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by

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Beltaos (42)

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## MANAGEMENT PERSPECTIVE

This is the fifth report from a continuing program of annual monitoring of ice processes aimed at developing solutions related to ice-jam flooding during breakup.

The data presented in this report support methods developed at NWRI to predict the onset of breakup and the release of ice jams in the upper portion of the study reach. The breakup process is more complex in the lower portion of the study reach due to the strong influence of Lake St. Clair on the water levels. Formulation of analogous predictive methods for this reach requires development of new knowledge on the interaction between an ice jam and the intact ice cover downstream.

Ice jam stages measured throughout the study reach support the use of an existing theory.

## PERSPECTIVE-GESTION

Ceci est le cinquième rapport d'un programme permanent de surveillance annuel d'amoncellement de glaces ayant pour but de trouver des solutions aux inondations provoquées par la débâcle.

Les données présentées dans ce rapport appuient les méthodes élaborées au INRE visant à prédire le début de la débâcle et le bris des embâcles dans la partie supérieure du bief à l'étude. Le phénomène de la débâcle est plus complexe dans la partie inférieure du bief à l'étude étant donné la forte influence du lac St. Clair sur le niveau de l'eau. Il faudra obtenir de nouvelles données sur les interactions entre l'embâcle et la couche de glace intacte en aval avant d'élaborer des méthodes de prédiction analogues pour ce bief.

Les embâcles mesurées dans ce bief confirment une théorie existante.

## ABSTRACT

Two breakup events occurred in 1984, one in February and one in March. The latter took place under conditions of low discharge and thin ice cover, thus causing no significant jamming. The February breakup, however, was similar to those of 1981 and 1982, occurring under conditions of intense runoff and fairly thick ice cover. Flooding caused by ice jams in 1984 was not as severe as that of 1981 and this was likely due to ice breaking operations near the river mouth, carried out as a remedial measure.

The 1984 observations have provided further confirmation of a previously developed conceptual model of breakup for the upper portion of the study reach. Here, the breakup process is fairly well understood and approximate forecasts of its onset and end are possible. However, much remains to be learned in the reach below Chatham where breakup is governed by intermittent, and so far unpredictable, movements of a jam.

Ice jam stages observed in 1984 adhere to a previously developed dimensionless relationship that is based on the theory of equilibrium jams.

# RÉSUMÉ

Deux débâcles se sont produites en 1984, une en février et l'autre en mars. La dernière a eu lieu dans des conditions de faible débit et la couche de glace était mince, ce qui n'a pas causé d'embâcle important. Toutefois, la débâcle de février, semblable à celles qui se sont produites en 1981 et en 1982, était accompagnée d'un fort débit d'eau de ruissellement et d'une couche de glace assez épaisse. Les inondations causées par les embâcles en 1984 n'ont pas été aussi graves qu'en 1981, probablement à cause des mesures qui ont été prises pour briser la glace près de l'embouchure de la rivière.

Les observations de 1984 ont confirmé encore une fois un modèle théorique de débâcle précédemment élaboré pour cette partie du bief à l'étude. Le processus de débâcle qui intervient ainsi est assez bien connu et on peut prédire de façon approximative le moment où elle prendra fin. Toutefois, beaucoup d'aspects restent à élucider dans le bief en aval de Chatham où la débâcle est produite par des mouvements intermittents, et jusqu'à maintenant imprévisibles, des amoncellement de glace.

Les amoncellements de glace observés en 1984 confirment une relation sans dimension établie précédemment et basée sur la théorie des embâcles à l'équilibre.

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## 1.0 INTRODUCTION

A major component of the National Water Research Institute's ice jam research program is the annual documentation of ice regime and jamming in two southern Ontario river reaches, i.e., the lower Thames and the upper Grand Rivers. This is a long-term effort, initiated in late 1979, aimed at both quantification of ice-related phenomena in the observation reaches and improvement of qualitative understanding as a guide to laboratory and theoretical research.

This report pertains to the Thames River and describes the results of the fourth year's observations. Earlier reports (Beltaos 1981, 1983, 1985a, 1985b) contain more detailed information on the rationale and objectives of the field observation program. The Thames River study reach extends from about Bothwell to the river mouth in Lake St. Clair (Fig. 1). An approximate water surface profile of the river, from the mouth to Middlemiss, is shown in Fig. 2. 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 are included in an earlier report (Beltaos, 1981).

## 2.0 FREEZE UP AND WINTER

Figure 3 shows that persistent cold weather began on December 15, 1983. In the morning of December 19, LTVCA* advised that an ice cover was already forming in Chatham. Field inspections were carried out during the next few days to document the expected formation of the ice cover above Chatham. The freeze up process is

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* Lower Thames Valley Conservation Authority

described next while illustrative photographs are included in Appendix B (#1-#6).

December 19 - From Dutton to Sherman Brown bridge, the river was open (1200 - 1420) but with varying amounts of pancake ice moving downstream. Through Chatham and downstream to the mouth, there was smooth ice cover (1430 - 1510). At 1535, the pancake ice was seen to move very slowly at Sherman Brown bridge. Thirty minutes later, the edge of stationary ice cover, composed of surface juxtaposition of ice pancakes, was located about 400 m below Sherman Brown bridge. The ice edge advanced to the bridge within one hour, producing a small rise in the water level (see Table 1). The pancake ice was already hard and could not be broken by dropping a 5 kg weight used for water level measurements. The speed of advance of the ice edge during 1605 to 1700, is calculated as 0.42 km/h.

December 20 - At 1035, the ice edge was observed at a location about 2 km downstream of Kent Bridge which suggests an average rate of advance of 0.80 km/h since 1700 on December 19. By 1315, the edge had advanced past Kent Bridge at a rate of about 0.9 km/h. The increased rate of advance appears to have been caused by the visibly increased ice discharge over that observed on the previous day.

December 22 - During 1100 to 1425, stationary ice cover was observed throughout the reach Thamesville to Sherman Brown bridge.

From the above description and the water level readings shown in Table 1, it is estimated that the stationary ice edge advanced to Thamesville sometime between 1620, December 10 and 0840 December 21. The corresponding value of $H_F$ (= stage at formation of a stable ice cover) is taken as the daily average for December 21, i.e., $H_F$ = 12.50 m. Similarly, $H_F$ is estimated as 176.98 m and 175.75 m for Kent Bridge and Sherman Brown bridge respectively. The formation of the ice cover at Thamesville occurred at a discharge of about 86.5 $m^3/s$* and following 66°C-days of frost.

Subsequent to ice cover formation in the study reach, the weather remained cold for about two months. During this time, the thickness of the ice cover was monitored by LTVCA (Lower Thames Valley Conservation Authority) while occasional measurements at Thamesville were made by Water Survey of Canada in conjunction with flow metering operations. These measurements are summarized in Table 2. Noteworthy is the decrease in thickness between January 30 and February 13, 1984.

## 3.0 FEBRUARY BREAKUP

Figure 3 shows that mild weather began on February 9 with 7 mm of rain falling on February 10 and 35.6 mm on February 13. The increased runoff led to breakup of the ice cover and complete clearance of the ice from the river by early morning of February 17. At Thamesville, the peak discharge during this runoff event was about 716 $m^3/s$, occurring on February 17. Flooding occurred throughout the study reach, becoming more serious and damaging in the downstream direction. A day-by-day account of the February breakup is given next.

<u>February 13</u> - The study reach between Bothwell West and Sherman Brown bridge was first inspected during 1130 to 1500 from various ground access points. There was intact ice cover throughout, with the exception of a 200 m long section below the mouth of a creek that enters the main river about 2 km upstream of the Highway 21 (Thamesville) bridge. A 100 m long surface jam was located just downstream of this section. Hinge cracks at the sides of the ice cover had already developed and there were side strips of open water whose width decreased in the downstream direction (Ph. #7,8). Occasional

* Water Survey of Canada records

transverse cracks were also noticed as far downstream as the golf course. Breakup was initiated at Thamesville between 1715 and 2045. At 2105, open water was also noted at the railway bridge near Thamesville but the ice cover at Kent Bridge was still intact at 2150. Detailed information on water levels and ice conditions at Thamesville, Kent Bridge and Sherman Brown bridge is presented in Fig. 4 and in Appendix A. Photographs of various features of the breakup are given in Appendix B.

February 14 - 0750-0900: Open water conditions prevailed from Bothwell to near Kent bridge. Measurements on ice blocks stranded on the right bank near Tecumseh Park (a few kilometres above Thamesville) indicated an average ice thickness of 26 cm with a range of 19-35 cm. At Kent Bridge, an ice jam had formed with its toe located 200 m downstream of the bridge (Ph. #9). The thickness of stranded ice blocks ranged from 22 to 30 cm and averaged 27 cm.

0900-1220: Downstream of the Kent bridge jam, the ice cover was mostly intact with open side strips and occasional open sections. More frequent transverse cracks were noticed. The longest open section began at the MacGregor Creek mouth and ended 1.3 km downstream. It was followed by a 200 m long surface jam and intact ice cover.

1350-1440: Ice conditions in the study reach were observed from the air, as illustrated in Fig. 5 and in various photos in Appendix B. Downstream of Chatham the ice cover appeared competent with minimal, if any, side strips of open water. Flooding in South Chatham was already occurring near Indian Creek (Ph. #17) where evacuation of a large area was advised (The Chatham Daily News, February 14, 1984). Numerous transverse cracks were noticed upstream of the LTVCA office, following a pattern similar to that observed in 1982 (Fig. 5, Ph. #15). Near the golf course, ice sheets were in motion at 1405, followed by a 500 m long open section and stationary but deteriorated ice upstream (Ph. #15). At the sharp bend downstream of Kent Bridge (Fig. 5) the toe of a jam was forming at 1407 as a large ice sheet was unable to negotiate the bend (Photos #10, 11, 12). Broken ice was moving in and consolidating above this location. This movement was the result of the release of the Kent Bridge jam at 1352. Simultaneous ground observations indicated that this release began at the toe of the jam (200 m below Kent Bridge) and within one minute, the entire jam was moving at about 3 m/s. This speed was quickly reduced, being 1.2-2 m/s at 1409. Very likely, the surge caused by the release was responsible for the moving ice noted near golf course at 1405 (estimated celerity = 9 m/s). It is noteworthy that while the surge may have lifted and set in motion the various ice sheets formed by earlier transverse cracking of the ice cover, it did not appear to cause any additional breakage except localized crushing between adjacent sheets.

1400-1930: The toe of the new jam below Kent Bridge stabilized shortly after it was observed at 1407 (Fig. 6, Ph. #13). Downstream of the jam, the ice cover continued to deteriorate with open sections developing near Louisville. Through Chatham, the river was mostly open. A 1 km long jam was noticed upstream of the Dolsen Cemetery (≈20 km above mouth). To help reduce possible flooding in the downstream reaches of the river, ice breaking operations commenced at the mouth (Ph. #18). At Thamseville, a discharge measurement was performed between 1810 and 2030 but considerable difficulty was experienced owing to interference by sporadic ice blocks transported by the current. After data processing, the discharge was calculated as 389 $m^3/s$ (Water Survey of Canada). The ice effect on the stage was 0.56 m, due to backwater from the jam near Kent Bridge, a distance of some 15 km.

February 15 - 0800-1030: The jam below Kent Bridge was still in place but released (Ph. #14) shortly after 1000 (LTVCA). Long open sections had developed between Kent Bridge and Sherman Brown bridge. The ice cover persisted to near the Chatham gauge location (30.7 km) but the river was open downstream to 15.0 km. Between 15.0 and 14.0 km (Prairie Siding) an ice jam had formed (Fig. 7).

1240-1310: The river was observed from the air and ice conditions are illustrated in Fig. 8. At the river mouth, a 400 m long section had been cleared of ice by ice breaking operations by the tug "Atomic" (Ph. #25). Upstream of this open area competent ice cover extended to Prairie Siding (Ph. #23, 24) where open leads had developed below the jam. Thee was open water and minor flooding upstream of the jam to the mouth of McGregor Creek in Chatham (Ph. #26). Further upstream, stationary ice cover prevailed to about 2 km above Sherman Brown bridge while moving ice was observed beyond this point (Fig. 8, Ph. #19). By noting the location of identifiable ice floes at different times, their speed was estimated as 1.4-1.5 m/s which is in close agreement with visual estimates by ground observers.

1500-1800: The moving ice (Fig. 8) was eventually arrested by stationary ice at Sherman Brown bridge, at about 1500, and a jam began to form. This jam released at 1603 (Ph. #20) and the ice run resumed. However, this movement ceased at 1700 suggesting that a new jam had formed not far downstream. At 1712, the toe of the new jam was found just upstream of the CP railway bridge (32.3 km). The jam was held in place by a large ice sheet lodged against the bridge piers (Ph. #26). Shortly afterward, holes began to form in the ice sheet near its downstream end but no ice blocks emerged downstream of the sheet. The water level at the toe remained stationary during this time. At 1748, irregular movements of the ice within the jam were noticed about 300 m upstream of the toe. The movements were then observed to occur closer and closer to the toe, arriving there at

1751 m. At this time, the ice sheet that held the jam was lifted slightly and then violently crushed against the bridge piers. This was followed by complete release of the jam and an ice run (Ph. #22). The resulting surge arrived at the next railway bridge (30.7 km) in about four minutes, i.e., with a celerity of about 6.6 m/s. Ice from the released jam arrived much later as expected*, and formed a new jam which released overnight.

2125-2145: The jam near Prairie Siding had advanced considerably as shown in Fig. 7.

Summary for February 15: The day started with two major jams in place. One near Kent Bridge and another near Prairie Siding. The former released at about 1015 and with intermittent stops, reformed at 1500 near Sherman Brown bridge. It released again at 1603 but reformed about 1.5 km downstream, held by an ice sheet lodged against the piers of the CP bridge. This new jam released at 1751 only to form again at the next railway bridge. Noteworthy was the unusual manner of release of the CP bridge jam which appeared to have been initiated within the main body of the jam, well upstream of the toe. The jam near Prairie Siding advanced slowly by intermittent releases to near St. Peter's Church. LTVCA reported that this jam released between 0040 and 0255 but reformed about 600 m downstream.

<u>February 16</u>: 0730-0845: The river was clear of ice except near the mouth where a jam was observed. The jam at the railway bridge that formed in the previous evening released at 0100 and had cleared the LTVCA office location by 0230 (LTVCA). By St. Peter's Church, ice piles were stranded on the river banks. The piled blocks consisted of good quality, blue ice, ranging in thickness from 21 to 37 cm and averaging 27 cm (Ph. #27).

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* The celerity of the surge, i.e., the rate of advance of the rise in water level, is known to exceed the actual water speed.

1345-1355: The river was observed from the air and ice conditions are illustrated in Fig. 9 (see also Photos #29, 30, 31, 32). Flooding was already evident and worsened as the day wore on. The ice breaking tug "Atomic" (Ph. #28) was stuck in jammed ice for part of the day.

February 17: The jam at the river mouth released at about 0500 (news item) and the river cleared shortly afterwards. Large areas adjacent to the river had been flooded, especially downstream of Jeannette's Creek (Gov't dock) where large ice piles were found (Ph. #33). Again, these consisted of blue ice, 22-38 cm thick with occasional "candling". Areas near the mouth were still flooded in late morning and deep washouts were encountered (see also Photos #34, 35, 36).

Summary of February breakup observations

The February 1984 breakup followed a pattern similar to that of previous years. It was caused by rainfall and initiated near Thamesville in the evening of February 13, progressing downstream thereafter. Below Chatham the breakup occurred independently of upstream ice conditions and consisted of intermittent movements of a jam that increased in length as it advanced.

Serious flooding occurred in Chatham near Indian Creek and later on, downstream of Chatham, especially near the river mouth. The tug "Atomic" was again used for ice breaking operations near the mouth where it cleared a large area to receive broken ice from upstream. The river was ice free by the morning of February 17.

## 4.0 MARCH BREAKUP

Figure 3 shows that cold weather resumed after February 25. A new ice cover was reported to be forming in Chatham (LTVCA). Consequently, the study reach was visited on March 10 and 11. It was found that a cover had already formed through most of the study reach.

There were occasional open sections between Bothwell and Chatham and frequent open leads through Chatham and downstream. Unlike the December freeze up when the cover comprised pancake ice as far downstream as Sherman Brown bridge, this time the pancake ice extended only to below Kent Bridge (Ph. #38). The ice cover was relatively smooth and uniform from the mouth to about 5 km downstream of Kent Bridge (Ph. #37). According to Matousek (1984) whether frazil slush or skim ice forms on the water surface depends on the ratio of the rising velocity of ice crystals, $u_i$, and the vertical fluctuating component of turbulence $v_z'$. The former depends on the initial size of ice crystals which in turn is dependent on the degree of supercooling of the water surface. The turbulence intensity, $v'_z$, depends on the average flow velocity as well as the roughness of the river bed. While the present data are not sufficient to enable a quantitative analysis of the matter, they are in qualitative agreement with Matousek's theory because the March freeze up occurred under lower flow ($\approx$45 $m^3/s$) and thence lower velocity than the December freeze up ($\approx$100 $m^3/s$).

From gauge readings and records, it is estimated that the stable freeze up levels, $H_F$, are 12.20 m for Thamesville (March 10); 176.20 m for Kent Bridge (March 10); and 175.70 m for Sherman Brown bridge (March 9).

The March freeze up occurred at a discharge of about 40.5 $m^3/s$ (Thamesville), after 102.5°C-days of frost. Ice thickness measurements by LTVCA on March 14 are summarized in Table 3. These values should be viewed as mere indications because they are mostly based on one or two measurements across the stream.

