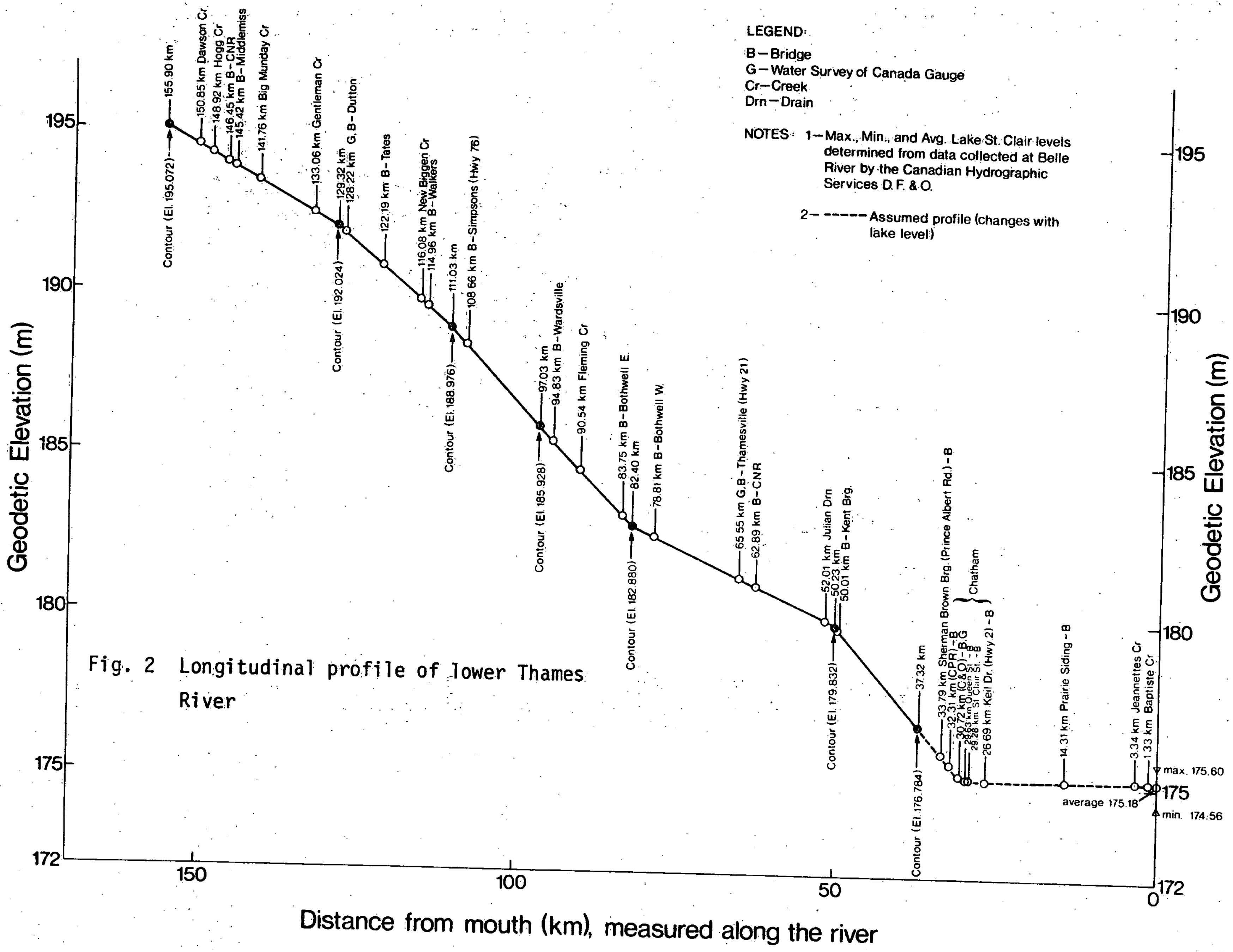


Fig. 2 Longitudinal profile of lower Thames River

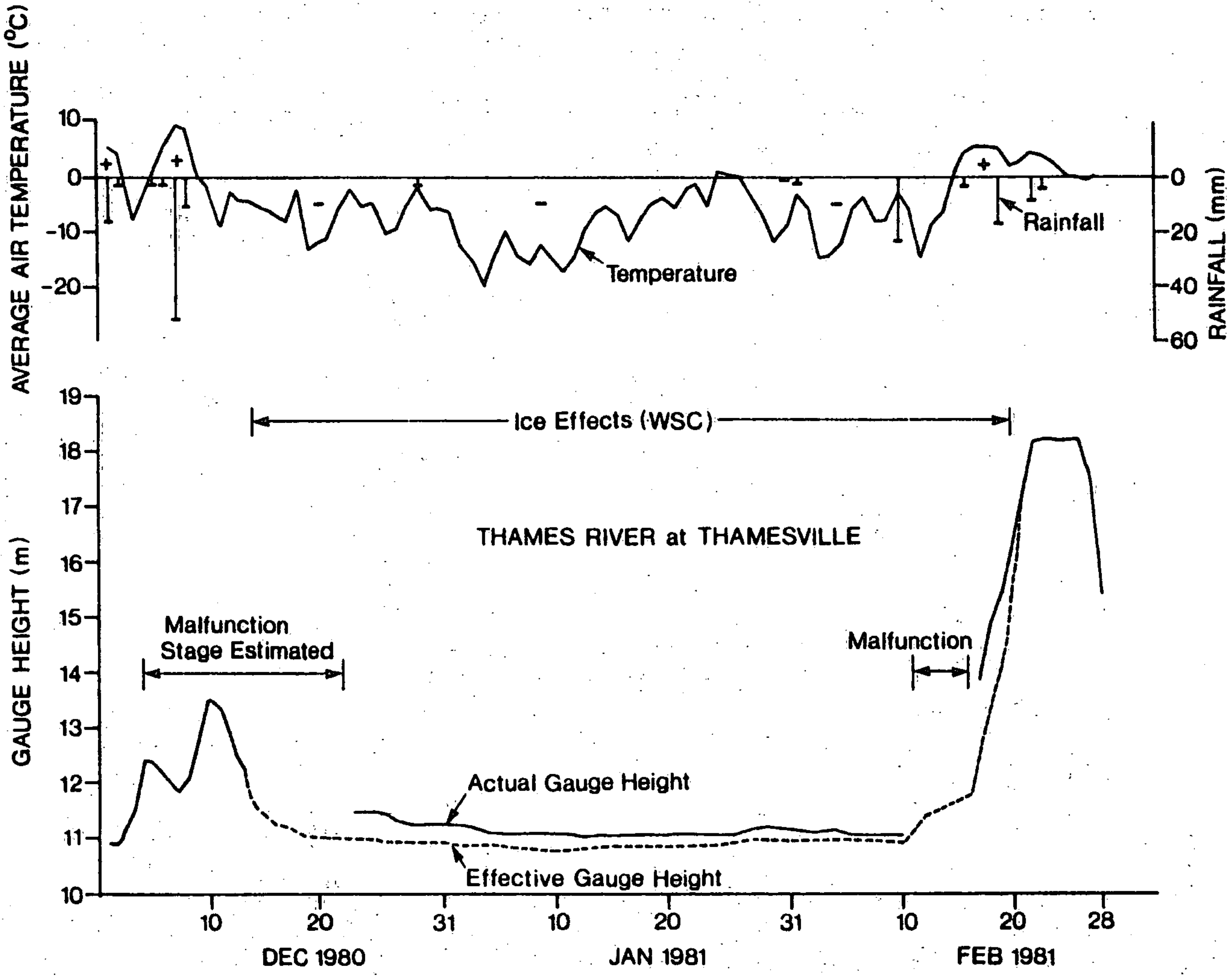


Fig. 3 Daily Meteorological data and water levels near Thamesville (Effective gauge height = gauge height for same dishcharge under open water conditions).

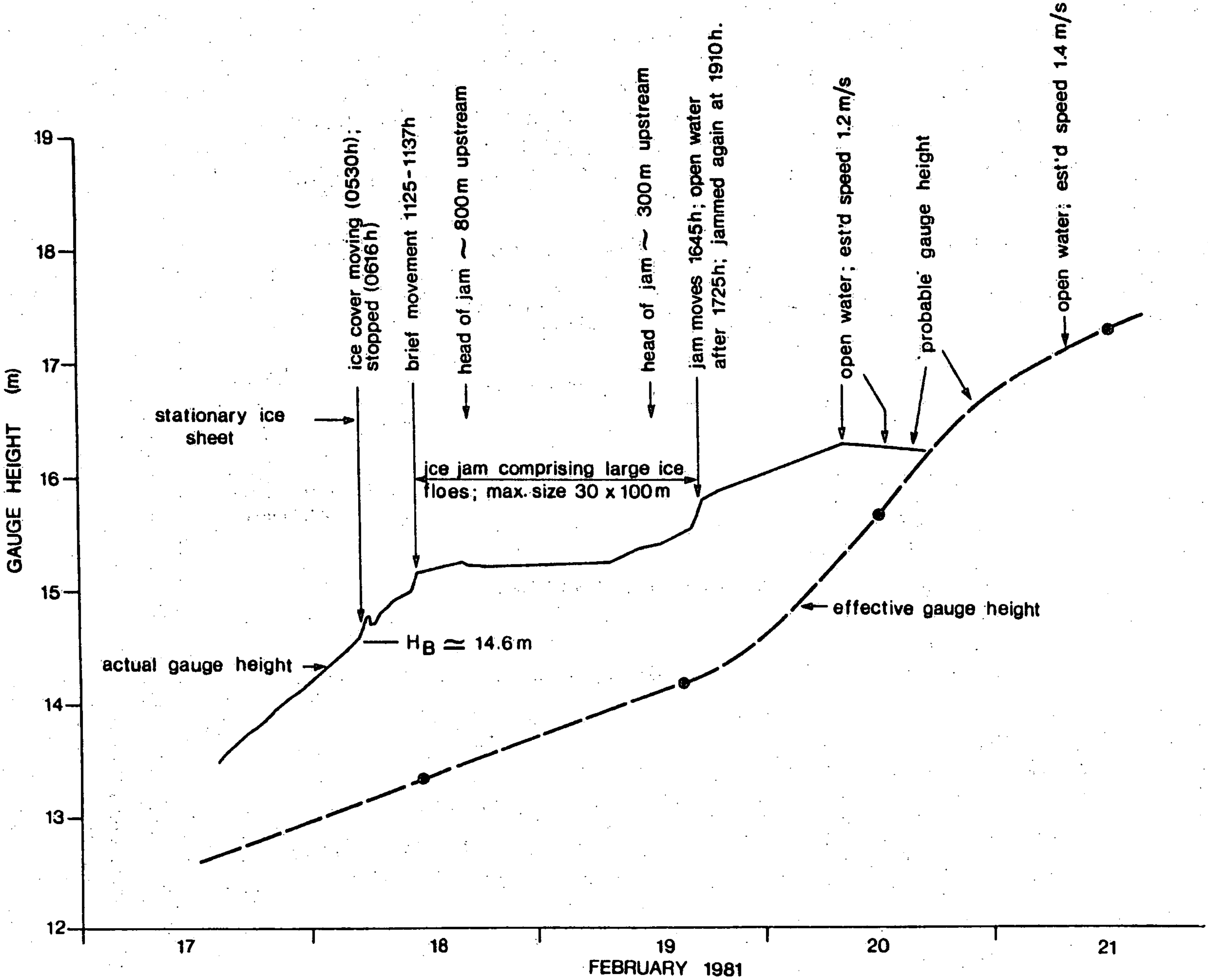


Fig. 4 Variation of stage at Thamesville gauge during the breakup period.