On March 14, the air temperature rose above 0°C and significant rainfall was forecast for the next two days. Accordingly, field observations commenced again in the evening of March 14. The anticipated breakup event was not expected to cause any problems or damage because of the relatively thin ice cover. However, it was considered important to document this event in order to test the various predictive methods developed so far under conditions of thin ice cover.

A day-by-day description of breakup events follows.

March 14: 1930-2245: Mostly ice cover with occasional open water sections and leads. See Appendix A for detailed descriptions and water levels at Thamesville, Kent Bridge and Sherman Brown bridge.

March 15: The temperature rose during the day but water levels remained steady owing to lack of rain which only started in late evening. Between Thamesville and Kent Bridge, the river was mostly ice-covered (Ph. #39). There were, however, occasional open water sections of substantial length. The frequency of open sections diminished sharply downstream of Kent Bridge.

March 16: Due to substantial rainfall that started in late evening of March 15, water levels began to rise at about 0300. This caused the ice cover to develop hinge cracks at the sides and then float higher so that open water strips became apparent near the shores. At Thamesville, the ice cover was set in motion near noon at a stage of 12.92-13.03 m (Ph. #40).

During 1530-1630, the river was inspected from the air. Sheet ice cover was present as far upstream as the west end of Thamesville. There were several open leads and a few open water sections. Upstream of Kent Bridge (Ph. #41) frequent transverse cracks were observed. They formed a pattern similar to those observed during the breakup events of March 1982 and February 1984 (Fig. 10, Ph. #42).

At Kent Bridge, breakup was initiated between 2040 and 2105 at a stage of about 177.40 m but downstream conditions changed little.

March 17: The weather turned cold overnight and new ice began to form. This was first noticed at Thamesville where newly formed frazil slush jams were moving downstream at a concentration of 10-20%.

0850-1000: Open water from Thamesville to 5.5 km below Kent Bridge. At Kent Bridge, the thickness of ice blocks stranded on the banks averaged 10 cm.

1000-1500: An ice run occured in the vicinity of the golf course, consisting of large ice sheets, followed by broken ice. By 1445, this run had been arrested and a short jam formed near Louisville. The average thickness of stranded blocks was 12 cm in this area (Ph. #43).

1700-1830: Aerial observation revealed considerable deterioration of the remaining ice cover, manifested by large open leads. The leads decreased in frequency and size in the downstream direction, almost disappearing by Prairie Siding.

March 18: 0730-1100: Ground observations revealed that ice conditions changed little overnight. The weather remained cold and water levels stabilized. Consequently observations were discontinued.

March 21: On March 20, the weather turned mild again with significant rain falling. Inspection on March 21 indicated open water to slightly downstream of Prairie Siding. Beyond this location, the river was mostly open with partial ice cover that appeared highly deteriorated.

Summary of March breakup observations

The March breakup took place under conditions of thin ice cover that had only formed a few days earlier. Rising runoff on March 16 initiated the breakup first at Thamesville and later on at Kent Bridge. Between Kent Bridge and Sherman Brown bridge, the breakup was effected during March 17 and 18 by a combination of rising water levels and thermal deterioration of the ice. Downstream of Sherman Brown bridge, the ice cover deteriorated in place, largely by thermal effects.

Only a few jams formed during the March event and all were of no consequence (Ph. #44, 45).

## 5.0 DATA ANALYSIS AND INTERPRETATION

### 5.1 Initiation of Breakup

Observations and analysis to date (Beltaos, 1981, 1983, 1985a, 1985b) have established that two main types of breakup occur within the study reach. From Thamesville to the downstream end of Chatham the breakup is initiated when large ice sheets, formed by transverse fractures in the cover, have enough room on the water surface to clear various bends and obstacles. Ice jams form behind sheets that have not yet moved and they release when further stage increases provide additional water surface width. Downstream of Chatham, where the stage is strongly influenced by that of Lake St. Clair, the intact ice cover rises by a relatively small amount whereby the above process has no opportunity to develop. Consequently, the breakup process consists of a series of movements of an ice jam that first forms in Chatham and gradually works its way to the river mouth.

Transverse crack patterns observed during the 1984 breakup events are illustrated in Figures 5 and 10 while Figure 11 shows the statistical distributions of the distance between consecutive transverse cracks. The distributions for the 1982 and February 1984 events coincide as might have been expected since they apply to the same reach under similar ice thickness conditions. The March 1984 distribution, however, suggests closer crack spacing which hints at possible ice thickness and width effects (see also Beltaos, 1985c for a detailed discussion of possible causes). Based on these findings, Beltaos (1984) formulated a criterion for breakup iniation as follows:

$$\frac{W_B}{W_i} = f\left(\frac{h_i}{W_i}\right) \qquad (1)$$

in which $h_i$ and $W_B$ are respectively ice cover thicknesses and water surface width at the time of breakup initiation; and $W_i$ = corresponding net width of the ice cover. The latter parameter can be estimated from the water surface width at the stable freeze up stage, $W_F$, after subtraction of the width of the side strips which are created by the hinge cracks (see Beltaos 1985c for details on hinge crack calculations). The function f in Eq. 1 is not unique but also depends on flow shear stress, ice strength and local plan geometry of the river. For the Thames River sites under consideration, plan geometry and shear stress do not vary excessively while ice strength could be indirectly related to a thermal index.

Table 4 summarizes parameters pertaining to breakup initiation at Thamesville, Kent Bridge and Sherman Brown bridge. The indicated values of $h_i$ have been estimated on the basis of the measurements summarized in Table 3 as well as on measurements performed on stranded blocks shortly after breakup. Figure 12 shows the data of Table 4 plotted in the form suggested by Eq. 1, along with data from previous years. The data points define a consistent relationship, thus confirming Eq. 1 and providing a means to forecast breakup events. To use Fig. 12, it is necessary to have cross-sectional data so that a graph of channel width versus stage can be prepared. A more convenient but completely empirical approach is to plot the rise above freeze up stage, $H_B$ - $H_F$, versus $h_i$. A satisfactory correlation has been obtained for Thamesville (Fig. 13). Forecasting in this instance requires only the freeze up level $H_F$ and the ice thickness, $h_i$.

The above discussion illustrates that the ice thickness is an important factor that requires careful evaluation, especially during the pre-breakup period when it begins to decrease. For example, Tables 3 and 4 show significant reductions in ice thickness during the few days preceding breakup. More frequent measurements would help define empirical methods to estimate ice thickness reductions. For example, Billello (1980) found that river ice decays in proportion to accumulated degree-days above a base of -5°C. The coefficient of proportionality varies from site to site and ranged from 0.4-1.0 cm/DD for sites in Alaska and Northern Canada. Analysis of the present data for the Thames River indicates this coefficient to be between 0.26 and 0.43 cm/DD, with an average value of 0.36. However, more data are needed before reliable values can be established.

## 5.2 Ice Jams

Several ice jams were observed during the February breakup, as summarized in Table 5. Figures 14 and 15 show water level profiles along three of these jams, as obtained from photos and later surveys. For the February 14 jam near Kent Bridge (Fig. 14) only the profile at the toe is available. It indicates a very steep local slope of about 6 m/km, in a reach where the normal open-water slope is only 0.15 m/km. For the February 15 jam in the same reach, the slope far upstream of the toe is estimated at 0.26 m/km while the applicable discharge is about 425 $m^3/s$. Using also cross-sectional data at 49.86, 50.05, 50.26 and 50.81 km, we find W = average width ≈ 93 m, H = average water depth ≈ 6.3 m. From these, the parameters $\eta$ and $\xi$* work out to 260 and 841, respectively. This pair is plotted in Fig. 16 and appears to be in agreement with previous data. However, the slope used in this calculation could be in considerable error as it is based on only three elevations (Fig. 14) determined by the crude photo-survey method. For example, if the jam had attained equilibrium, the slope would have been equal to the open-water value, i.e., 0.15 m/km. The values of $\eta$ and $\xi$ would then be 466 and 1847. This pair is also plotted in Fig. 16 and is also in agreement with previous data.

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Note that $\eta = H/WS$ and $\xi = [(Q/W)^2/gS]^{1/3}/WS$ in which g = acceleration due to gravity, Q = discharge and S = slope. Beltaos (1986) has found a good relationship between $\eta$ and $\xi$ using field data from several rivers.

For the February 16 jams (Fig. 15), only the morning one can be analyzed because the available elevations for the afternoon jam are not sufficient to determine the slope. The discharge for the afternoon jam is estimated as 460 $m^3/s$ based on the Thamesville hydrograph, however, flooding was already occurring upstream of the jam whereby the flow under the jam should be somewhat less than 460 $m^3/s$. Using cross-sectional data for 0.82, 1.41 and 2.19 km, we calculate $H \approx 5.6$ m, $W \approx 109$ m and $\xi < 1101$, $\eta = 288$ which is consistent with the average line defined by previous data in Fig. 16.

## 5.3 Release of Ice Jams

Another important aspect of ice jams is the conditions of their release. For jams above Chatham which are normally held in place by isolated ice sheets, Beltaos (1985a) has argued that release is effected when the water surface width is large enough to permit the sheets to move. This leads to a partial criterion for release, i.e.,

$$\frac{W_R}{W_i} \leq f_R\left(\frac{h_i}{W_i}\right) \tag{2}$$

Here $W_R$ is the water surface width at the time of release and $f_R$ is a function to be determined empirically. The "less-or-equal" sign signifies that Eq. 2 gives only an upper limit, beyond which jamming would not be possible. Jams may release, however, at lower stages (and thence $W_R$'s) due to thermal deterioration or mechanical destruction of the ice sheet. Table 6 summarizes the February 1984 data on the release of ice jams.

Using the 1984 and previous years' data, we may first try empirical plots such as $v_R$ and $Q_R$ vs $h_{i,max}$ (Figs. 17 and 18). Here $v_R$ is the average flow velocity just downstream of the toe at the time of release; $Q_R$ is the release discharge and $h_{i,max}$ is the thickness of the ice cover at the start of breakup, i.e., no account of thermal reductions is made. It may be noted that both $v_R$ and $Q_R$ increase generally with ice thickness but there is large scatter which reflects additional effects. Of particular interest is the 1981 point for Louisville (Fig. 18) which plots much higher than the rest of the data points. This is probably the result of local channel geometry effects at the toe of the jam, i.e., sharp bend and deep section with steep banks.

For the jams above Chatham which are known by observation to release according to the mechanism implied in Eq. 2, the data can be plotted in the dimensionless form suggested by this equation (Fig. 19). While there is still considerable scatter, the "anomalous" point of Fig. 18 no longer stands out.

## 6.0 DISCUSSION

Two breakup events occurred in 1984, one in February and one in March. The latter event took place under conditions of relatively low discharge and thin ice cover, thus causing no significant jamming. On the other hand, the February breakup was similar to those of 1981 and 1982 in that it occurred while the ice cover was fairly thick and the runoff was large. Flooding due to ice jams in 1984 was not as serious as that of 1981 but was considerably worse than that of 1982. The peak discharge during the February 1984 breakup was about 560 $m^3/s$ which lies between those of 1982 (450 $m^3/s$) and 1981 (630 $m^3/s$). The peak flow during the runoff event that caused breakup was about 720 $m^3/s$ and might have caused much more serious flooding, had the jam at the river mouth not released while the discharge was still considerably less. This fortunate occurrence is thought to have been assisted by the ice breaking operations that were carried out at the river mouth.

A consistent pattern of breakup has emerged, based on the five years' observations performed to date. Within the study reach breakup is first initiated near Thamesville while downstream reaches break up later. However, through and below Chatham, breakup develops independently of upstream ice conditions. It is common to find substantial river stretches upstream of Chatham that are ice covered while the river is open in Chatham and beyond, to Prairie Siding. Eventually, the ice upstream of Chatham releases and joins the downstream jam. The combined jam is only a few kilometres long which suggests significant melting and transport under the intact ice cover.

Quantitative interpretation of the 1983-84 observations focused on three major aspects of the ice regime, i.e., breakup initiation, ice jam levels and ice jam release. The data gathered to date support the writer's conceptual model for the sub-reach Thamesville to Chatham. Briefly, this model assumes that the ice cover is first fractured into a sequence of separate sheets by transverse cracking. Breakup is then initiated when the water level becomes high enough so that there is sufficient room on the water surface for the ice sheets to move. Direct confirmation of this hypothesis was first obtained in 1982 by means of the observed pattern of transverse cracks. Similar patterns were also observed during both 1984 breakup events, thus providing further confirmation to the conceptual model. Downstream of Chatham, the breakup process differs from and is more complex than that upstream. Here, the water level is strongly influenced by that of Lake St. Clair. The intact ice cover cannot rise high enough for transverse fractures to develop; instead, it is broken up by intermittent movements of a jam that first forms near the downstream end of Chatham.

Ice jam stages observed in 1984 are consistent with the writer's dimensionless relationship between water depth and discharge (Fig. 16). This has also been the case for jams observed in previous years so that Fig. 16 can be used with confidence for quick predictions of the flooding potential of anticipated jams.

The release of ice jams is an important question that often governs the maximum breakup stage. Our findings to date suggest that channel geometry, discharge and ice cover thickness are important factors. However, it is only in the sub-reach Thamesville-to-Chatham, that an approximate release criterion can be formulated. This criterion derives from the conceptual model mentioned earlier and is based on the premise that jam release is effected by dislodgement of single ice sheets (Fig. 19). For the sub-reach downstream of Chatham, only a broad indication of ice-clearing discharge as a function of ice thickness is available at present (Figs. 17 and 18).

## 7.0 SUMMARY AND CONCLUSIONS

Of the two breakup events that occurred in 1984, only the one in February caused problems. Flooding due to ice jams was considerable but not as serious as that of 1981 and this was likely due to timely ice breaking operations at the river mouth.

The 1984 observations have provided further confirmation of the writer's conceptual model of breakup for the reach Thamesville - Chatham. In this reach, the breakup process is fairly well understood and quantitative predictions of its onset and end are possible. However, much remains to be learned in the reach below Chatham where the breakup process is governed by the intermittent movements of a jam.

## ACKNOWLEDGEMENTS

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## REFERENCES


Beltaos, S. 1981. Ice Freeze Up and Breakup in the Lower Thames River: 1979-80 Observations. NWRI Unpublished Report.

Beltaos, S. 1983. Ice Freeze Up and Breakup in the Lower Thames River: 1980-81 Observations. NWRI Unpublished Report.

Beltaos, S. 1984. A conceptual Model of River Ice Breakup. Canadian J. of Civ. ng., Vol. 11, No. 3, pp. 516-529.

Beltaos, S. 1985a. Ice Freeze Up and Breakup in the Lower Thames River: 1981-82 Observations. NWRI Unpublished Report.

Beltaos, S. 1985b. Ice Freeze Up and Breakup in the Lower Thames River: 1982-83 Obervations. NWRI Unpublished Report.

Beltaos, S. 1985c. Initial Fracture Patterns of River Ice Cover. NWRI Contribution No. 85-139.

Beltaos, S. 1986. Monograph on River Ice Jams, Chapter 4: Theory. Submitted to NRCC Working Group on River Ice Jams.

Bilello, M.A. 1980. Maximum Thickness and Subsequent Decay of Lake, River and Fast Sea Ice in Canada and Alaska. U.S. Army CRREL Report 80-6.

Matousek, V. 1984. Types of Ice Run and Conditions for Their Formation. Proc. IAHR Ice Symposium, Hamburg, W. Germany, pp. 315-327.

**TABLE 1.**

**Water Level Readings During Freze Up, December 1983**

| Thamesville | | | Kent Bridge | | | Sherman Brown bridge | | |
|---|---|---|---|---|---|---|---|---|
| Time/Day | Reading | Remarks | Time/Day | Reading | Remarks | Time/Day | Reading | Remarks |
| 1302/19 | 12.76 | moving ice | 1340.19 | 176.78 | moving ice | 1420/19 | 175.86 | moving ice |
| 1635/19 | 12.73 | pans | 1640/19 | 176.78 | pans | 1550/19 | 175.87 | pans |
| 1730/19 | 12.72 | \| | 0820/20 | 176.90 | \| | 1705/19 | 175.90 | ice cover |
| 0730/20 | 12.55 | \| | 1145/20 | 177.18 | | 0850/20 | 175.77 | \| |
| 0830/20 | 12.53 | \| | 1318/20 | 177.30 | ice cover | 1130/20 | 175.75 | \| |
| 1250/20 | 12.47 | \| | 1135/22 | 176.66 | \| | 1425/22 | 175.69 | |
| 1620/20 | 12.41 | | | | | | | |
| 0840/21 | 12.67 | ice cover | | | | | | |
| 1620/21 | 12.44 | \| | | | | | | |
| 0806/22 | 12.65 | | | | | | | |

Gauge height (m); add 167.56 m to determine geodetic elevation

Geodetic elevation of water level (m)

**TABLE 2**

Ice Thickness Measurements, Winter 1984

| Location | Average Ice Thickness/ (cm) Number of Measurements Across River | | | |
|---|---|---|---|---|
| | Jan. 16 | Jan 24 | Jan. 30 | Feb. 13 |
| Lake St. Clair | | | | 36.8/1 |
| Lighthouse dock 0.2 km | | | 42.2/4 | 31.1/4 |
| Gov't dock, 2.2 km | 34.3/4 | | 41.7/4 | 30.2/4 |
| Prairie Siding bridge, 14.3 km | 32.0/4 | | 36.8/4 | 29.0/4 |
| LTVCA Office 29.7 km | 32.0/4 | | 39.4/3 | 33.3/3 |
| Kent Bridge 50.0 km | 30.5/2 | | 33.5/2 | |
| Thamesville (Hwy 21), 65.6 km | 40.6/1 | 36.8/17 | 40.1/2 | |

River distance upstream of the mouth.
From Water Survey of Canada discharge measurement notes.
All other measurements were performed by Lower Thames Valley Conservation Authority.