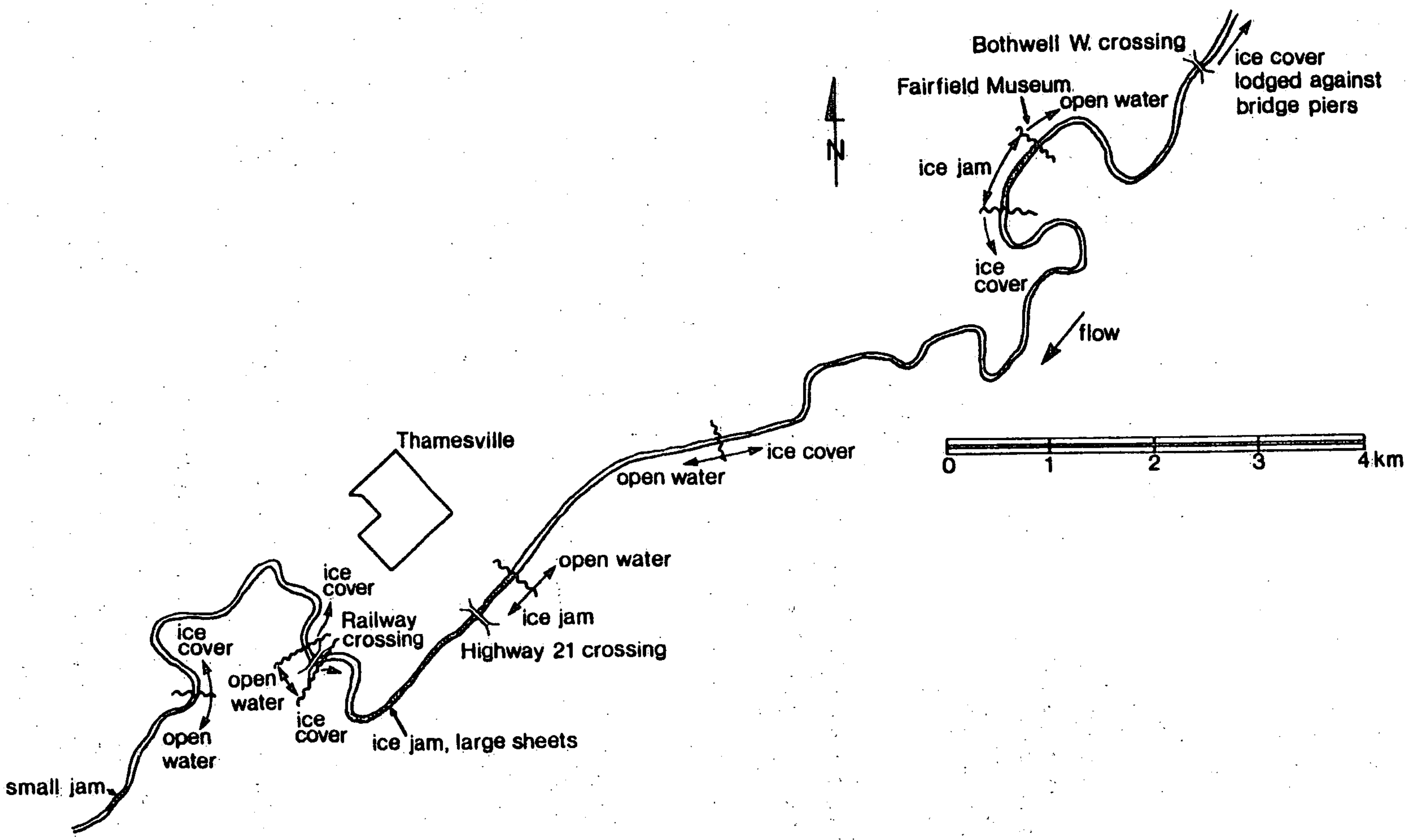


Fig. 5 Ice conditions near Thamesville, 0930h - 1200h, February 18, 1981.

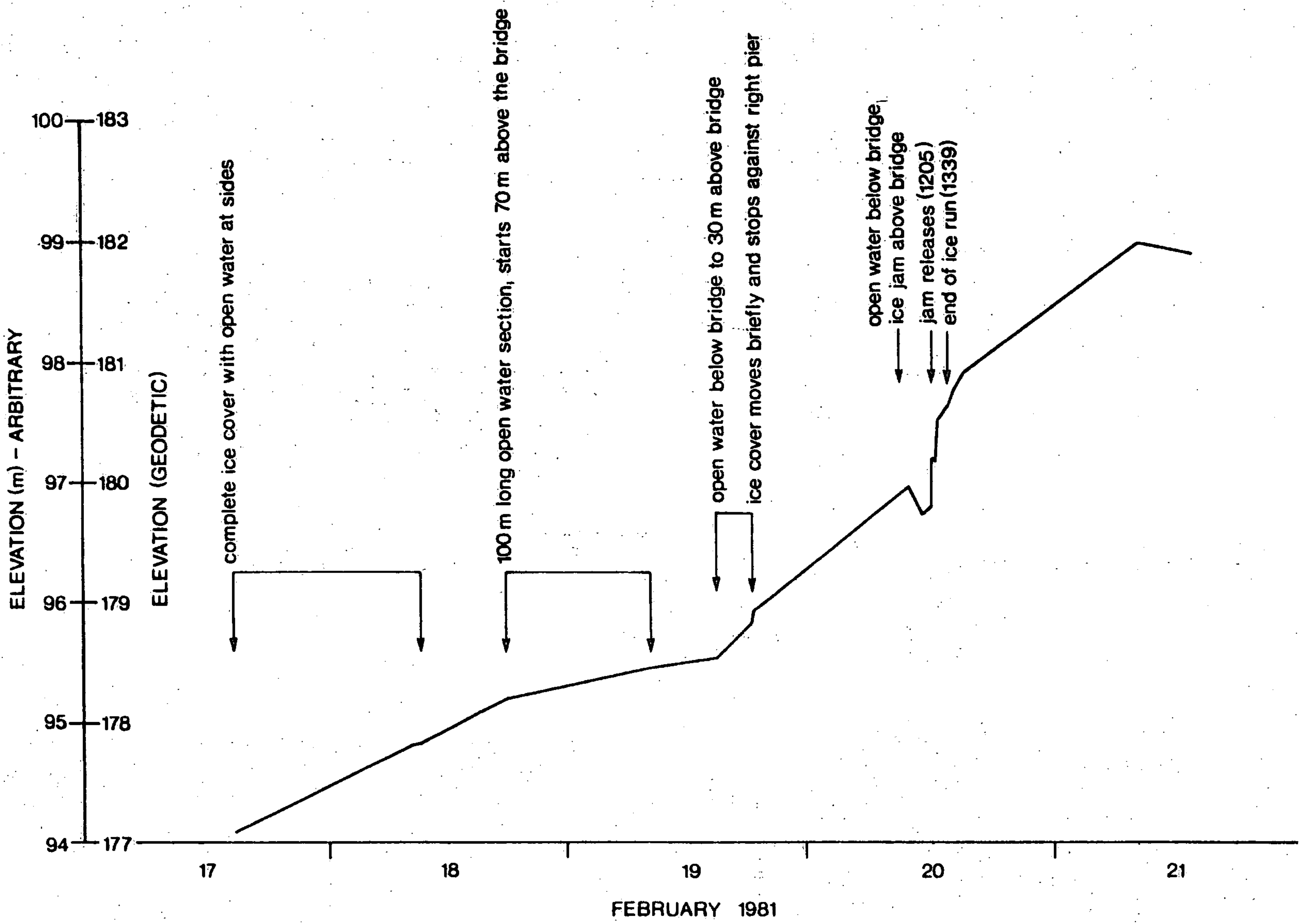


Fig. 6a Stage variation at Kent Bridge during the breakup period.

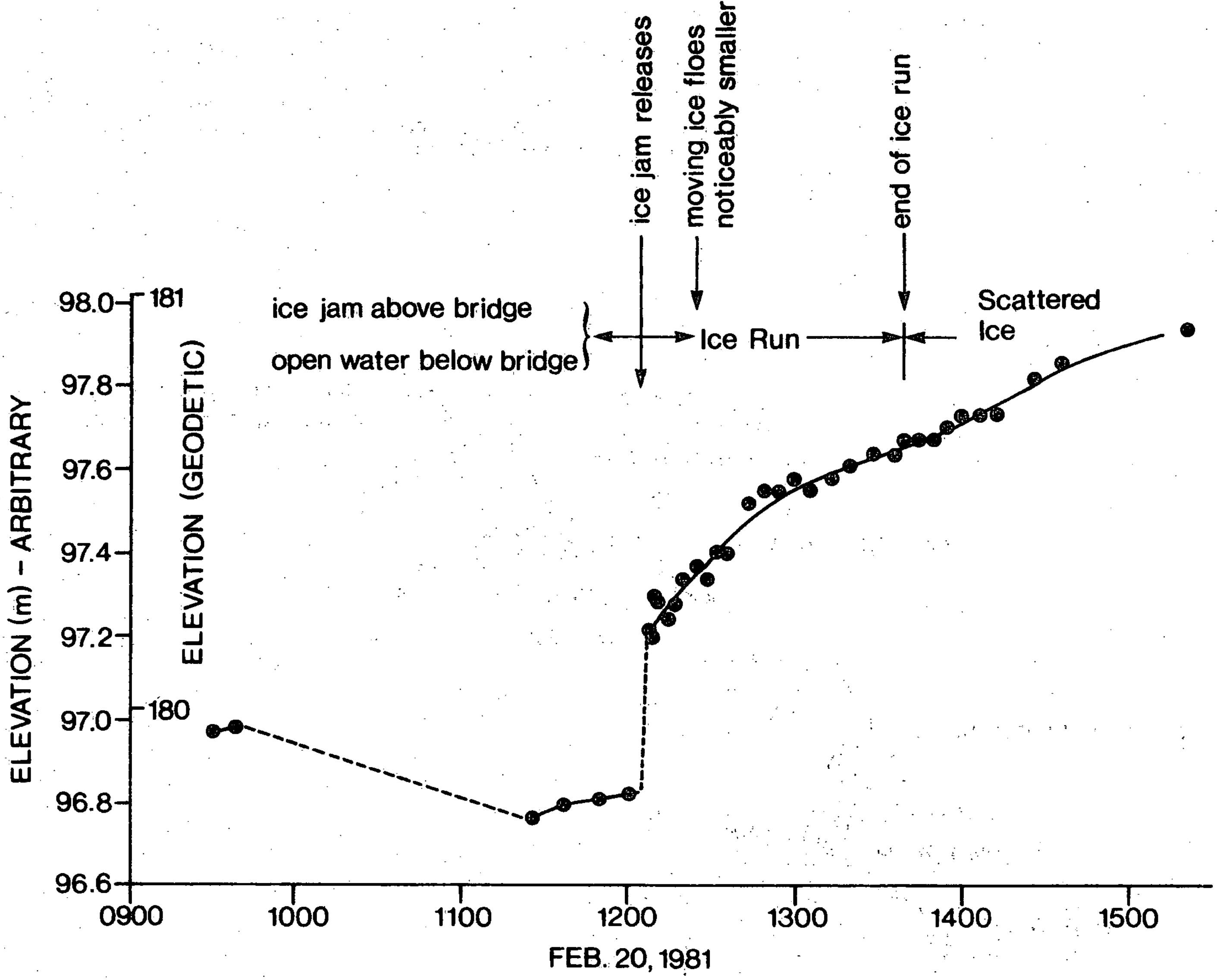


Fig. 6b Stage variation at Kent Bridge during release of ice jam, February 20, 1981.

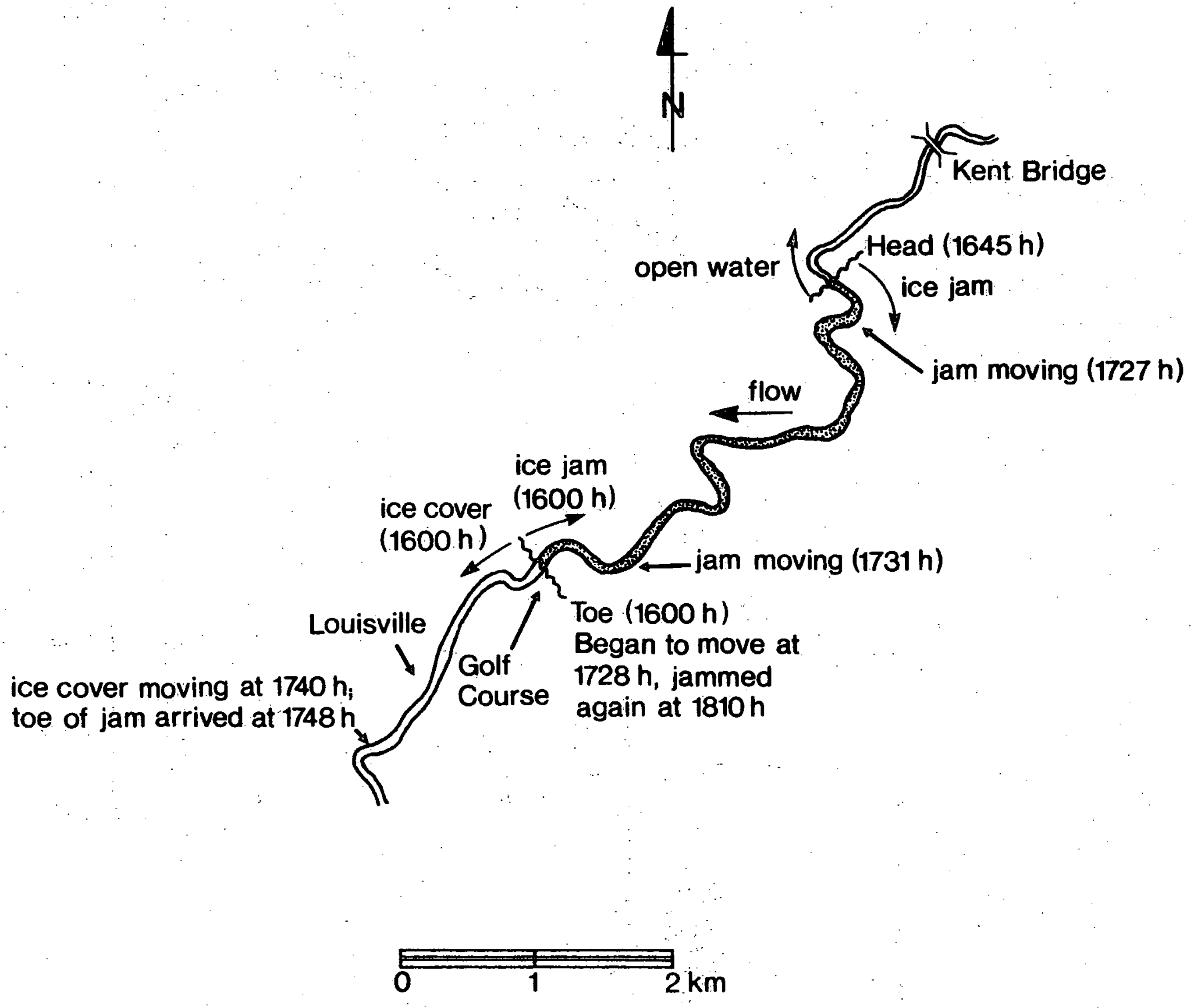


Fig. 7 Ice conditions near Louisville, 1600h - 1800h, February 20, 1981.

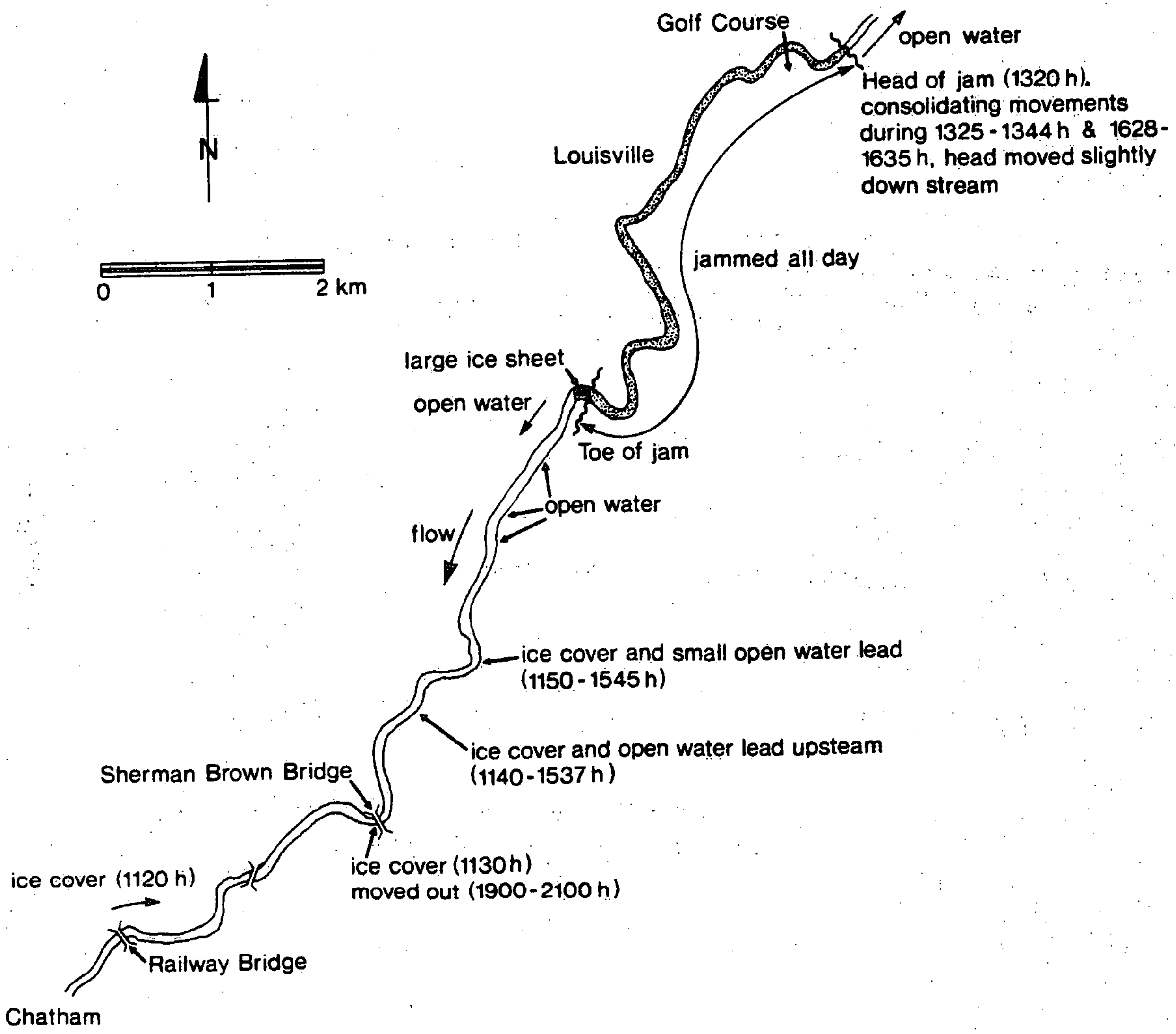


Fig. 8. Ice conditions above Chatham, February 21, 1981.