TABLE 3

Ice Thickness Measurements, March 14, 1984 (LTVCA)

| Location | Average thickness (cm)/number of measurements across the river |
|---|---|
| Lighthouse dock (0.2 km) | 5.9/3 |
| Government dock (2.2 km) | 6.4/2 |
| Prairie Siding bridge, (14.3 km) | 10.2/1 |
| LTVCA Office (29.7 km) | 7.6/1 |
| Thamesville (Hwy 21) (65.6 km) | 15.2/1 |

**TABLE 4**

Breakup Invitation Parameters for 1983-84

| Location | $H_F$(m) / date | $H_B$(m) / time/date | $h_i$ (cm) | $W_i$ (m) | $W_B$ (m) | $100\,h_i / W_i$ | $W_B / W_i$ | Remarks |
|---|---|---|---|---|---|---|---|---|
| Thamesville | 12.50 / Dec.20/21 | 14.50-14.94 / 1713-2050/Feb.13 | 27 | 31.5 | 50.2-52.1 | 0.86 | 1.59-1.65 | H's are gauge heights; add 167.56 m to find geod. elevations |
| Kent Bridge | 176.98 / Dec. 20 | >178.18 / after 2130/Feb.13 | 27 | 45.5 | >64.0 | 0.59 | >1.41 | H's are geodetic elevations |
| Sherman Brown bridge | 175.75 / Dec. 20 | 179.01 / 1325/Feb.15 | 28 | 62.5 | 85.2 | 0.45 | 1.36 | - u - |
| Thamesville | 12.20 / Mar. 10 | 12.75-13.03 / 1048-1231/Mar.16 | 10 | 34.7 | 41.3-42.7 | 0.29 | 1.19-1.23 | Same as above |
| Kent Bridge | 176.20 / Mar. 10 | 177.43 / 2015-2105/Mar.16 | 10 | 46.0 | 57.5 | 0.22 | 1.25 | - u - |
| Sherman Brown bridge | 175.70 / Mar. 9 | 176.71-176.91 / 1825/Mar.17-0726/Mar.18 | 12 | 66.4 | 75.0-75.7 | 0.18 | 1.13-1.14 | - u - |

**TABLE 5**

Ice Jams Documented During the 1983-84 Ice Season

| Location Distances are in km above river mouth | Time of Formation | Time of Release | Approximate Flow Discharge ($m^3/s$) | Probable Causes |
|---|---|---|---|---|
| Toe at 49.8; head above Kent Bridge (50.0) | 2150/Feb. 13 to 0806/Feb. 14 | 1352/Feb. 14 | 340 at time of release | Large ice sheets |
| Toe at 48.64; head above Kent Bridge (50.0) | ≈1410/Feb. 14 | 1000-1030/Feb.15 | 430 at time of release | Large ice sheet lodged at sharp bend |
| Toe at Sherman Brown bridge (33.8) head at ≈38.6 | 1500/Feb. 15 | 1603/Feb. 15 | 430 at time of release | Large ice sheets |
| Toe at CP rail bridge (32.3) head at ≈33.8 | ≈1700/Feb. 15 | 1751/Feb. 15 | 440 at time of release | Ice sheet held by bridge piers |
| Toe by St. Peter's Church (9,5); head ≈0.9 km upstream | ≈1800/Feb. 15 | ≈0630/Feb. 16 | 450 at time of release | Continuous ice cover |
| Toe in Lake St. Clair, head near 4 km | night of Feb. 15 to 16 | ≈0500/Feb. 17 | <560 at time of release | Lake ice |

**TABLE 6**

Data on Ice Jam Releases, February 1984

| Jam Location | Date | Approx. $h_i$ (cm) | Approx. $W_F$ (m) | Approx. $W_i$ (m) | Approx. $W_R$ (m) | Approx. $Q_R$ (m /s) | Remarks |
|---|---|---|---|---|---|---|---|
| Lake St. Clair to 4 km | 17.02.84 | - | NA | NA | NA | <560 | Serious flooding |
| St. Peter's Church 9.5 km to 10.4 km | 16.02.84 | 43/24 | NA | NA | NA | 450 | Minor flooding |
| CP Rail Bridge 32.3 km to 33.8 km | 15.02.84 | 41/28 | 90 | 81 | 102 | 440 | No flooding |
| Sherman Brown bridge 33.8 km to 38.6 km | 15.02.84 | 41/28 | 63 | 54 | 80 | 430 | No flooding |
| Below Kent Bridge 48.65 km to past 50.0 km | 15.02.84 | 40/27 | 71 | 62 | 97 | 430 | Minor flooding |
| Kent Bridge 49.8 km to past 50.0 km | 14.02.84 | 40.27 | 55 | 46 | 80 | 340 | No flooding |

The first number is estimated maximum thickness attained; the second number is estimated thickness at the time of release.

# APPENDIX A

## Water Levels and Ice Conditions

Note: The following abbreviations have been used in Appendices A and B

U/S = upstream
D/S = downstream
BDG = bridge
HWY = highway
RWY = railway
= view toward

## LOCATION: THAMESVILLE/FIRST EVENT

| Date February 1984 | Time | Stage (m) [Gauge Height] | Comments (Stages are Approximate) |
|---|---|---|---|
| 13 | 1134 | 14.14 | ice cover |
| | 1153 | 14.16 | - " - |
| | 1257 | 14.20 | - " - |
| | 1350 | 14.29 | - " - |
| | 1525 | 14.39 | - " - |
| | 1630 | 14.49 | - " - |
| | 1713 | 14.50 | - " - |
| | 2045 | | open water |
| | 2050 | 14.94 | - " - |
| | 2210 | 15.04 | - " - |
| 14 | 0750 | 16.01 | - " - jam @ Kent Bridge, |
| | 0850 | 16.06 | - " - toe 200 m d/s of bridge |
| | 1200 | 16.39 | - " - - " - |
| | 1230 | 16.41 | - " - - " - |
| | 1245 | 16.42 | - " - - " - |
| | 1300 | 16.69 | - " - - " - |
| | 1600 | 17.06 | - " - - " - |
| | 1748 | 16.99 | - " - jam released at 1352 h, new toe |
| | 1815 | 17.07 | - " - formed at bend 1.3 km below bridge |
| | 1930 | 17.05 | - " - Discharge measured at 389m /s, 1810 - |
| | 2023 | 17.09 | - " - 2030 h, mean stage = 17.049, |
| | 2300 | 17.24 | - " - backwater = .56 m |
| 15 | 0300 | 17.30 | - " - |
| | 0600 | 17.30 | - " - |
| | 0700 | 17.30 | - " - |
| | 0815 | 17.36 | - " - |
| | 1000 | 17.42 | - " - jam at Kent B. released between 1000 |
| | 1200 | 17.55 | - " - and 1030 h |
| | 1245 | 17.59 | - " - |
| | 1630 | 17.59 | - " - |
| | 1800 | 17.76 | - " - |
| | 2100 | 17.81 | - " - |
| | 2230 | 17.87 | - " - |
| | 2300 | 17.96 | - " - |
| | 2400 | 18.02 | - " - |

**LOCATION: THAMESVILLE/FIRST EVENT**

| Date February 1984 | Time | Stage (m) [Gauge Height] | Comments (Stages are Approximate) |
|---|---|---|---|
| 16 | 0030 | 17.99 | - " - (staff = 17.77?) |
| | 0100 | 18.11 | - " - (staff = 18.19?) |
| | 0130 | 18.06 | - " - (staff = 18.14?) |
| | 0135 | 18.11 | - " - (staff = 18.19?) |
| | 0205 | 18.12 | - " - (staff = 18.12 OK) |
| | 0215 | 18.13 | - " - |
| | 0245 | 18.14 | - " - |
| | 0300 | 18.22 | - " - |
| | 0330 | 18.21 | - " - |
| | 0420 | 18.30 | - " - |
| | 0530 | 18.33 | - " - |
| | 0630 | 18.36 | - " - |
| | 0700 | 18.43 | - " - |
| | 0730 | 18.46 | - " - |
| | 0830 | 18.59 | - " - |
| | 0900 | 18.55 | - " - |
| | 1000 | 18.57 | - " - |
| | 1100 | 18.66 | - " - |
| | 1200 | 18.68 | - " - |
| | 1300 | 18.72 | - " - |
| | 1530 | 18.84 | - " - |
| | 1600 | 18.88 | - " - |
| | 1700 | 18.91 | - " - |
| | 1800 | 19.01 | - " - |
| | 1900 | 19.01 | - " - |
| | 1930 | 19.07 | - " - |
| | 2000 | 19.06 | - " - |
| | 2100 | 19.04 | - " - |
| | 2200 | 19.07 | - " - |
| | 2300 | 19.18 | - " - |

**LOCATION: KENT BRIDGE/FIRST EVENT**

| Date February 1984 | Time | Stage (m) Geodetic | Comments (Stages are Approximate) |
|---|---|---|---|
| 13 | 1405 | 177.72 | ice cover |
| | 1510 | 177.78 | - " - |
| | 2130 | 178.18 | - " - |
| 14 | 0806 | 180.27 | jammed under bridge; toe 200 m d/s of bridge |
| | 0826 | 180.27 | - " - |
| | 0903 | 180.32 | - " - |
| | 0910 | 180.26 | - " - |
| | 0928 | 180.32 | - " - |
| | 0949 | 180.32 | - " - |
| | 1011 | 180.38 | - " - |
| | 1149 | 180.41 | - " - |
| | 1352 | | jam moves, speed 3 m/s |
| | 1353 | 180.57 | |
| | 1356 | | toe of jam out of sight 650 m d/s of bridge |
| | 1409 | 181.08 | still moving, speed 1.5 - 2 m/s |
| | 1416 | 181.08 | - " - |
| | 1426 | | jammed d/s; o.w. under bridge; moderate amount of ice fragments still arrive from u/s and diverted over LB to old ox-bow |
| | 1434 | 181.41 | - " - head of jam advnces u/s |
| | 1442 | 181.43 | - " - |
| | 1450 | 181.39 | - " - |
| | 1500 | 181.44 | - " - |
| | 1520 | 181.51 | - " - |
| | 1528 | 181.60 | - " - |
| | 1606 | 181.63 | - " - |
| | 1608 | 181.63 | - " - |
| | 1648 | 181.83 | head of jam under bridge; toe 1.3km d/s bridge |
| | 1703 | 181.83 | head of jam 60 m u/s of bridge |
| | 1730 | 181.84 | |
| | 1850 | 181.83 | jammed as far as can see |
| | 2215 | 182.15 | |
| 15 | 0840 | 182.09 | jammed; toe still at same place |
| | 0940 | 182.09 | - " - |
| | 1038 | | head cleared bridge |
| | 1108 | 182.13 | |
| | 1125 | 182.15 | light to moderate amount of ice fragments moving past bridge |
| | 1133 | 182.18 | |

**LOCATION: SHERMAN BROWN BRIDGE/FIRST EVENT**

| Date February 1984 | Time | Stage (m) Geodetic | Comments (Stages are Approximate) |
|---|---|---|---|
| 14 | 1034 | 177.86 | ice cover |
| | 1037 | 177.82 | - " - |
| | 1218 | 178.00 | - " - |
| | 1525 | 178.28 | - " - |
| | 1732 | 178.49 | - " - |
| | 1834 | 178.36 | - " - |
| 15 | 0940 | 178.73 | - " - |
| | 1135 | 178.82 | - " - |
| | 1325 | 179.01 | - " - u/s, open water section d/s of bridge |
| | 1348 | 179.01 | u/s cover fractured considerably |
| | 1439 | 179.13 | - " - |
| | 1449 | 179.16 | broken ice seen to arrive at bend u/s bridge |
| | 1450 | 179.16 | brief movement of ice cover; jamming u/s |
| | 1457 | 179.19 | |
| | 1459 | | more ice movement just u/s of bridge |
| | 1502 | 179.20 | movement continues; crushing |
| | 1503 | | general movement - slow |
| | 1505 | 179.22 | |
| | 1507 | | still moving |
| | 1513 | 179.16 | |
| | 1517 | 179.07 | stationary |
| | 1530 | 179.07 | - " - |
| | 1545 | 178.98 | - " - |
| | 1601 | | brief movement of large ice sheet |
| | 1602 | 179.10 | |
| | 1603 | | large sheet moves - ice run starts |
| | 1604 | 179.13 | - " - |
| | 1610 | 179.31 | ice speed 0.5 m/s |
| | 1615 | 179.28 | |
| | 1623 | 179.34 | |
| | 1628 | 179.31 | ice run still |
| | 1634 | 179.40 | ice run |
| | 1639 | 179.59 | ice run |
| | 1659 | | stopped, jammed under bridge, toe of new jam |
| | 1700 | 179.71 | noticed at Rwy bridge at 1712 h; new jam |
| | 1705 | 179.74 | released at 1751 h |
| | 1800 | 179.40 | thinning ice run, high water mark = 179.9 |
| | | | occurred between 1705 and 1800 h |
| | | | <u>Notes</u> open water section d/s bdg developed |
| | | | between 1135 and 1310 h on Feb. 15, $H_B$ 178.82 - |
| | | | 178.94 m, final movement of u/s sheets @ 1603 h |
| | | | $H_B$ = 179.11 m. |
| 16 | 1445 | 179.33 | open water, surface speed 1 m/s |

**LOCATION: THAMESVILLE/SECOND EVENT**

| Date March 1984 | Time | Stage [Gauge Height] m | Comments (Stages are Approximate) |
|---|---|---|---|
| 14 | 2014 | 11.99 | ice cover; no open water at sides; some |
| | 2157 | 12.00 | melt water on top of ice |
| 15 | 0745 | 11.99 | no change in ice conditions |
| | 0926 | 11.99 | - " - |
| | 1212 | 12.01 | rising in past two hours, hinge cracks evident |
| | 1226 | 12.02 | |
| | 1305 | 12.03 | |
| | 1402 | 12.03 | |
| | 1431 | 12.04 | |
| | 1458 | 12.04 | |
| | 1500 | 12.04 | occasional open holes upstream of bridge |
| | 1532 | 12.03 | |
| | 1612 | 12.02 | |
| | 1725 | 12.01 | |
| | 1807 | 12.00 | |
| | 2014 | 12.00 | |
| | 2205 | 12.00 | |
| | 2315 | 12.01 | |
| 16 | 0150 | 12.04 | |
| | 0300 | 12.06 | |
| | 0750 | 12.32 | |
| | 0805 | 12.34 | |
| | 0823 | 12.38 | |
| | 0845 | 12.42 | |
| | 0900 | 12.46 | open water strips on both banks;main cover still |
| | 0915 | 12.50 | intact; creek just d/s of bdg causing thermal |
| | 0930 | 12.51 | erosion of ice cover - open lead all across ice |
| | 0945 | 12.57 | cover completed by 0940 |
| | 1000 | 12.61 | |
| | 1017 | 12.66 | |
| | 1030 | 12.70 | |
| | 1045 | 12.74 | |
| | 1048 | - | ice d/s of open lead begins to move |
| | 1101 | 12.80 | ice breaking up d/s of bdg, ice u/s remains in place |
| | 1115 | 12.83 | |
| | 1130 | 12.87 | |
| | 1145 | 12.92 | open water d/s of bdg |
| | 1200 | 12.97 | |
| | 1216 | 13.00 | |
| | 1230 | 13.03 | |

**LOCATION: THAMESVILLE/SECOND EVENT**

| Date March 1984 | Time | Stage [Gauge Height] m | Comments (Stages are Approximate) |
|---|---|---|---|
| | 1232 | | ice u/s of bdge begins to move |
| | 1237 | 13.04 | large ice sheets moving |
| | 1243 | 13.08 | - " - |
| | 1249 | 13.06 | - " - |
| | 1300 | 13.08 | - " - |
| | 1311 | 13.18 | movement slowing down |
| | 1340 | 13.30 | |
| | 1351 | | jammed |
| | 1400 | 13.35 | |
| | 1800 | 13.83 | |
| | 1841 | 13.91 | |
| 17 | 0910 | 15.18 | open water; fast current; peaked at 15.30 m at 0300 |
| | 1417 | 14.78 | |

**LOCATION: KENT BRIDGE/SECOND EVENT**

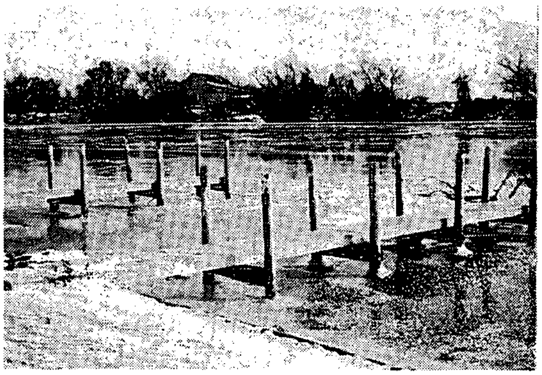
| Date March 1984 | Time | Stage [Geod. Elev.] m | Comments (Stages are Approximate) |
|---|---|---|---|
| 14 | 2215 | 175.90 | ice cover; no open water at sides |
| 15 | 1637 | 175.99 | - " - |
| 16 | 0850 | 176.27 | ice cover; open water begins to appear at sides |
| | 0929 | 176.33 | - " - |
| | 1110 | 176.45 | ice fragments heard and seen moving under ice cover |
| | 1204 | 176.54 | |
| | 1222 | 176.60 | |
| | 1243 | 176.63 | |
| | 1348 | 176.69 | |
| | 1426 | 176.78 | open area near LB on u/s side of bdg and across |
| | 1445 | 176.87 | river on d/s side |
| | 1500 | 176.87 | |
| | 1515 | 176.87 | |
| | 1545 | 176.94 | |
| | 1615 | 176.97 | |
| | 1635 | 177.00 | |
| | 1700 | 177.08 | |
| | 1710 | 177.09 | slight movement of u/s cover, transverse crack visible u/s bdg |
| | 1750 | 177.15 | |
| | 1805 | 177.21 | |
| | 1825 | 177.24 | |
| | 1900 | 177.30 | no significant change |
| | 2015 | 177.42 | open lead d/s bdg |
| | 2105 | 177.45 | open water; breakup initiated at 177.43 |
| 17 | 0730 | 178.00 | open water; ice blocks stranded on banks thickness range: 6-11 cm |
| | 0958 | 178.67 | open water; surface speed 1.3 m/s |
| | 1359 | 178.49 | |
| | 1432 | 178.49 | |
| 18 | 0900 | 179.10 | open water |

**LOCATION: SHERMAN BROWN BRIDGE/SECOND EVENT**

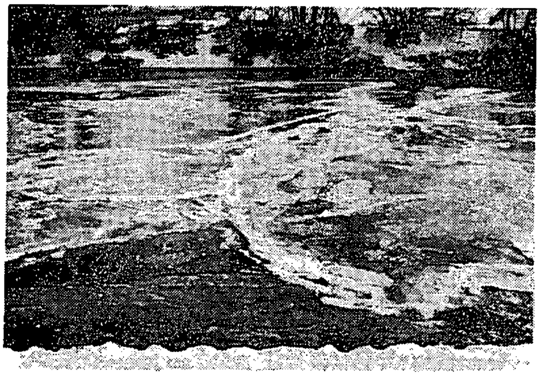
| Date March 1984 | Time | Stage [Geod. Elev.] m | Comments (Stages are Approximate) |
|---|---|---|---|
| 14 | 2230 | | ice cover; open lead under bdg; no open water at sides |
| 15 | 1016 | 175.37 | - " - |
| 16 | 0912 | | - " - |
| 17 | 0826 | 176.56 | open lead is longer; extends 50 m d/s |
| | 0900 | 176.63 | |
| | 0923 | 176.63 | |
| | 0940 | 176.63 | |
| | 1000 | 176.64 | |
| | 1030 | 176.65 | ice blocks moving under ice cover |
| | 1215 | 176.66 | |
| | 1300 | 176.75 | |
| | 1330 | 176.76 | ice sheets moving u/s |
| | 1400 | 176.76 | |
| | 1430 | 176.66 | |
| | 1525 | 176.64 | ice jam a few kilometres u/s |
| | 1630 | 176.65 | |
| | 1710 | 176.66 | |
| | 1750 | 176.71 | |
| | 1825 | 176.72 | still ice covered |
| 18 | 0726 | 176.91 | open water d/s bdg; open lead u/s |
| | 0815 | 176.92 | |
| | 0900 | 176.95 | |
| | 0930 | 176.96 | |
| | 1015 | 176.96 | no change; water level steady |

# APPENDIX B

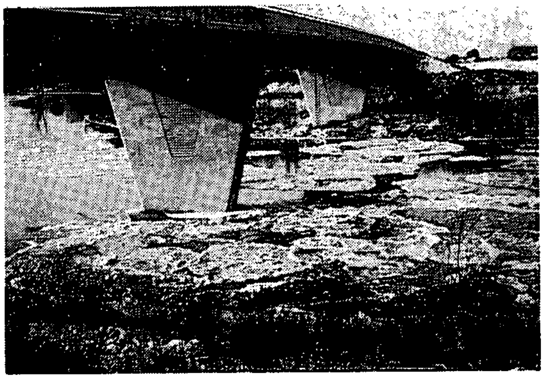
## Photographs



1. Smooth cover at Yacht Club 1510, Dec. 19, 1983.

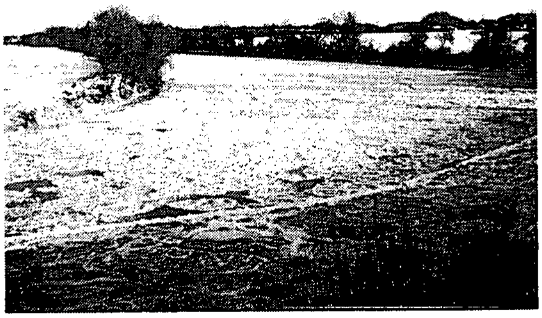


2. Ice Cover at Chatham, near C+O rail bridge, 1435, Dec. 19, 1985



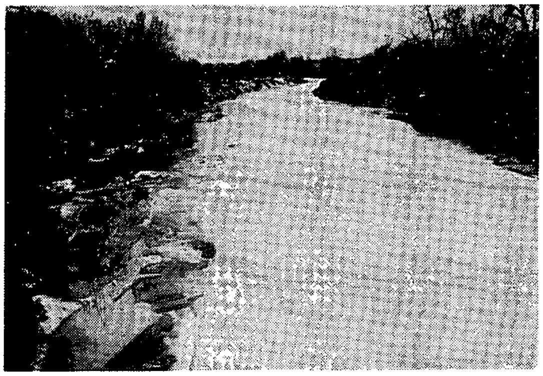
3. →RB, Sherman Brown Bridge moving slush pans, 1420, Dec. 19, 1983

4. Slush pan under Sherman Brown bridge, 1425, Dec. 19, 1983

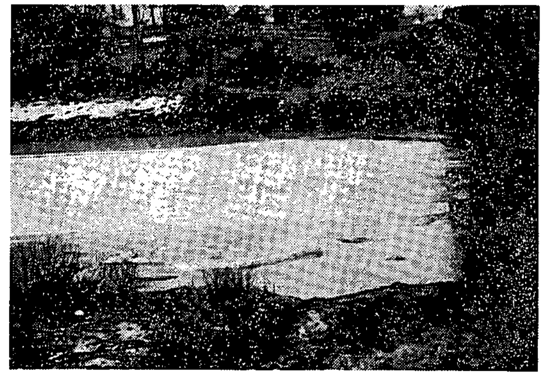


5. →u/s, newly formed ice cover at Sherman Brown bridge, 0855, Dec. 20, 1983

6. →LB, Kent Bridge, 1315, Dec. 20, 1983, newly formed cover.

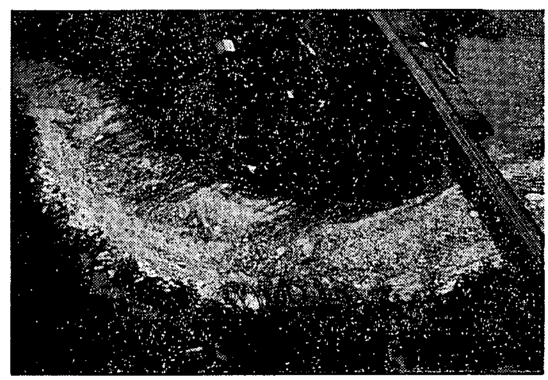


7. →d/s, Hwy 21 bdg, 1150, Feb. 13, 84. Intact ice cover - note hinge cracks and submerged side strips of ice.



8. →LB, Kent bdg, 1405, Feb.13. Intact ice cover and open water at sides.

9. →LB, Kent B., 0915, Feb. 14 Ice jam.



10. →LB, Kent B., 1407, Feb. 14. Moving ice fragments. Jam forming d/s - see next photos.

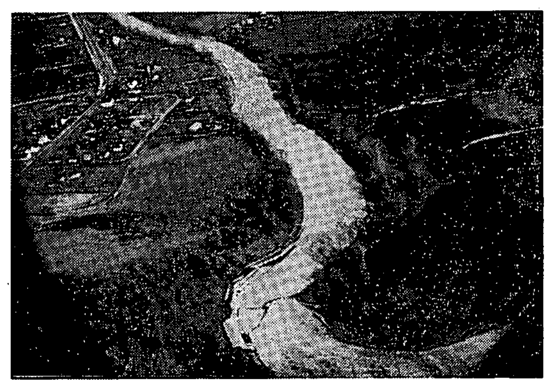
11. →u/s, near Kent B., 1406 Feb. 14. Jam forming due to large ice sheet at right end of photo (see also next photo)

12. →LB near Kent B. ≈1600, Feb. 14. Better view of jam formation point of previous photo. Courtesy LTVCA.

13. →LB, d/s side of Kent B. 1700, Feb. 14. Note ice jam in main channel and overflow onto old oxbow channel, (see also next photo)

14. →LB, Kent B., 1300, Feb. 15. Jam gone from main river but broken ice is stranded in oxbow channel.

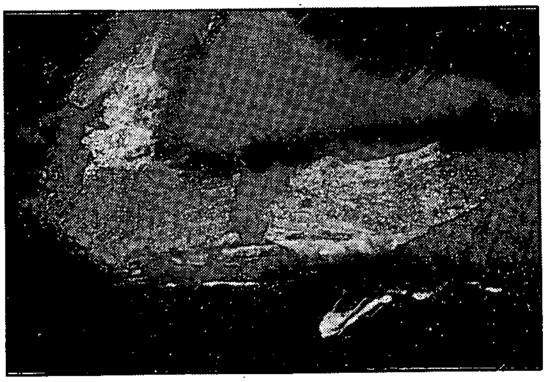
15. →u/s near Golf Course, 1405 Feb. 14. Moving ice sheets



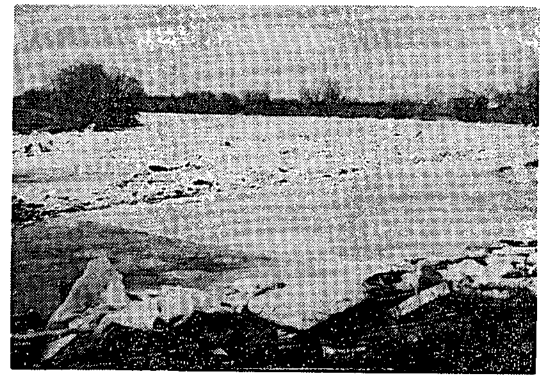
16. →u/s by Louisville (on left side of photo), 1405, Feb. 14. Note stationary ice sheets and transverse cracks.

17. Flooding in S. Chatham, 1500, Feb. 14. Courtesy LTVCA.

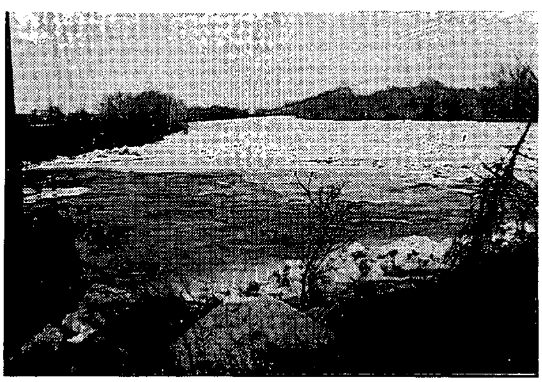
18. Ice breaking in L. St. Clair 1600, Feb. 14, courtesy LTVCA.



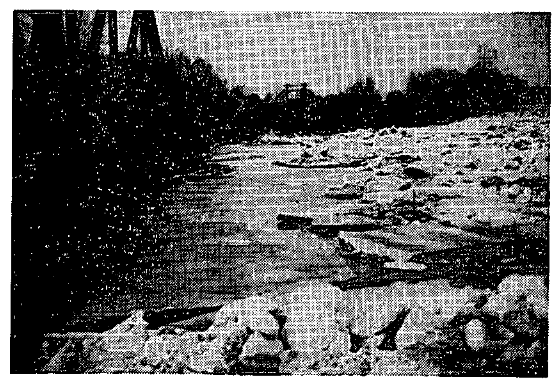
19. →u/s, a few km above SBB 1254, Feb. 15. Curved sheet broke in two on impact with channel banks.



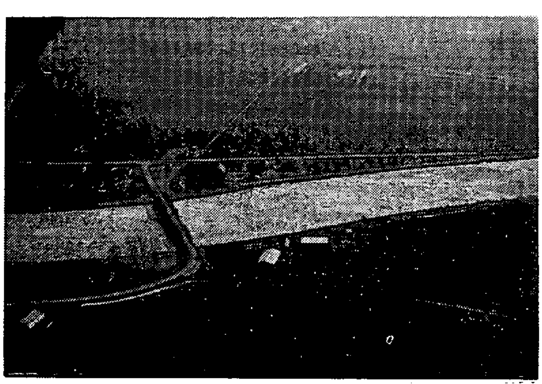
20. →u/s at SBB, 1606, Feb. 15. Shortly after release of ice jam.



21. →u/s 1715, Feb. 15. Toe of jam at CP bdge in Chatham.

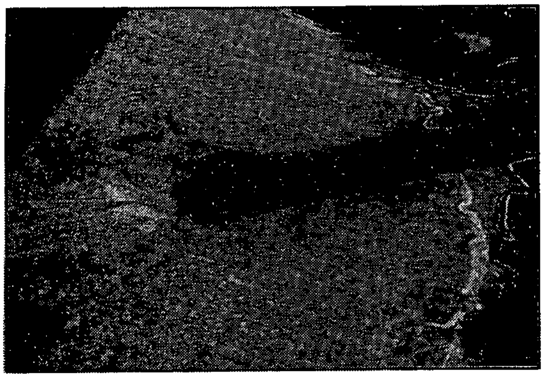


22. →RB, 1751, Feb. 15. Shortly after release of jam at CP bdge.



23. →LB, 1250, Feb. 15. Jam at Prairie Siding.

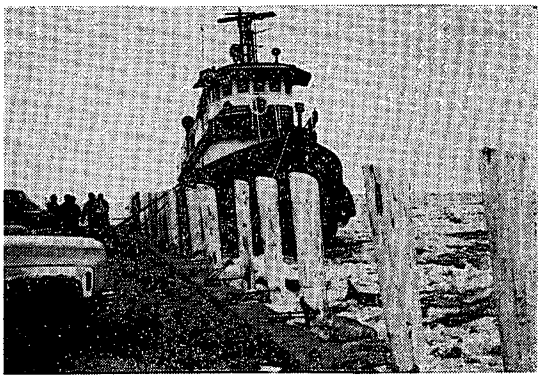
24. →LB, Prairie Siding lift bdge, 1040, Feb. 15.



25. At river mouth, 1245, Feb. 15. Open area in L. St. Clair created by ice breaking.

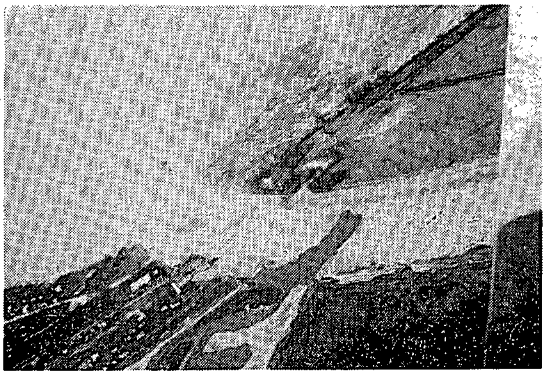
26. Flooding in Chatham 0900, Feb. 16, (courtesy LTVCA).

27. Ice block near St. Peter's Church, 0815, Feb. 16



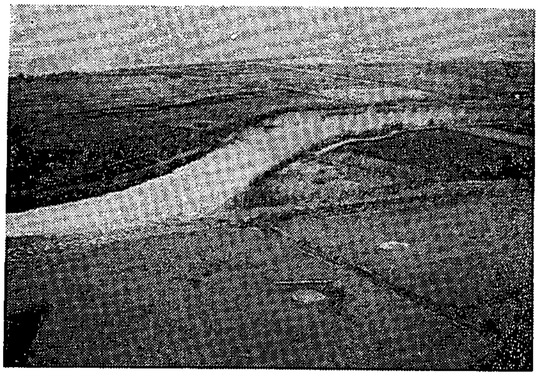
28. Tug used for ice breaking at river mouth, 0845, Feb. 16.

29. Floding on LB near mouth 0920, Feb. 16.



30. →d/s, 1347, F3b. 16. Toe of jam in L. St. Clair.

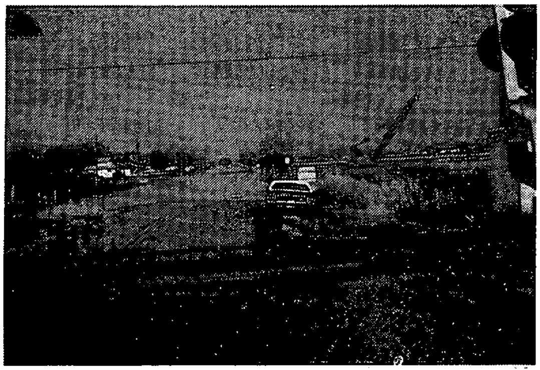
31. →d/s, 1352, Feb. 16. Flooding on LB.



32. →u/s to head of jam, 1345, Feb. 16. Note flooding.

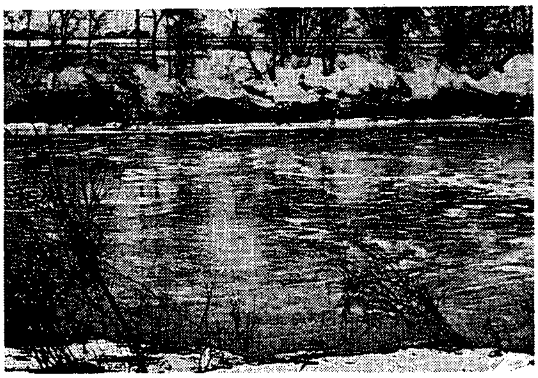
33. Ice piles @ Gvt. dock, 0830, Feb. 17.