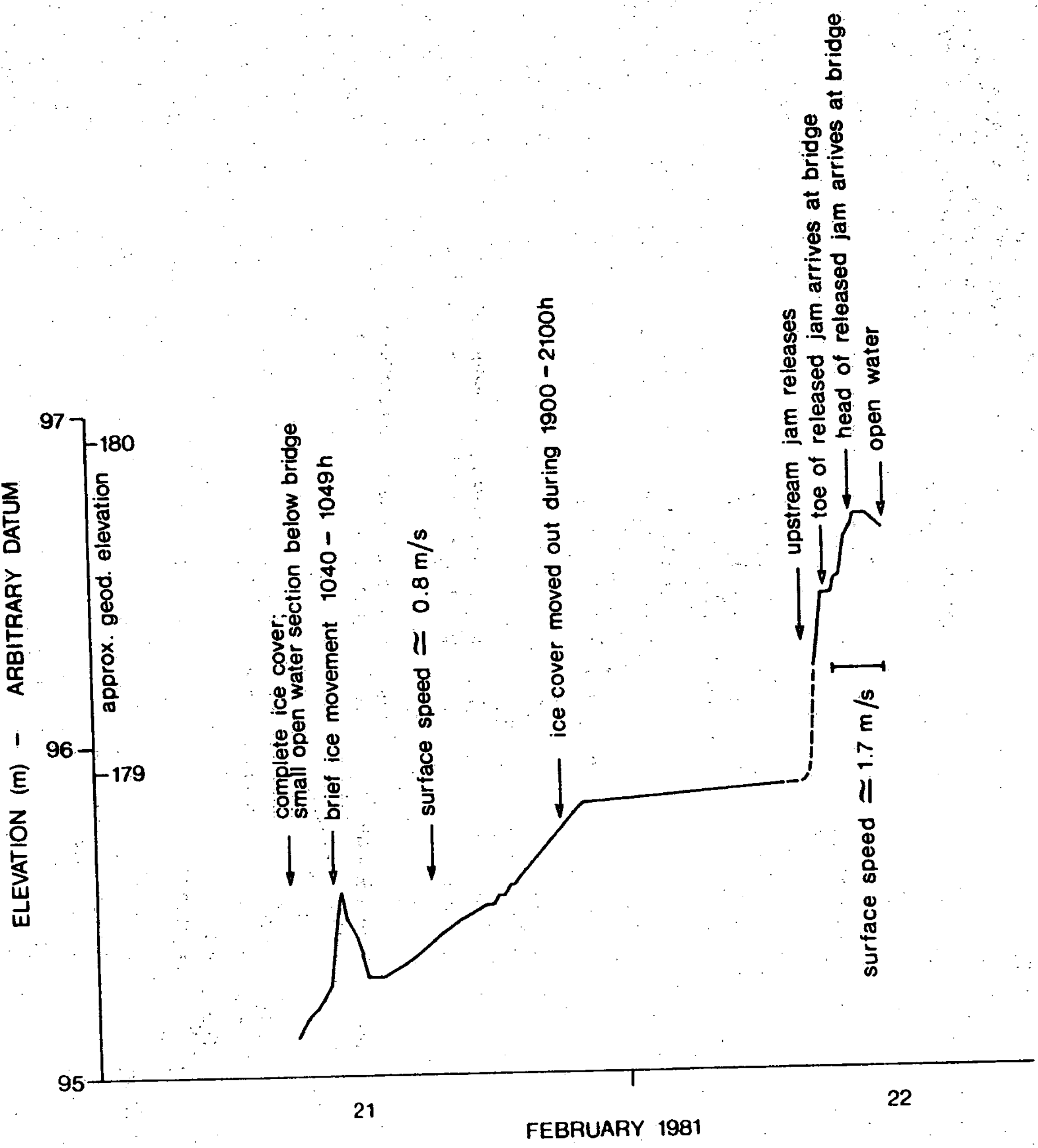


Fig. 9. Stage variation at Sherman Brown bridge during the breakup period.

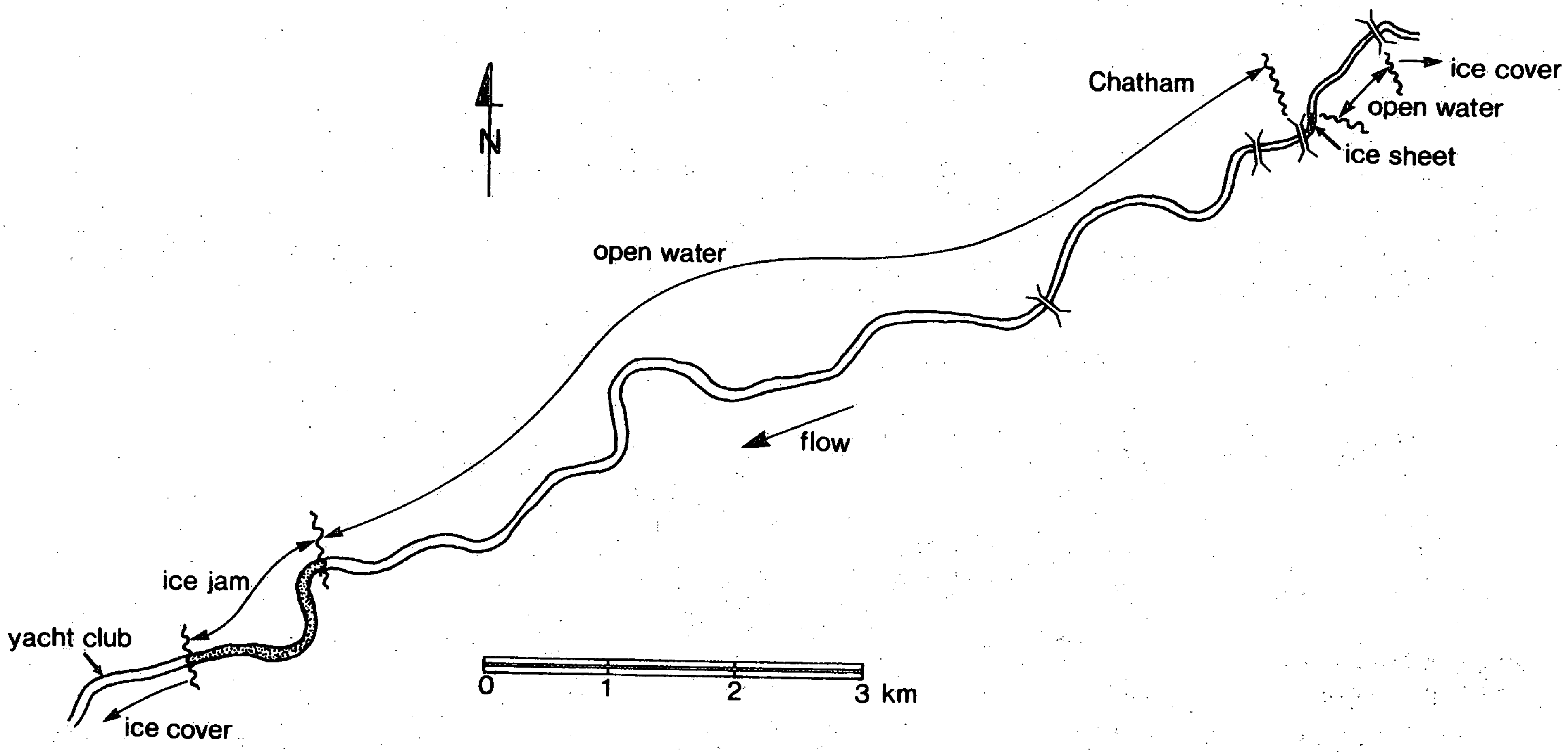


Fig. 10 Ice conditions below Chatham, 1000h - 1100h, February 21, 1981.

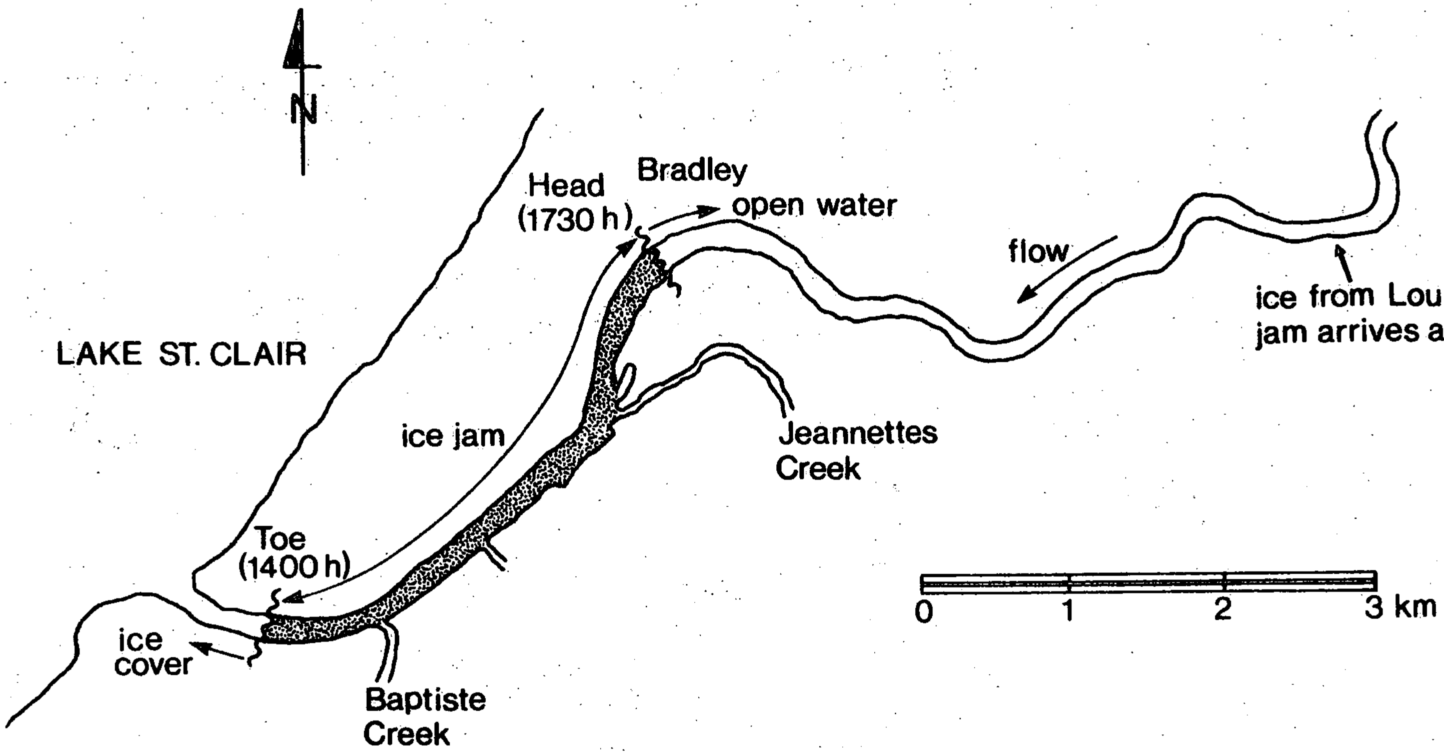


Fig. 11 Ice conditions near river mouth, 1400h - 1730h, February 22, 1981

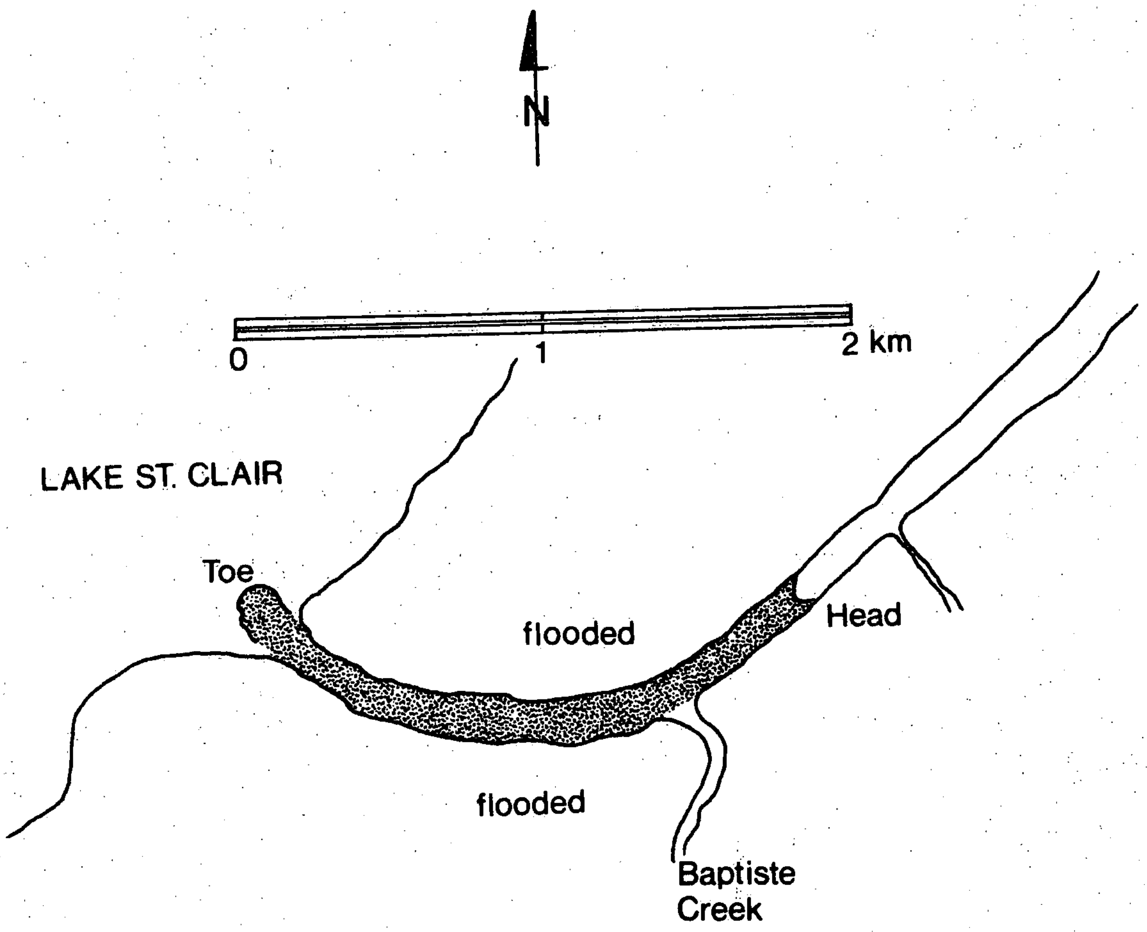


Fig. 12 Ice conditions near river mouth, morning of February 23, 1981.

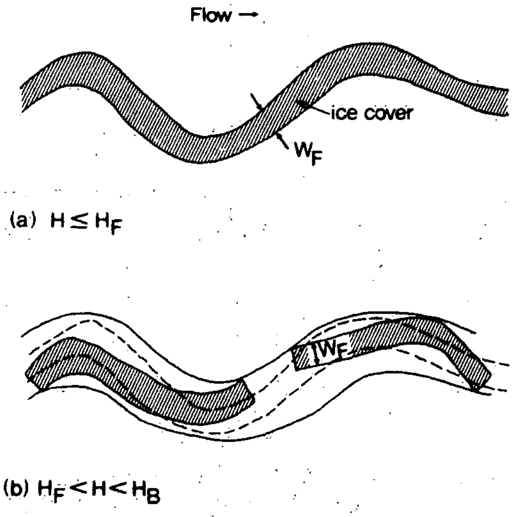


Fig. 13 "Loose" arrangement of large ice sheets.

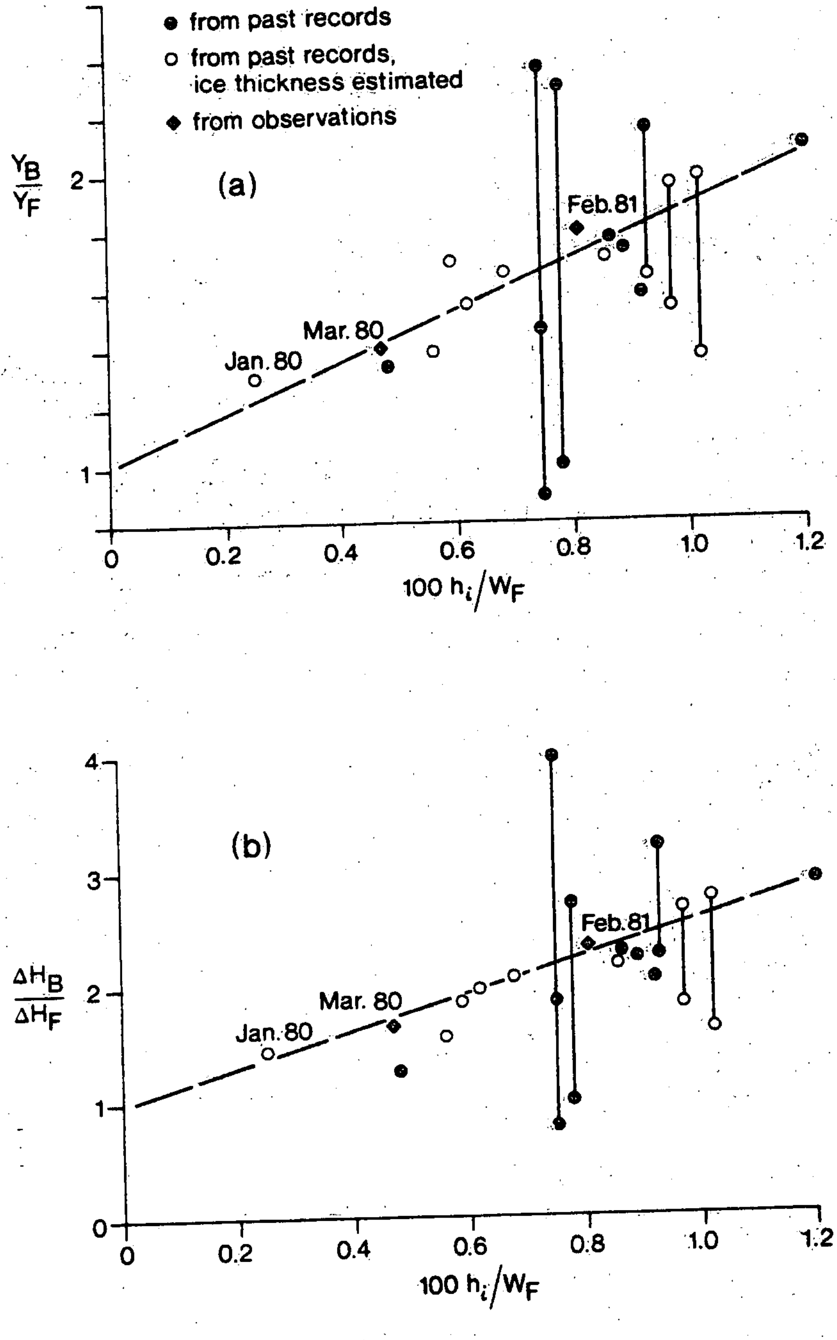


Fig. 14 Dimensionless breakup initiation stages and depths versus dimensionless ice thickness, Thames R. at Thamesville.

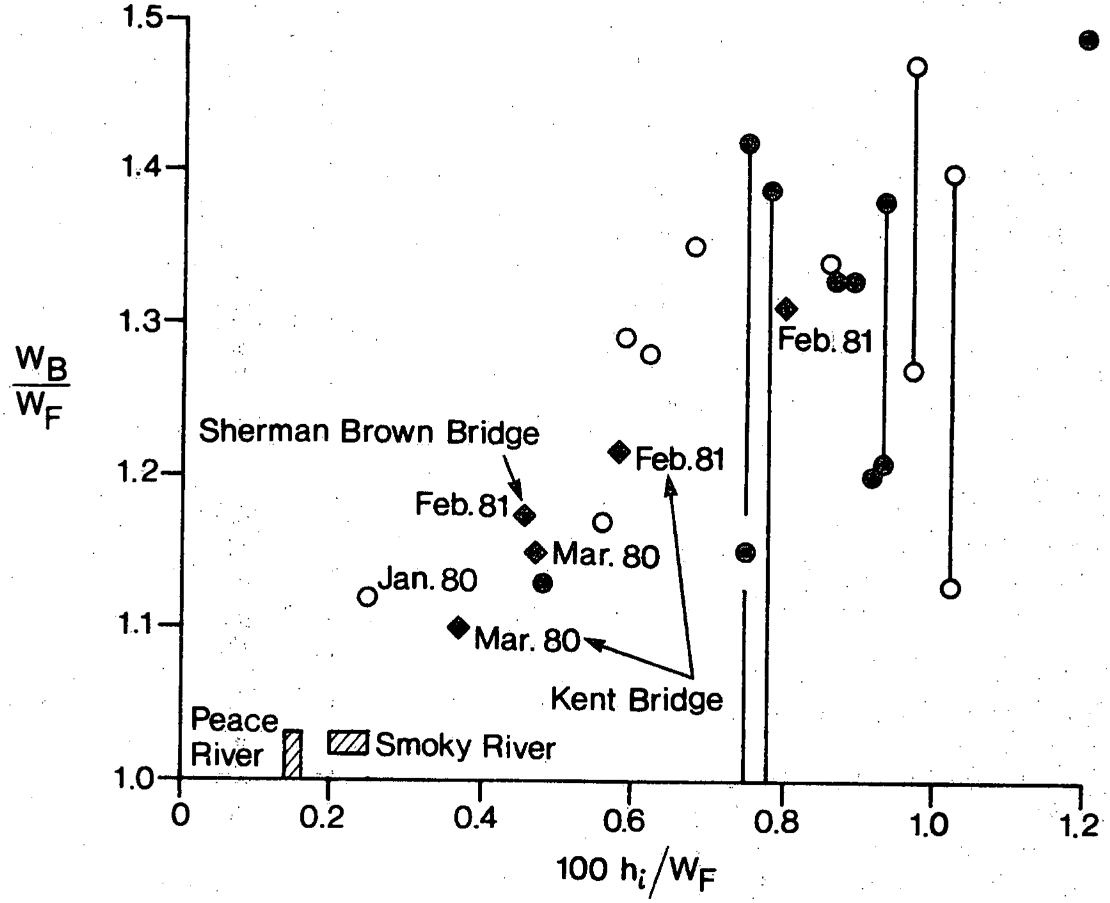


Fig. 15 Dimensionless breakup initiation width versus dimensionless ice thickness. Unidentified data points are for the Thamesville gauge. Legend is same as for Fig. 14.