34. Flooding near Gvt. dock, 0850, Feb. 17, Note high water marks on house.

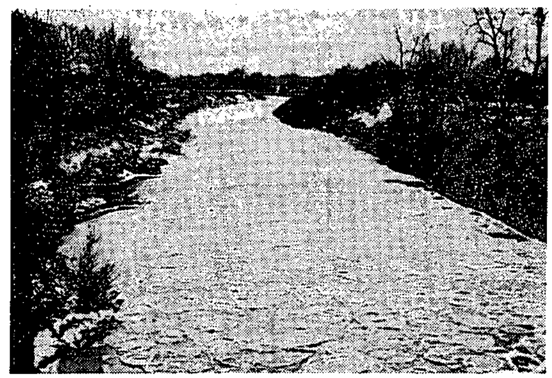


35. Access road to lighthouse flooded 0920, Feb. 17.

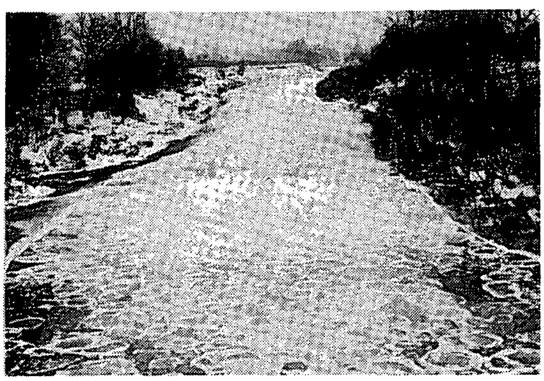
36. Ice on road near river mouth. Note high water marks on trees. 1000, Feb. 17.



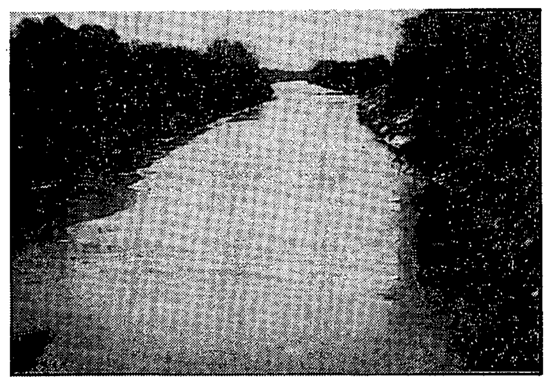
37. →RB at Golf Course, 1725, Mar. 10. Newly formed, smooth ice cover.



38. →d/s, Hwy 21 bdg, 1630 Mar 10. Newly formed cover, made of slush pans.

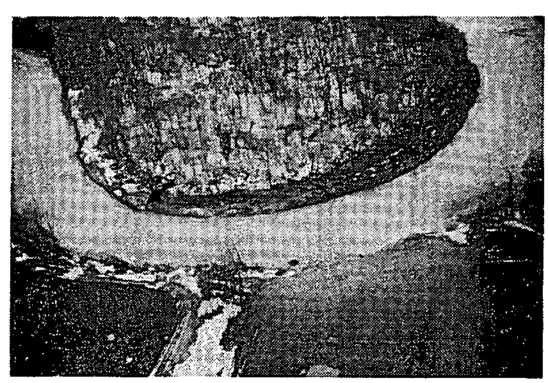


39. →d/s, Hwy 21 bdge, Mar. 15. Note intact ice cover and hinge cracks.

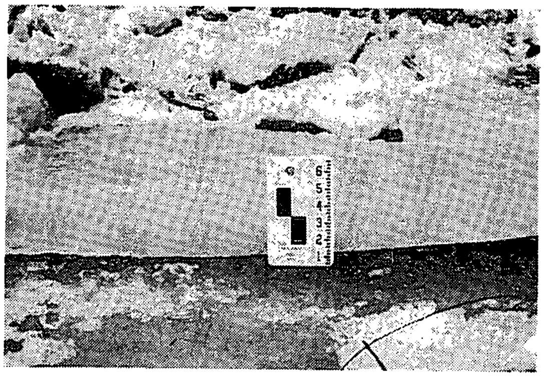


40. →u/s, Hwy 21 bdg, 1805 Mar 16. Moving ice sheet

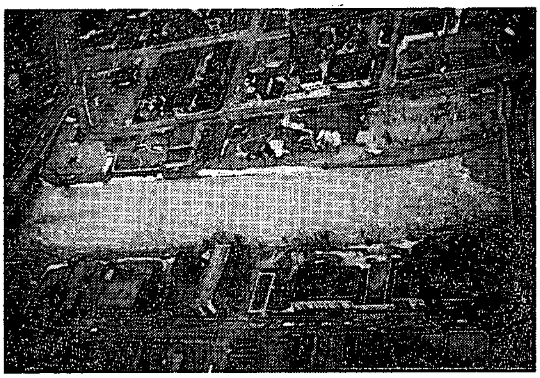
41. →LB, 1550, Mar. 16. Intact ice cover at Kent B.



42. →RB, 1602, Mar. 16, a few km above Kent B. Note intact cover and transverse cracks (locations indicated by arrows).



43. View of stranded ice block near Golf Course 1240, Mar 17.



44. →RB, 1745, Mar. 17. Minor jam in Chatham.

45. →RB, 0805, Mar. 18. Toe of minor jam below Louisville.

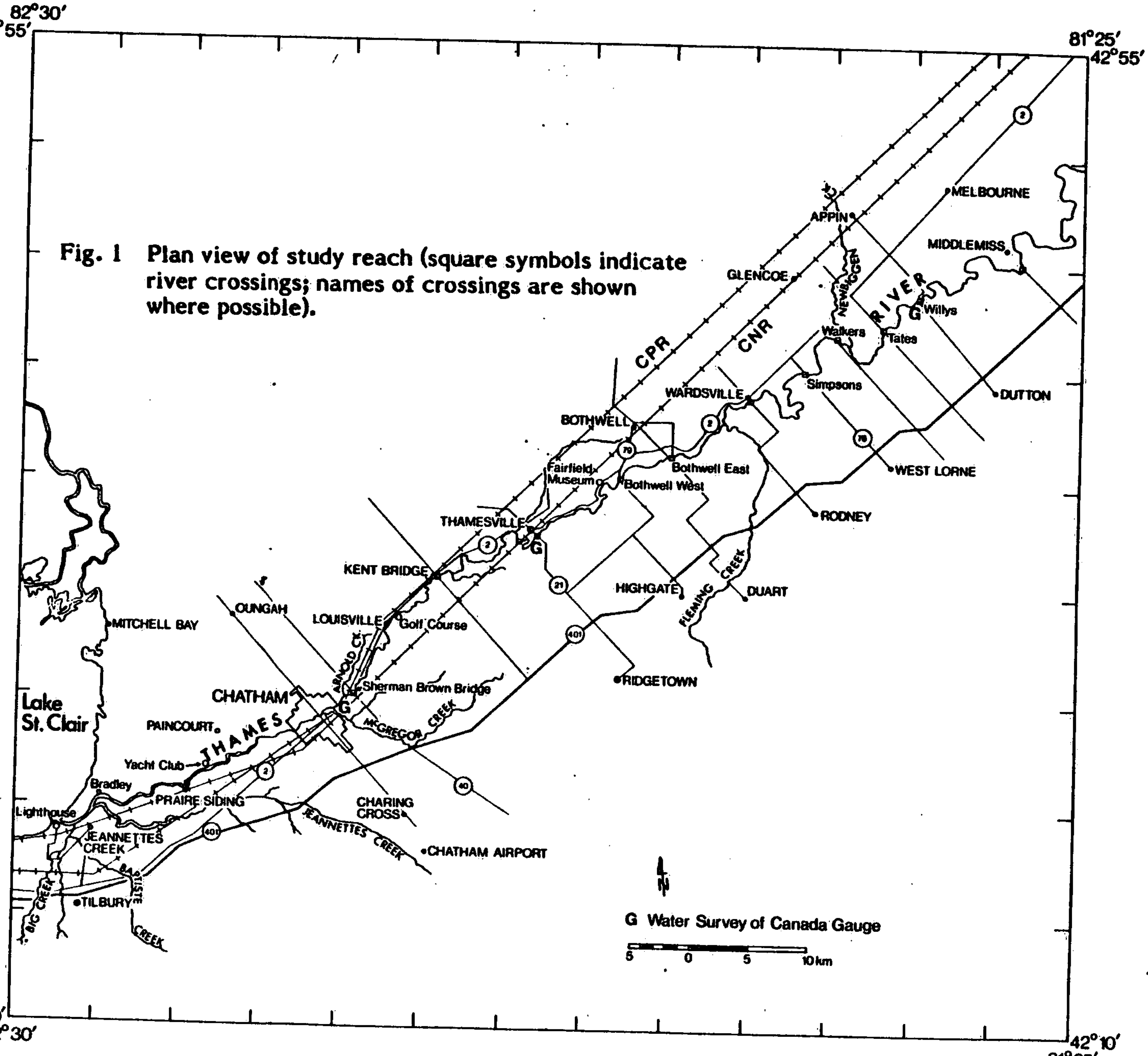



Fig. 1 Plan view of study reach (square symbols indicate river crossings; names of crossings are shown where possible).