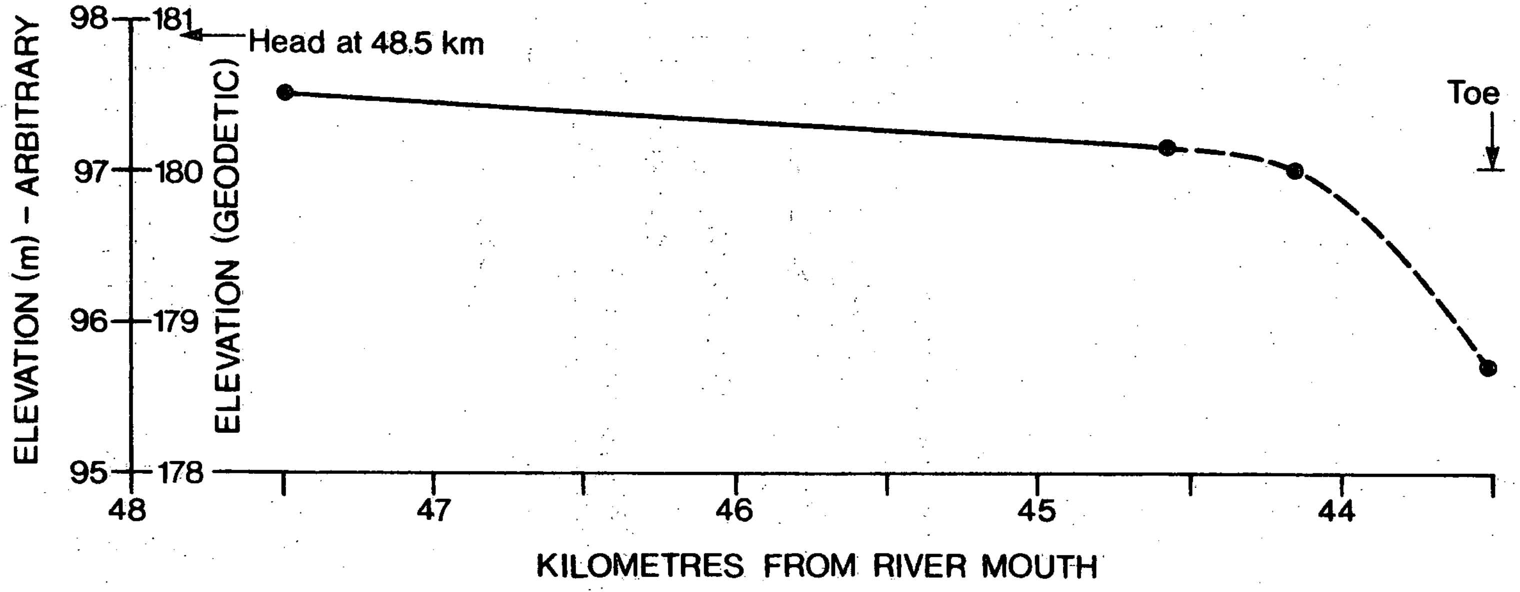


Fig. 16 Water surface profile of ice jam near Golf Course, 1620h - 1700h, February 20, 1981.

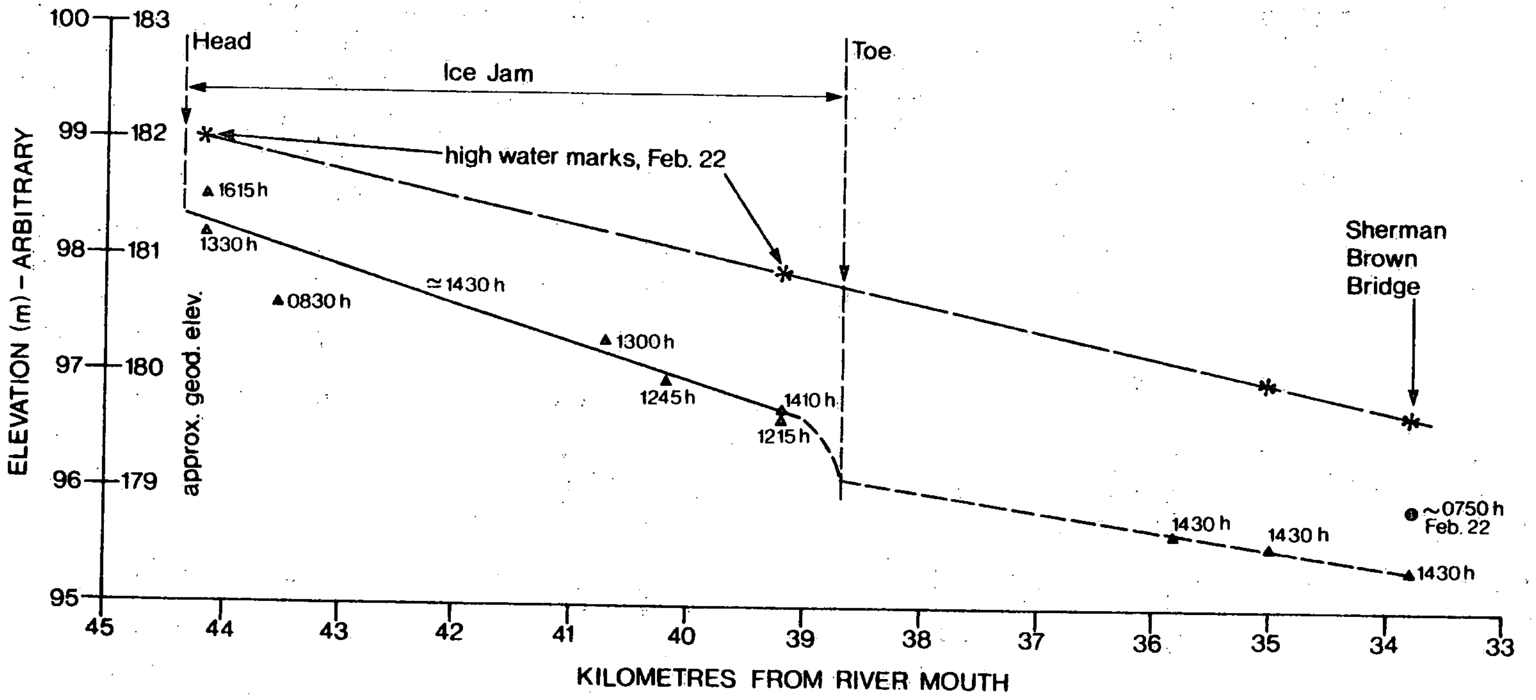


Fig. 17 Water surface profile of ice jam near Louisville, February 21, 1981.

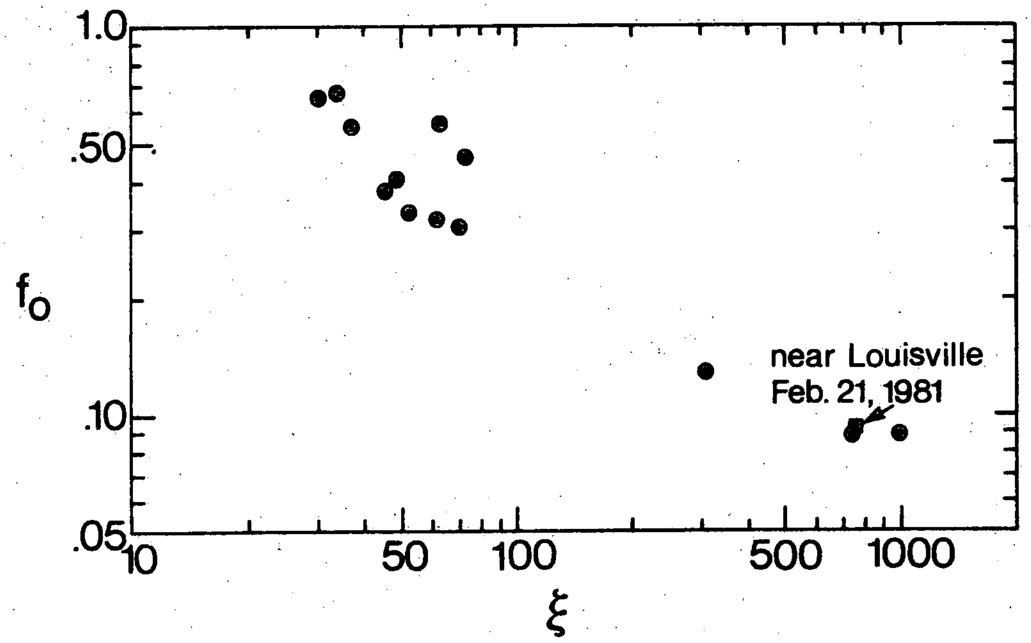


Fig. 18 Variation of f_o with ξ

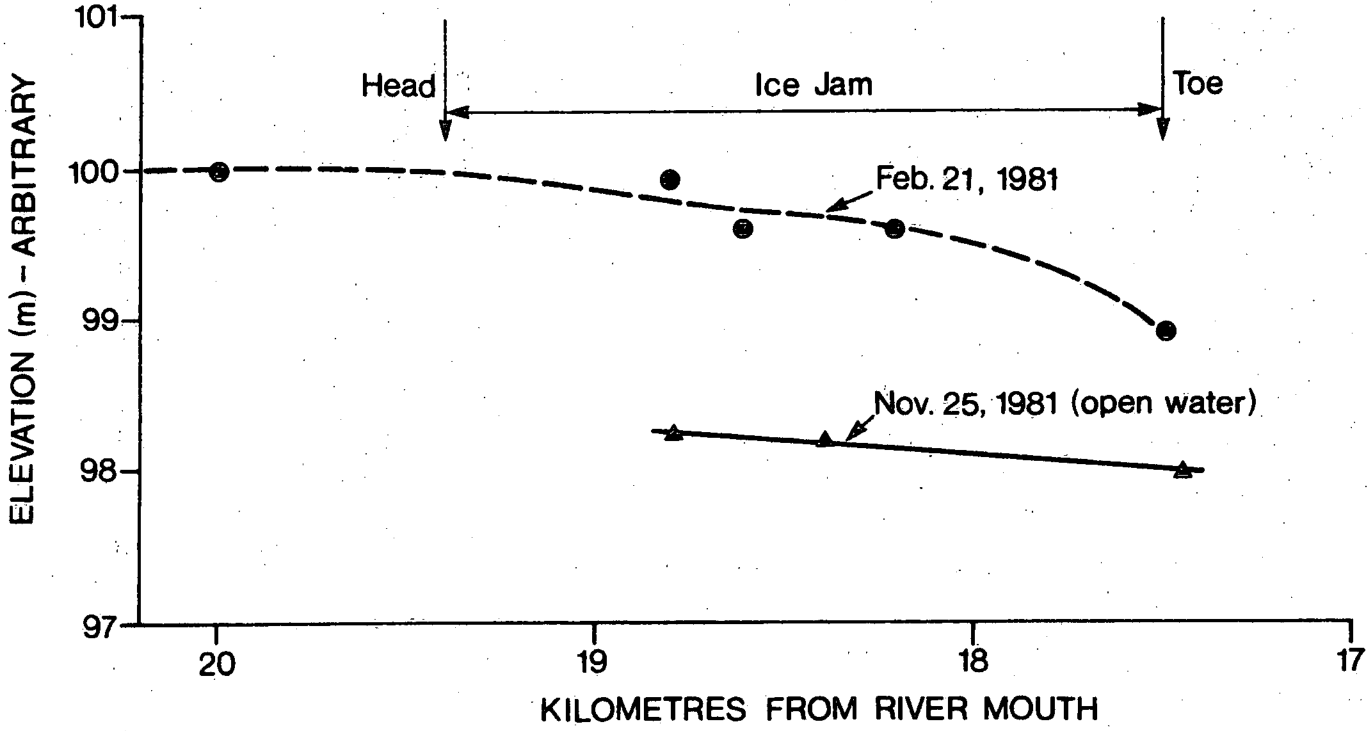


Fig. 19 Water surface profile of ice jam near Yacht Club, February 21, 1981.

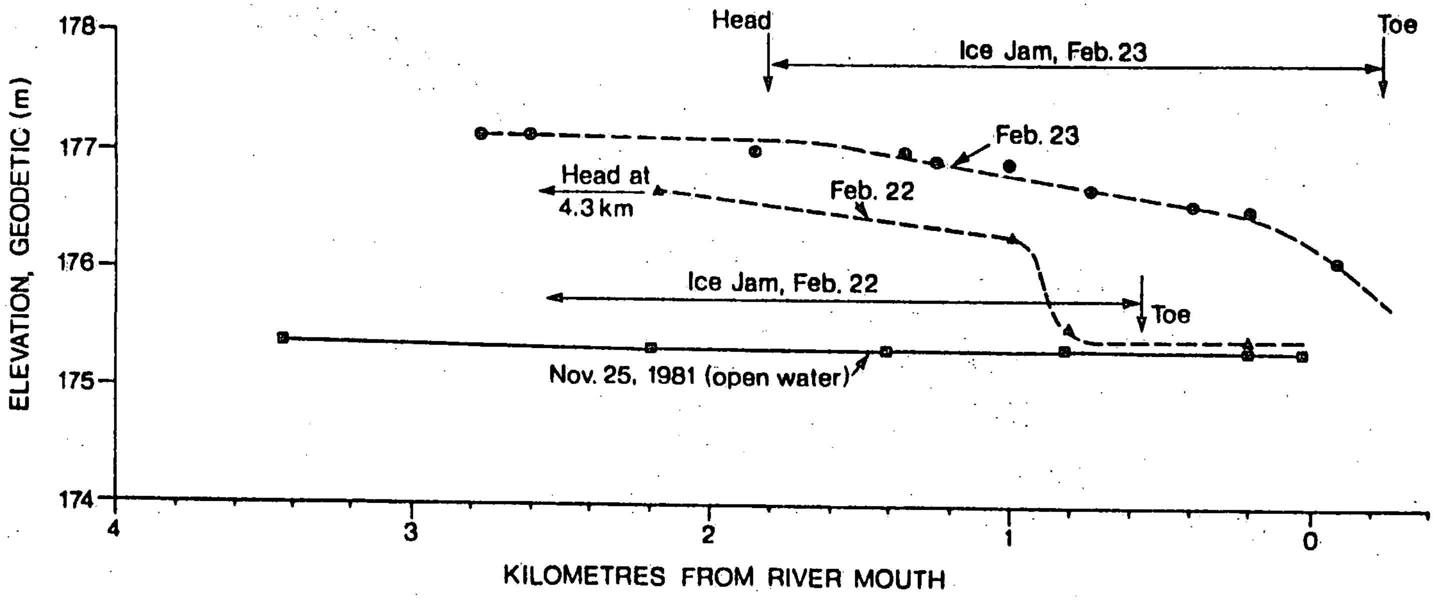


Fig. 20 Water surface profiles of ice jams near the river mouth, February 22 and 23, 1981.

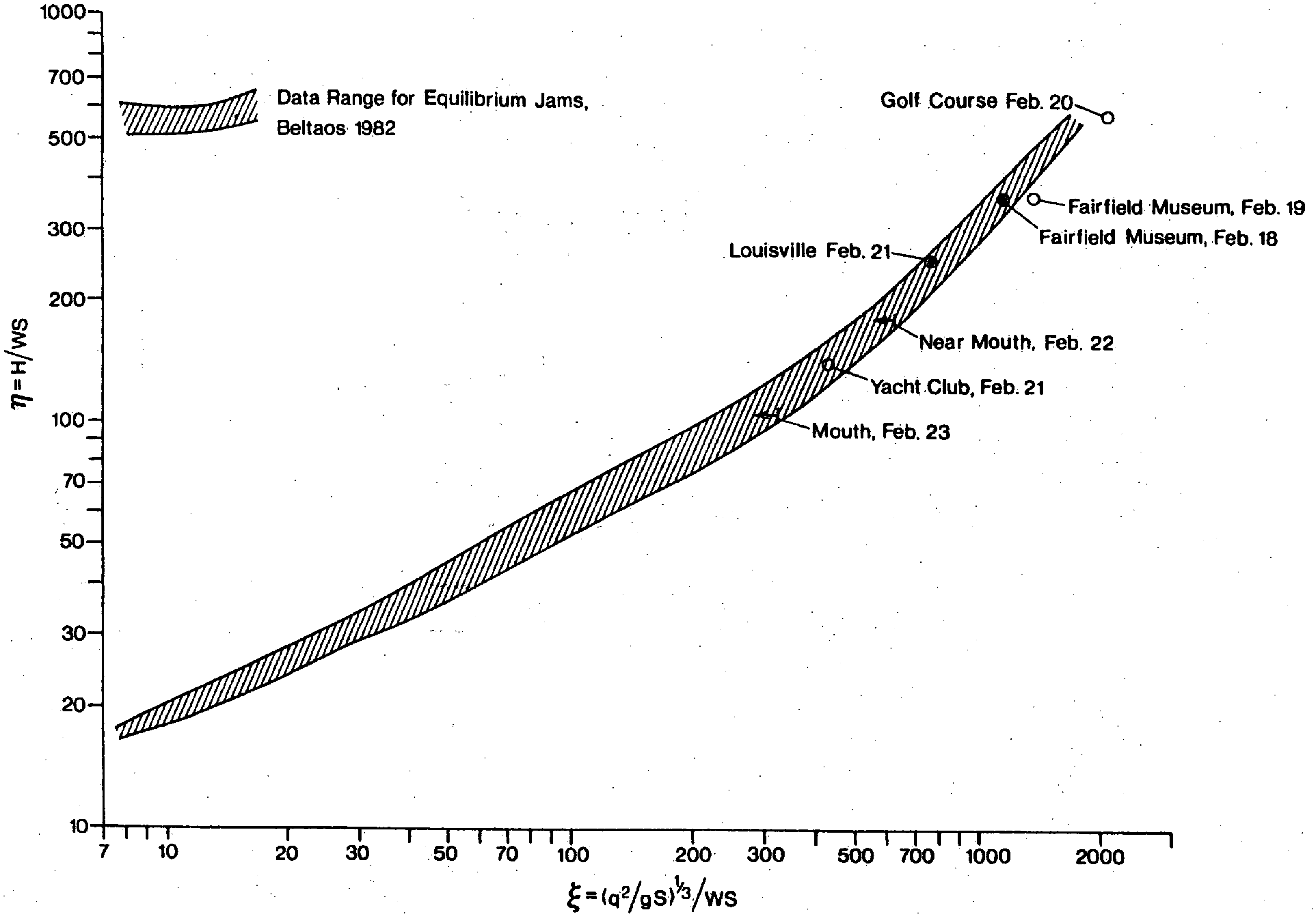


Fig. 21 Dimensionless jam stage versus dimensionless discharge (solid circles denote equilibrium jams).

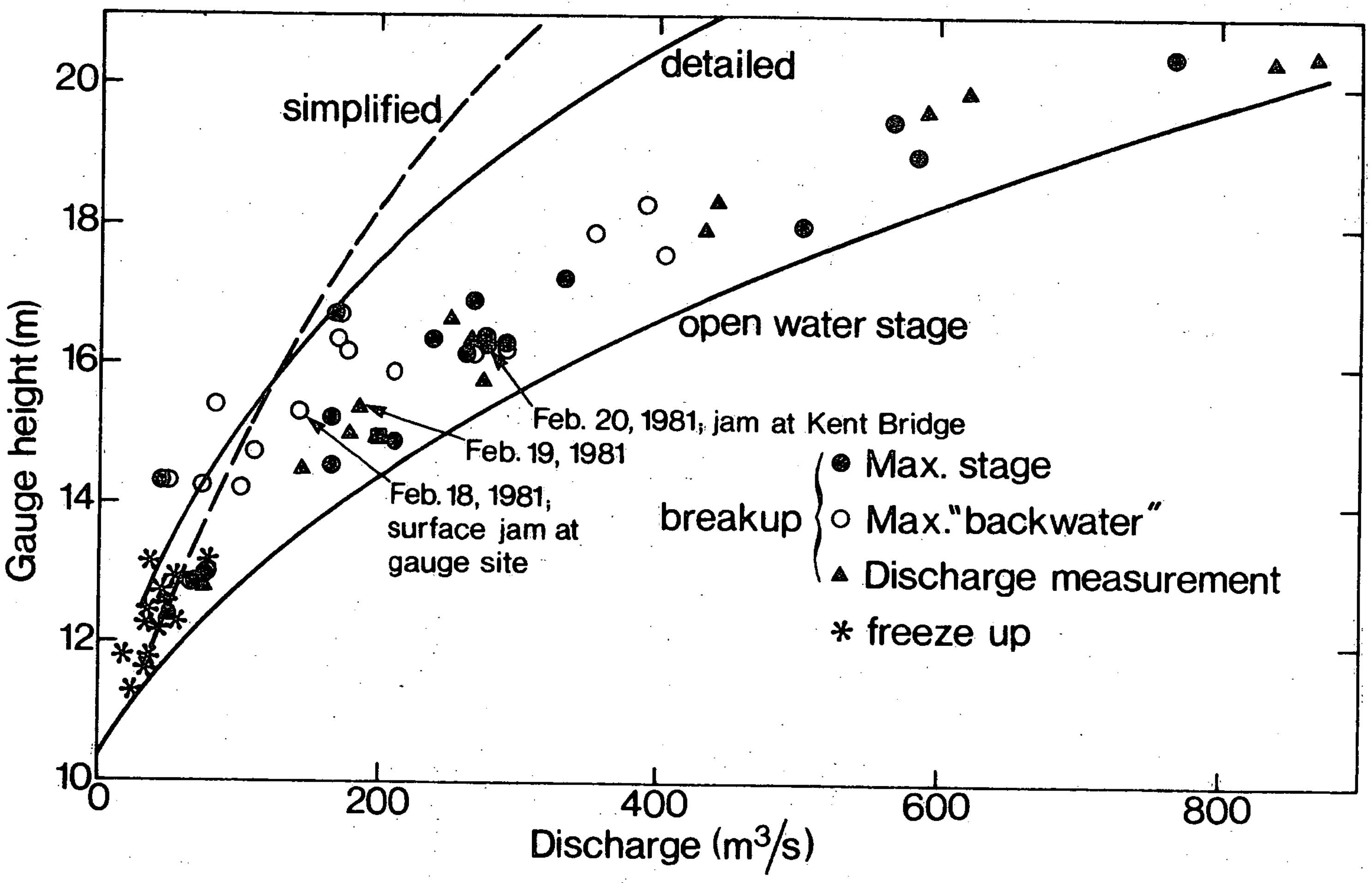


Fig. 22 Freeze up and breakup stages versus discharge; Thames R. at Thamesville.