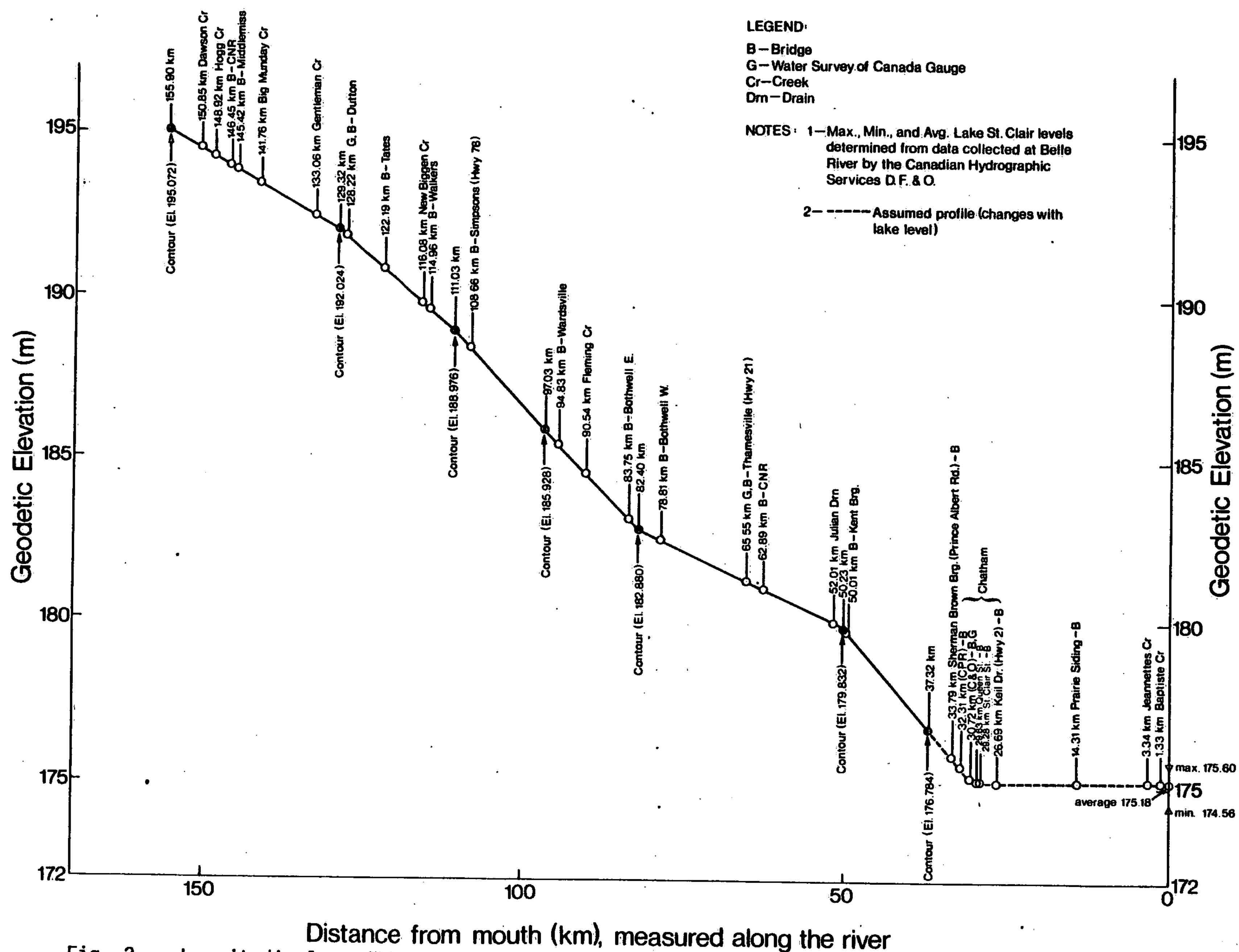



Fig. 2 Longitudinal profile of lower Thames River

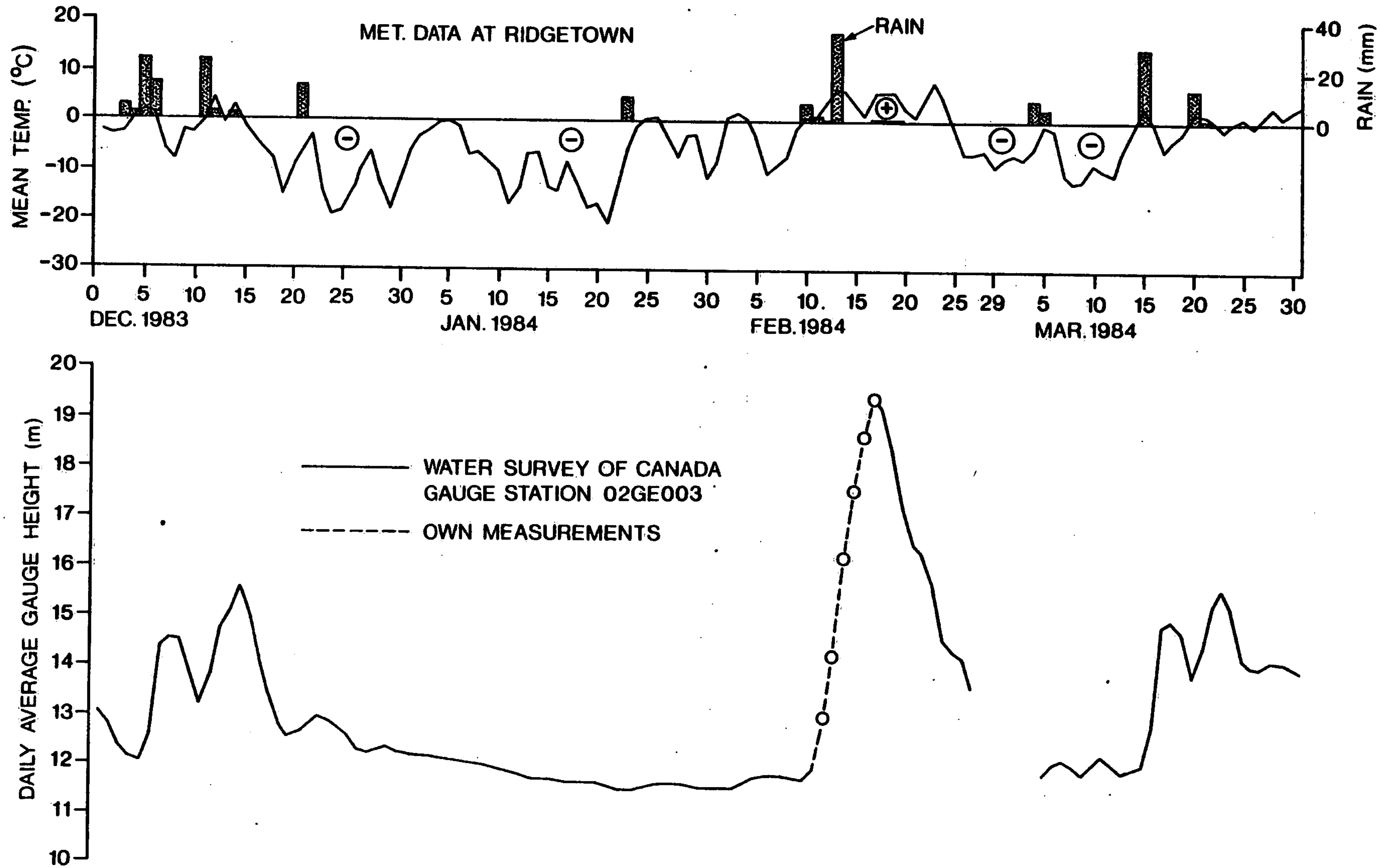



Fig. 3 Meteorological data and water levels near Thamesville

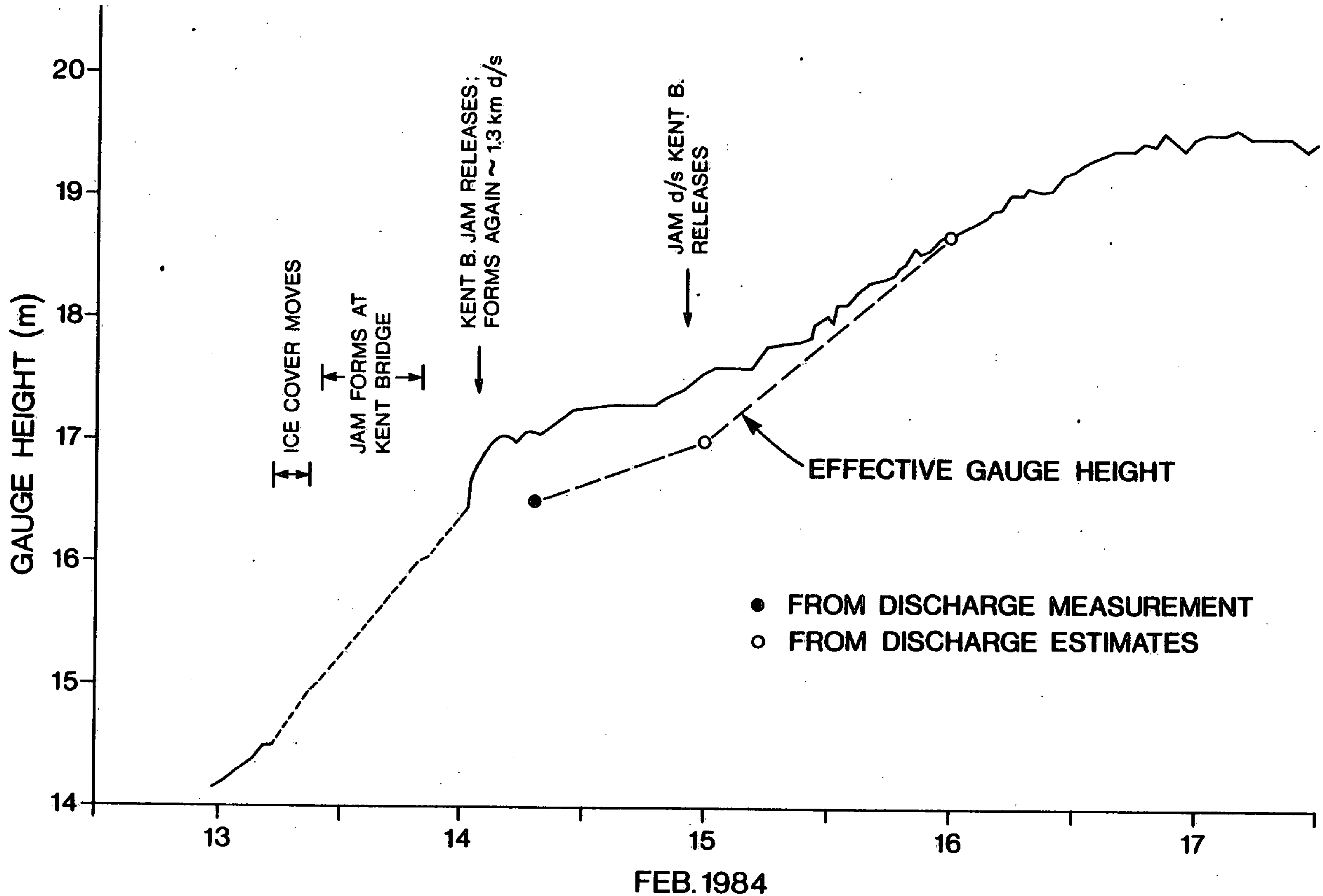



Fig. 4 Variation of water level at Thamesville during the breakup period (effective gauge height = gauge height for same discharge under open-water conditions).

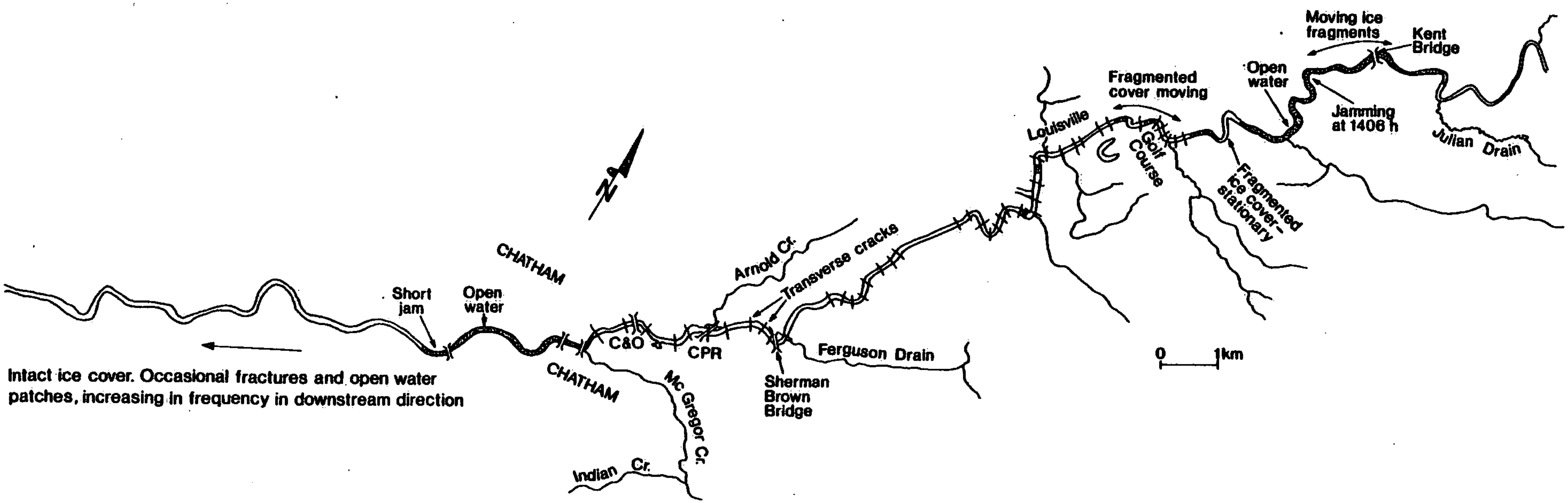



Fig. 5 Ice conditions during 1350 - 1430 h, Feb. 14, 1984.

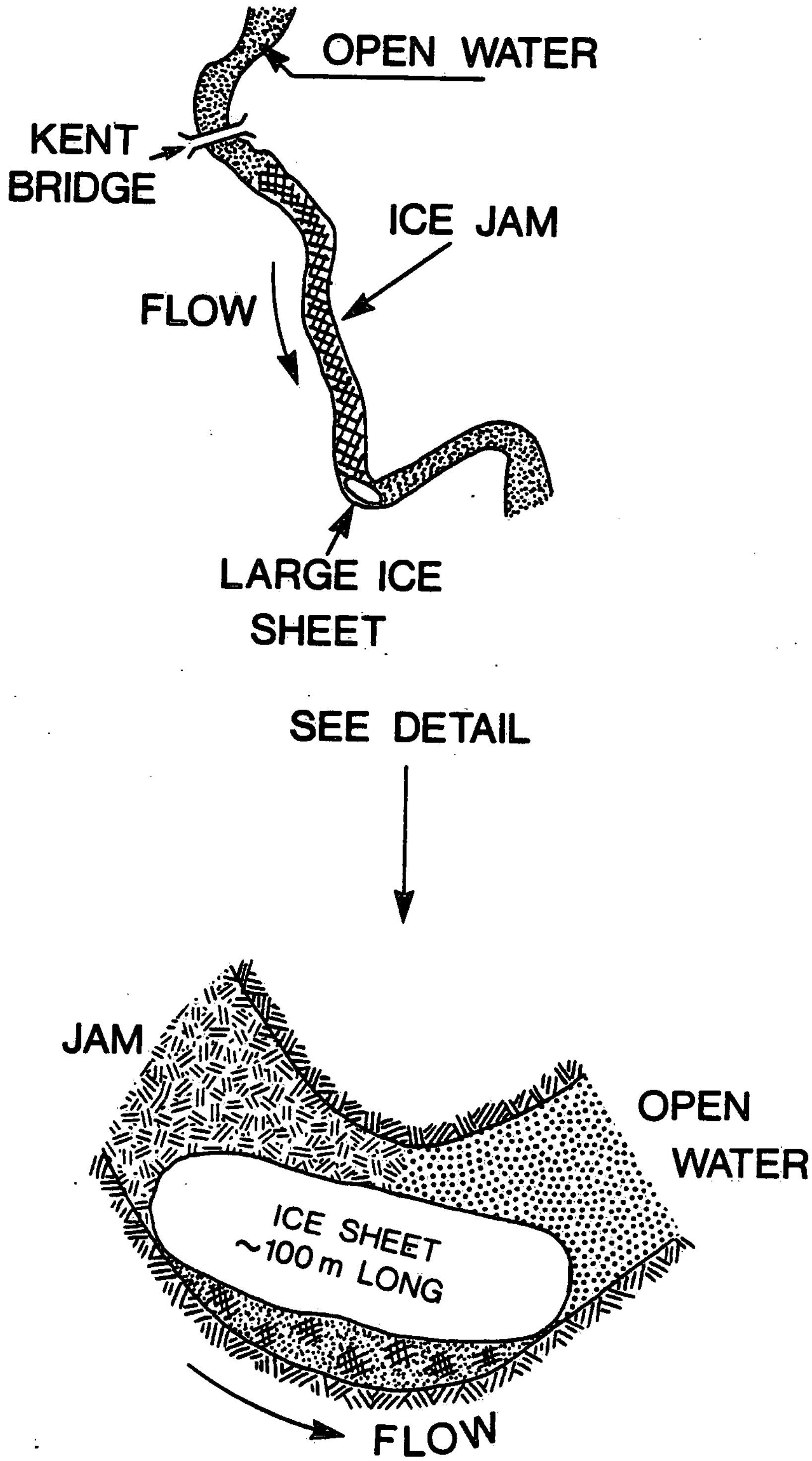



Fig. 6 - Configuration of ice jam near Kent Bridge at 1615 h, Feb. 14, 1984.

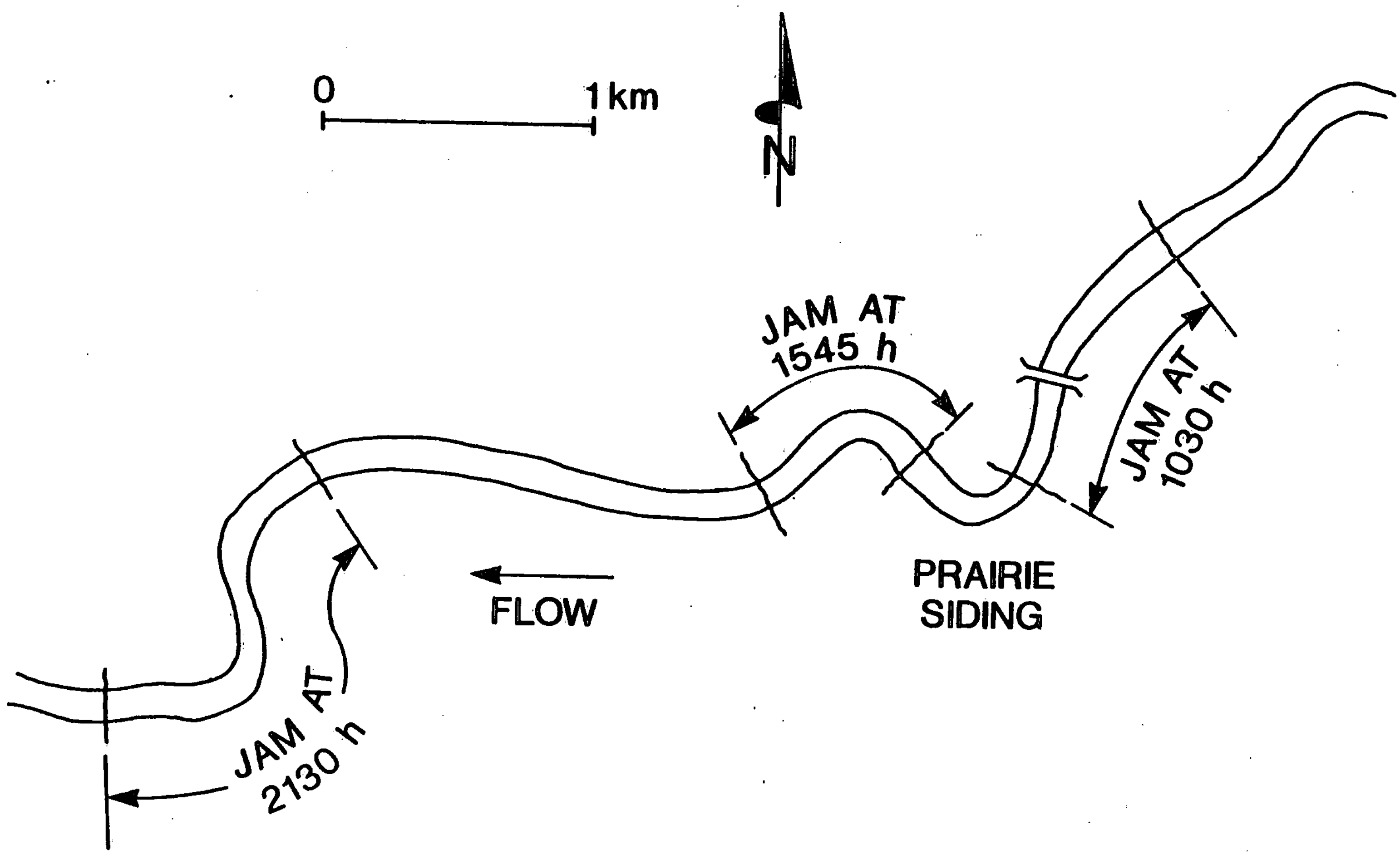



Fig. 7 Locations of jam below Chatham at different times on Feb. 15, 1984.

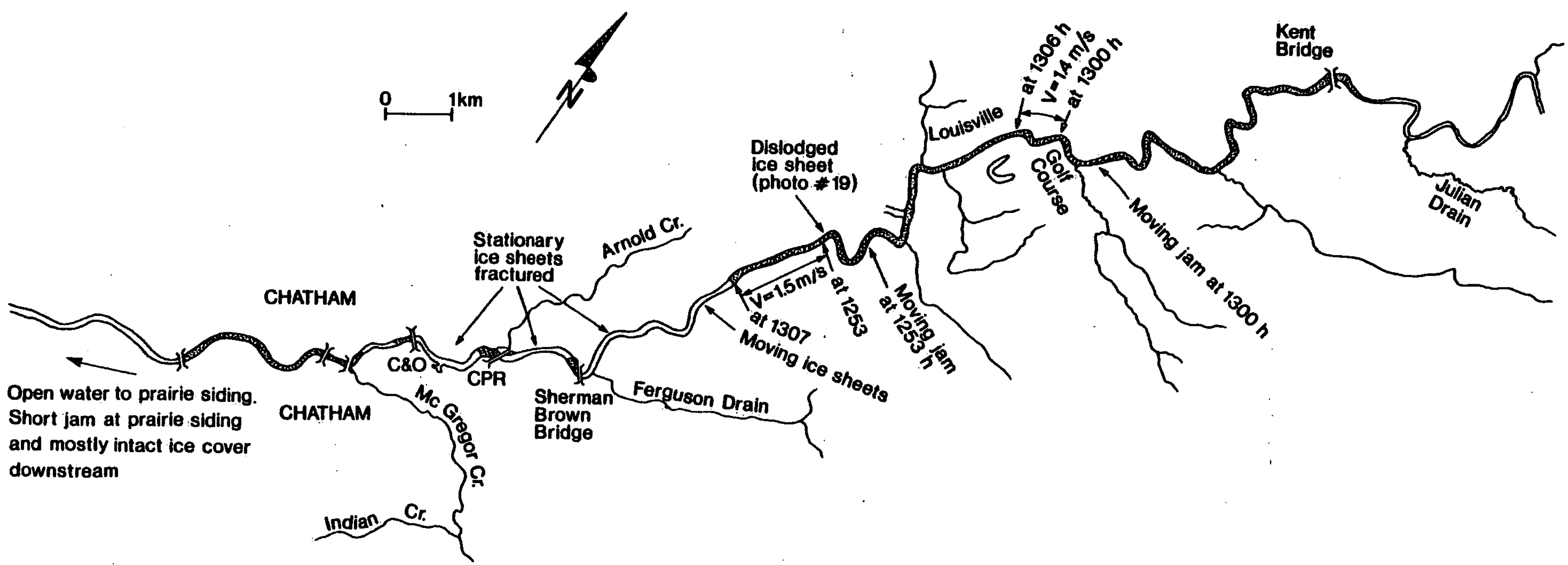



Fig. 8 Ice conditions during 1230 - 1330 h, Feb. 15, 1984.

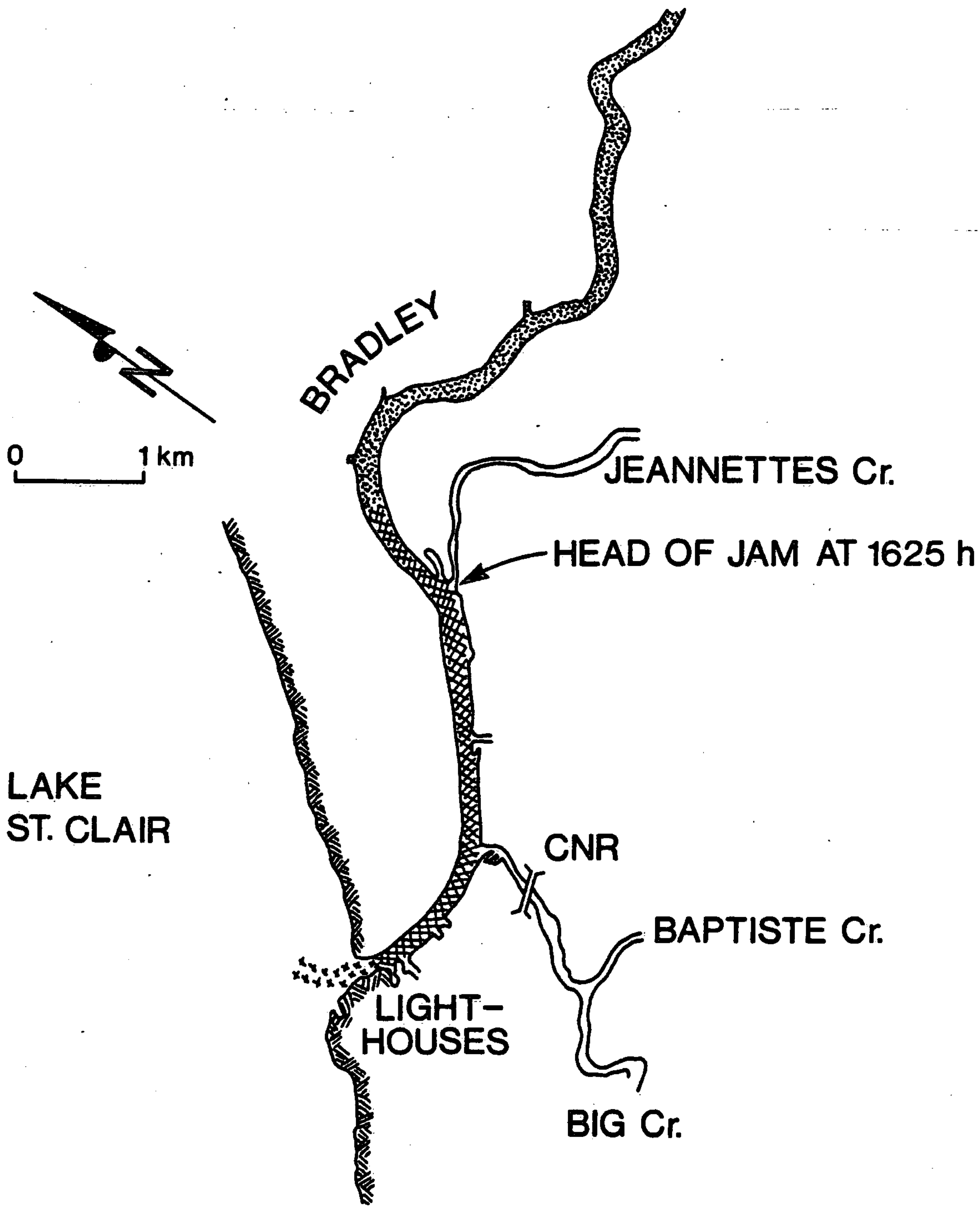



Fig. 9 Ice conditions at 1345 h, Feb. 16, 1984.

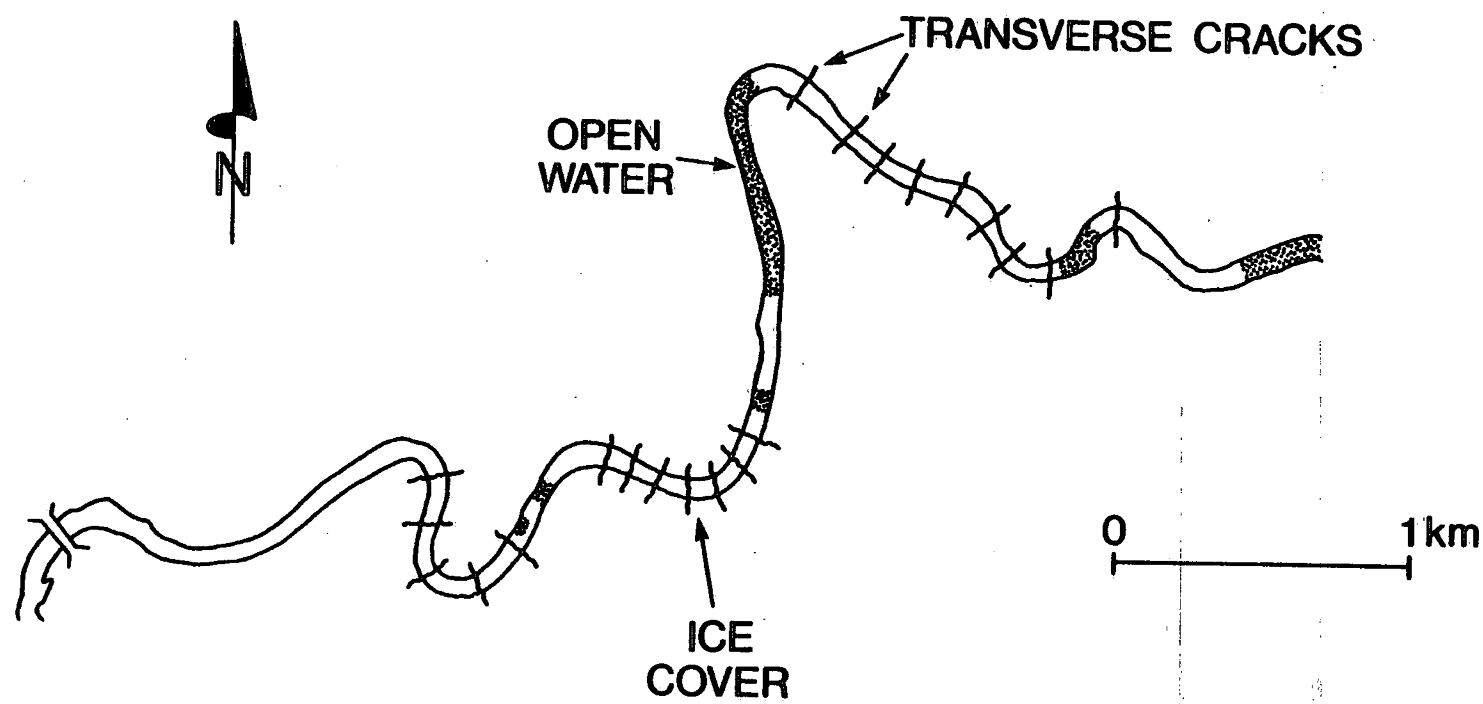



Fig. 10 Transverse crack pattern, observed during 1530 - 1630 h, Mar. 16, 1984.

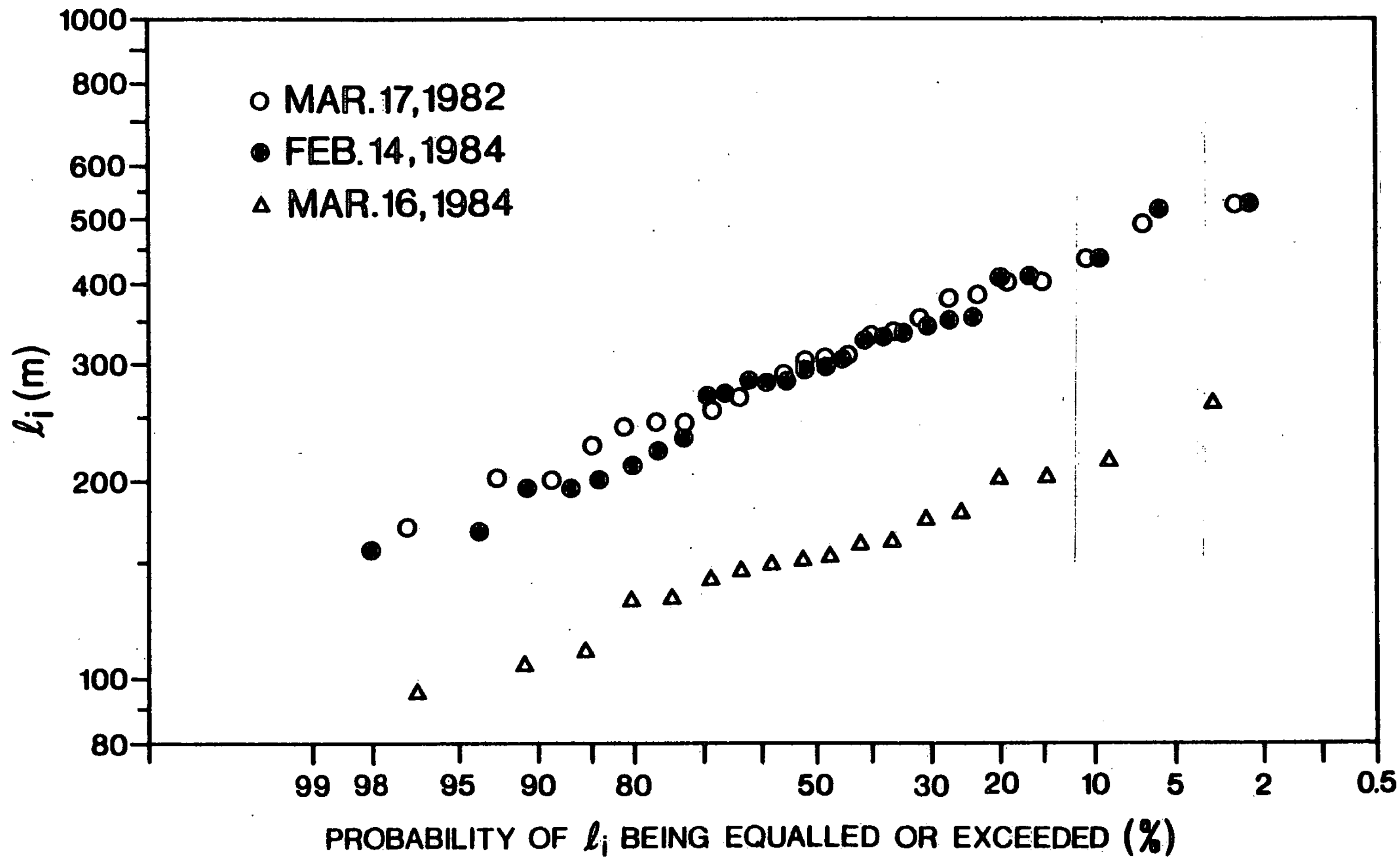



Fig. 11 Statistical distributions of lengths ($\ell_i$) of ice sheets observed in the Thames River.

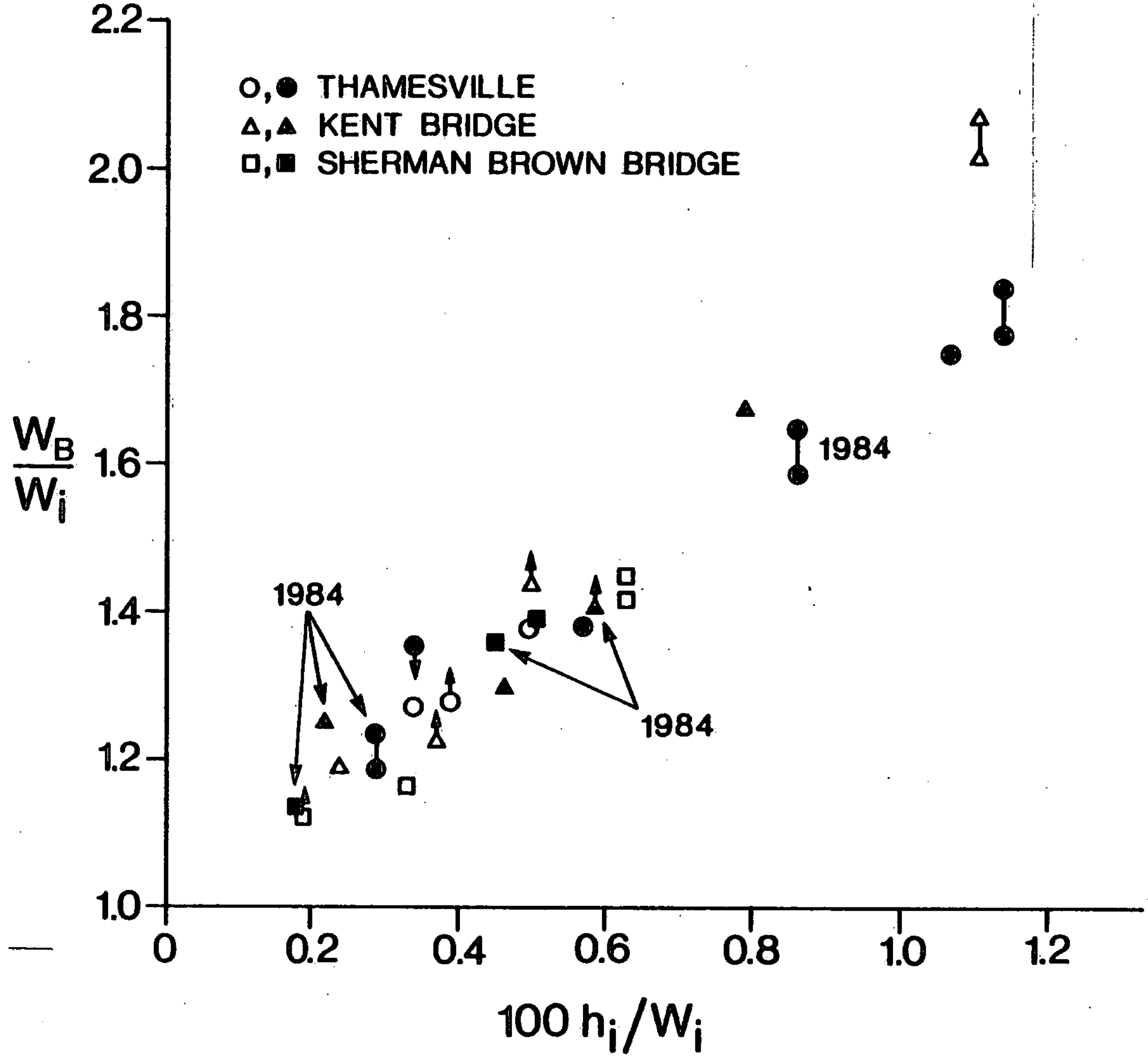



Fig. 12 Dimensionless breakup initiation relationship. (Arrows imply that actual point should plot higher than indicated. Open symbols denote uncertain data.)

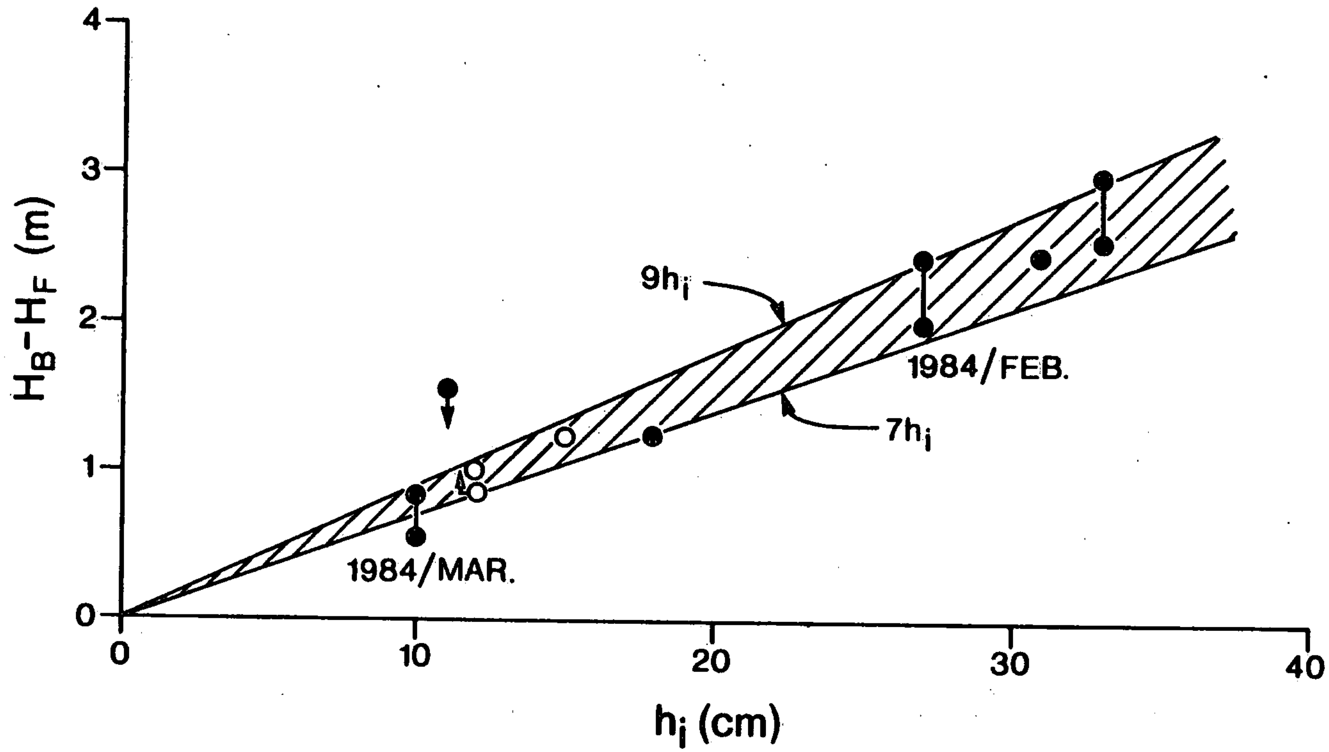



Fig. 13 Empirical relationship to forecast breakup initiation at Thamesville. (Legend same as in Fig. 12).