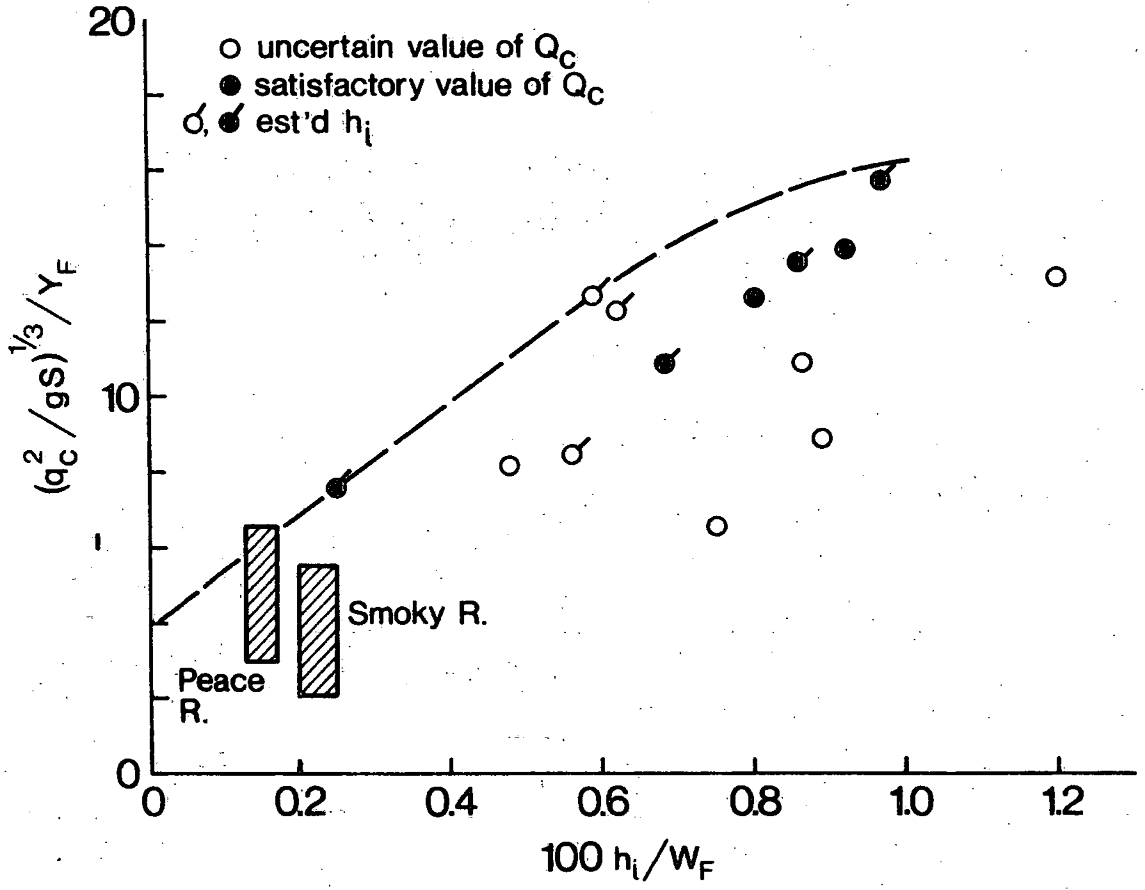
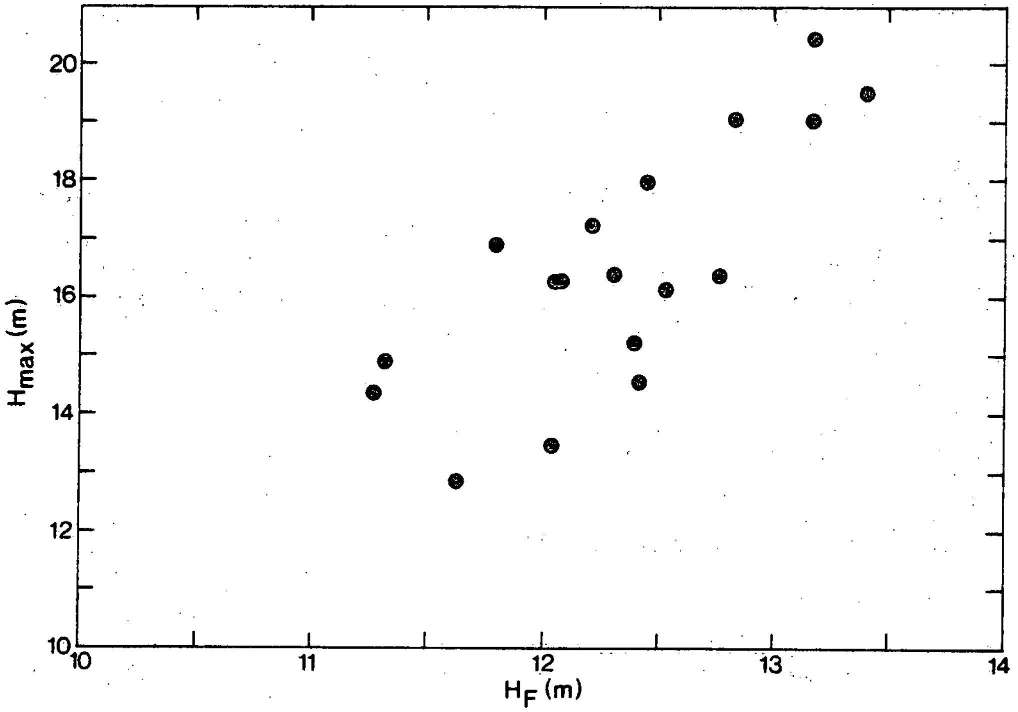


Fig. 23 Dimensionless "ice-clearing" discharge versus dimensionless ice thickness. Unidentified data points are for the Thamesville gauge.

Fig. 24 Maximum breakup stage versus H_F (Thamesville gauge).



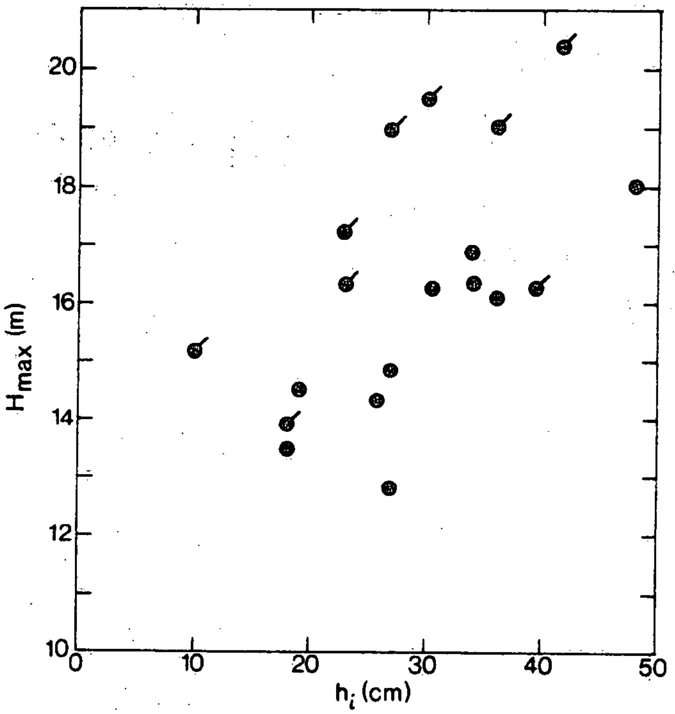


Fig. 25 Maximum breakup stage versus ice thickness (Thamesville gauge).

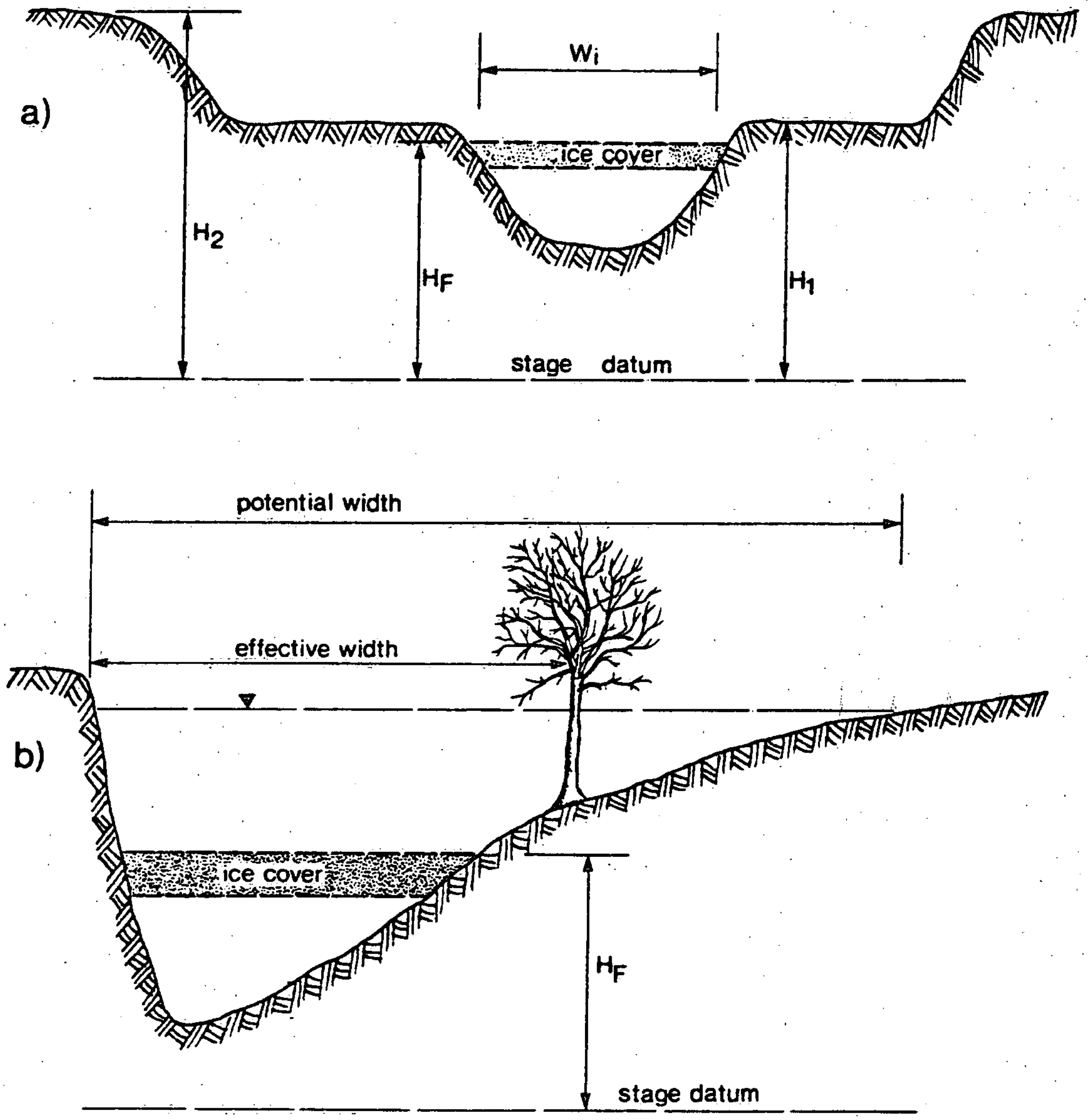


Fig. 26 Illustrations of:

(a) "efficient cross-section to reduce severity of breakup;

(b) detrimental effects of trees on channel banks.