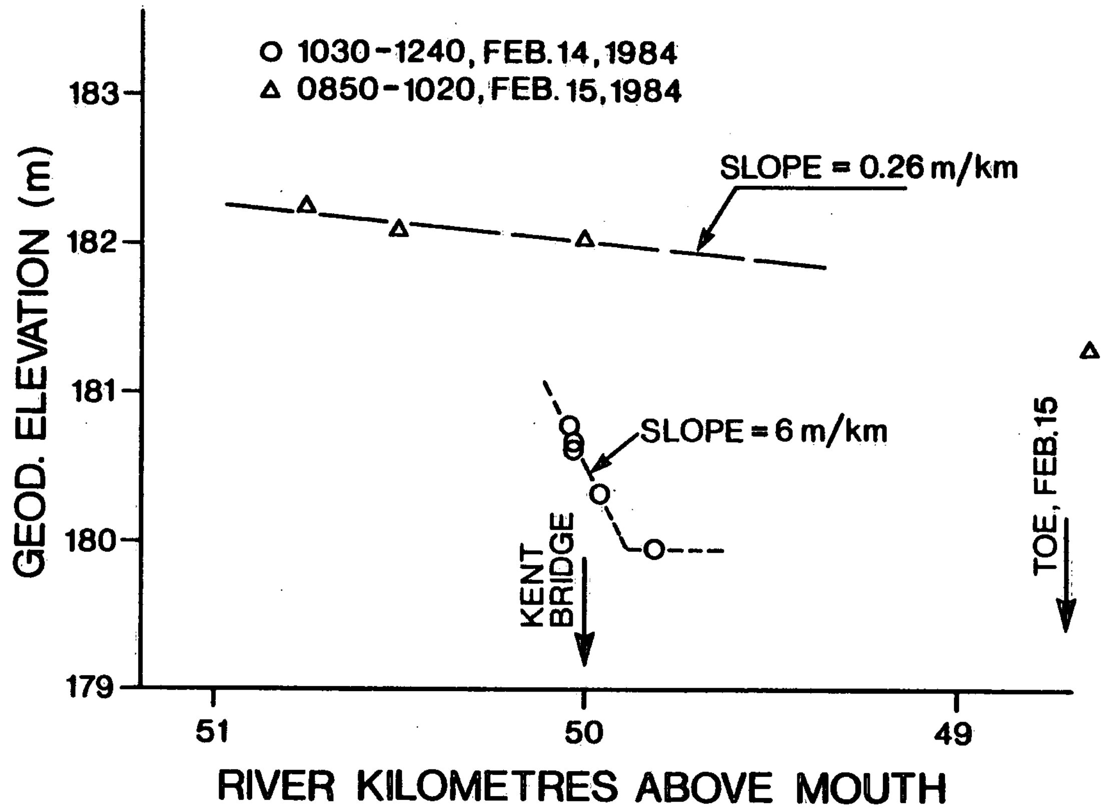



Fig. 14 Water surface profiles due to ice jams near Kent Bridge.

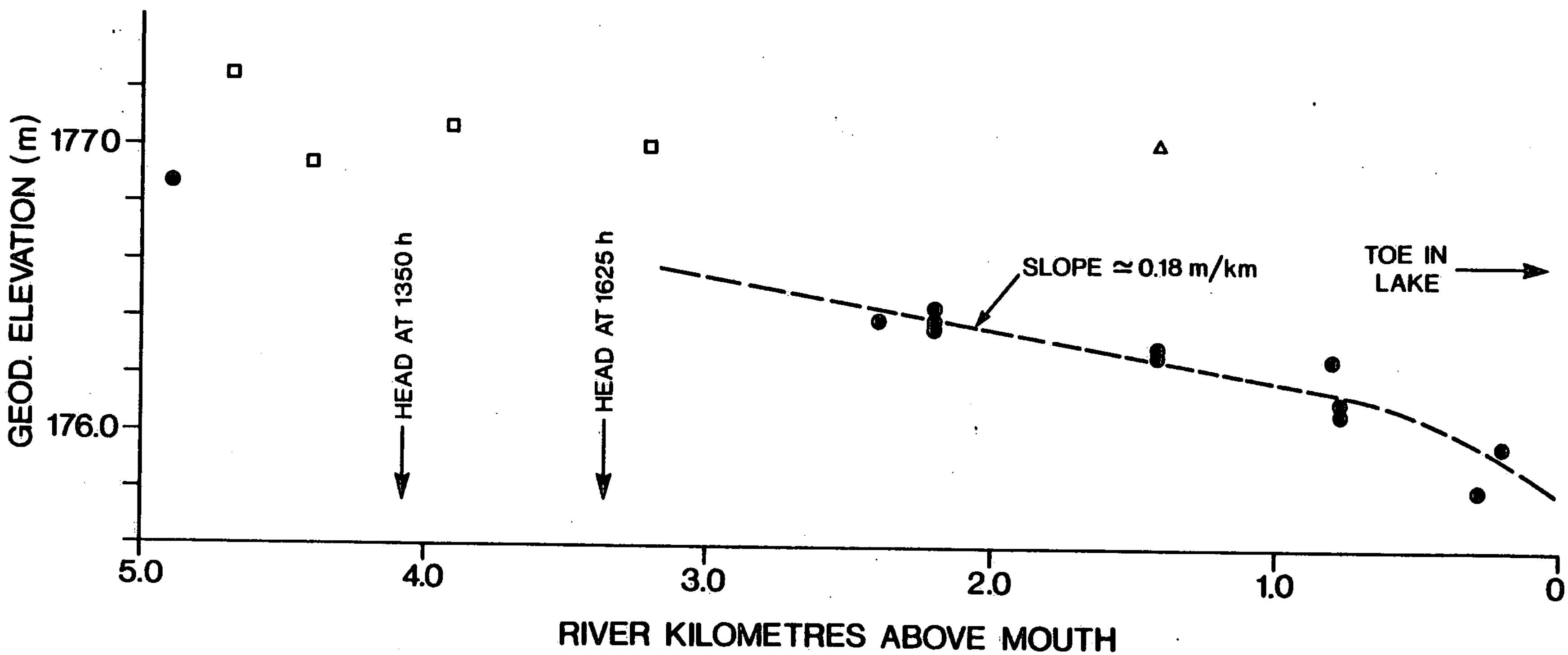



Fig. 15 Ice jam water levels near river mouth, Feb. 16, 1984. (circles: 0900 - 1200 h; squares: 1600 - 1700 h; triangle: high water mark observed on Feb. 17).

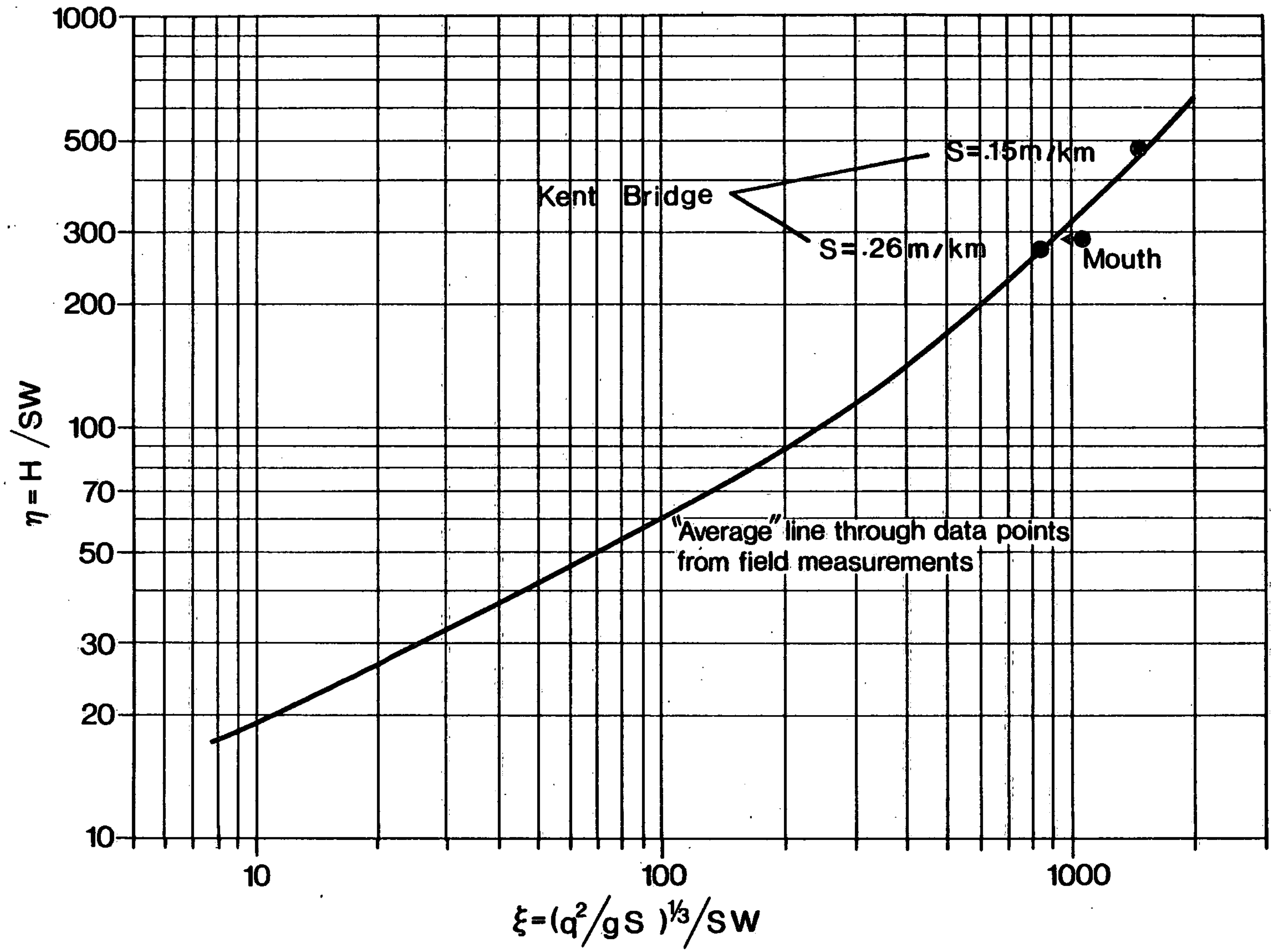
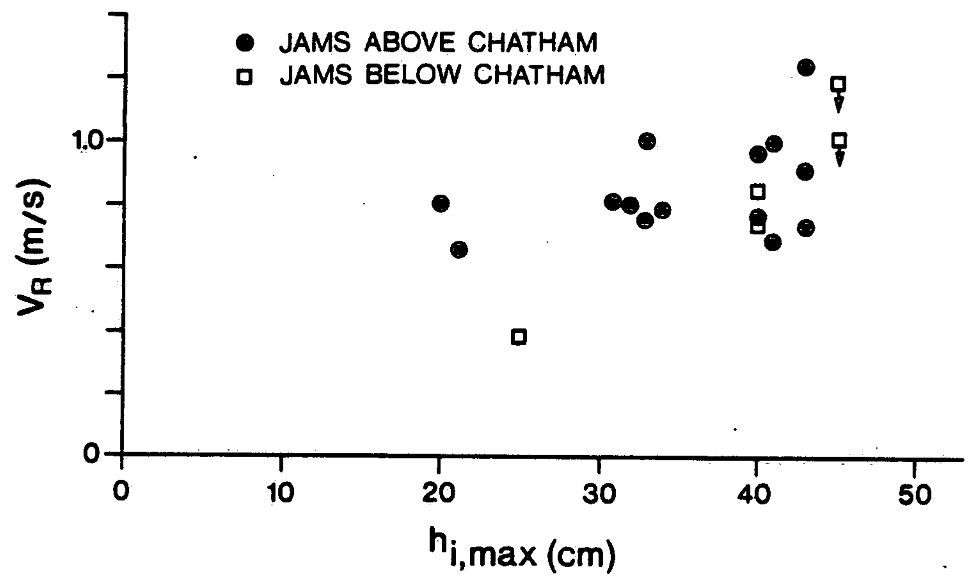



Fig. 16 Dimensionless 1984 ice jam depths versus dimensionless discharges and comparison with existing relationship based on field data in other river reaches.

Fig. 17 Estimated flow velocity just downstream of jam toe at the time of release versus ice cover thickness prior to breakup.



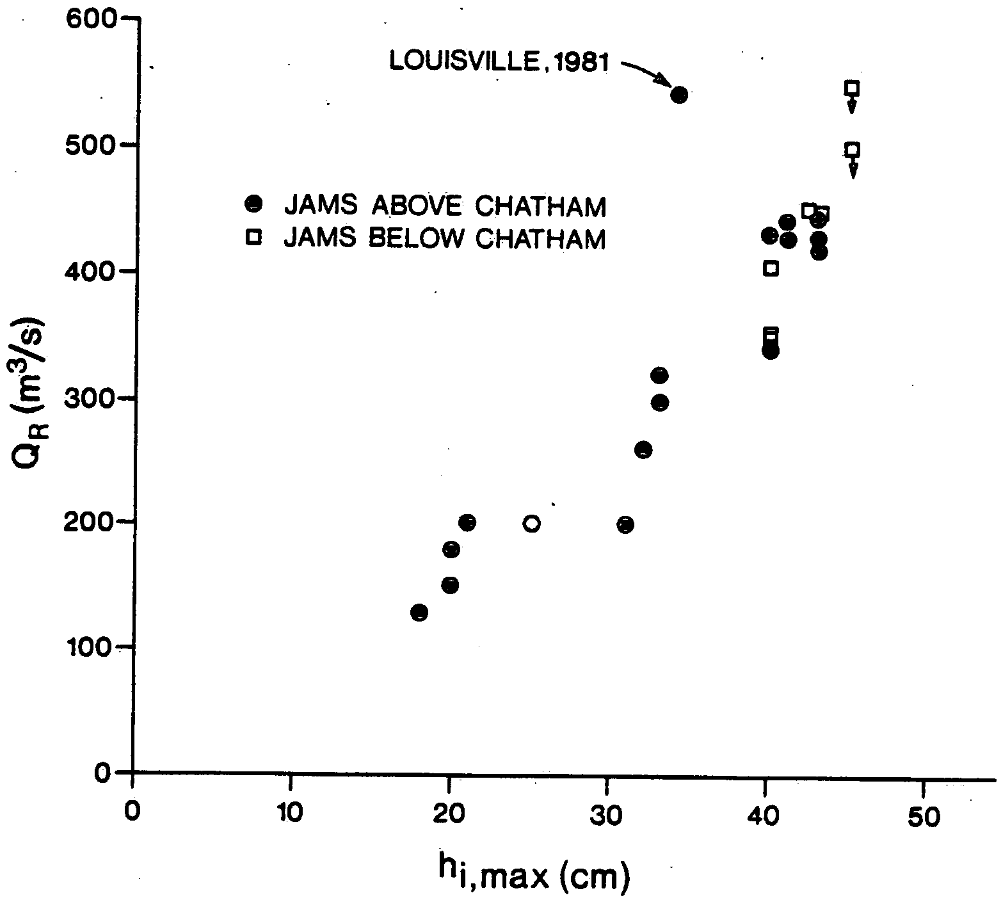




Fig. 18 Flow discharge at the time of jam release versus ice cover thickness prior to breakup.

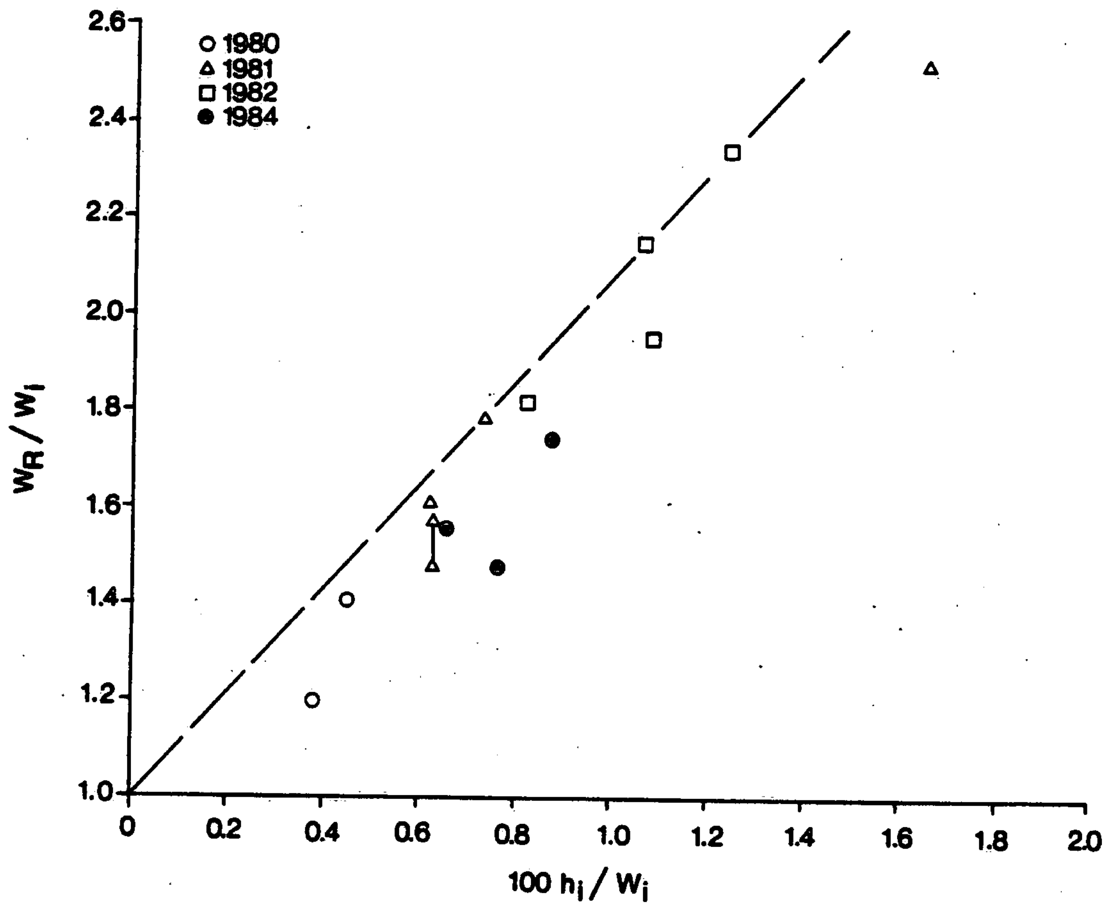



Fig. 19 Dimensionless plot of ice jam release data in Thames River above Chatham.