Wong (4)

Beltaos (21)

ICE FREEZE-UP AND BREAKUP OBSERVATIONS IN THE UPPER GRAND RIVER: 1980-81 AND 1981-82 OBSERVATIONS

by

J. Wong and S. Beltaos

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

May 1983

ABSTRACT

The first two years' ice observations on the Upper Grand River are described and interpreted. Flooding was experienced during both the 1980-81 and 1981-82 breakup seasons and was caused by major ice jams. Breakup initiation data for the Marsville and Upper Belwood gauge sites are consistent with earlier findings on other rivers. This was not the case for West Montrose. A possible cause of this discrepancy is the local formation and behaviour of slush jams during freeze up. Potential peak breakup stages, as predicted by the theory of equilibrium floating jams, were not exceeded by any of the four major jams that were documented. This is in agreement with expectation since three of these jams did not attain equilibrium and the fourth appeared to be associated with overestimated flow discharge.

RÉSUMÉ

Dans le présent article, sont présentées et interprétées les deux premières années d'observations glaciologiques dans la partie supérieure de la Grande-Rivière. Pendant les périodes de débâcle de 1980-1981 et 1982, ont eu lieu des inondations, causées par d'importants embâcles. Les données sur le début de la débâcle, dans les stations de jaugeage de Marsville et d'Upper Belwood, concordent avec les résultats antérieurs obtenus pour d'autres cours d'eau. Par contre, ce n'était pas le cas pour West Montrose. Cette déviation pourrait s'expliquer par la formation locale et le comportement d'embâcles de neige fondant pendant la phase d'englacement. Les stades potentiels de débâcle maximum, que laisse prévoir la théorie des embâcles flottants à l'équilibre, n'ont été surpassés par aucun des quatre principaux embâcles étudiés. Ceci concorde avec les résultats attendus, puisque trois de ces embâcles n'étaient pas parvenus à un état d'équilibre et que dans le cas du quatrième, le débit avait apparemment été surestimé.

MANAGEMENT PERSPECTIVE

This report gives the results of a field observation program which is used to validate and correct hypotheses on the water levels created by floating ice jams. Data was obtained giving support to equations relating flood level to ice and river variables for floating jams.

The results are tranferable by the theory to other locations, but additional data especially for other parts of the country is highly desirable. Eventually, the ideas and theories developed here, will be very useful in evaluating the downstream effects of hydro developments on ice regime and flood levels.

T. Milne Dick
Chief, Hydraulics Divison

PERSPECTIVE DE GESTION

Dans le présent rapport, sont présentés les résultats d'un programme d'observations in situ, qui permettra de justifier et de perfectionner l'hypothèse concernant les niveaux d'eau en présence d'embâcles flottants. Les données obtenues ont confirmé la validité des équations corrélant le niveau de crue aux variables caractéristiques du cours d'eau, en présence d'embâcles flottants.

La théorie permet l'extrapolation des résultats à d'autres localités, mais il serait très souhaitable de receuillir des données en d'autres parties du pays. Enfin de compte, les idées et théories présentées seront utiles, lorsqu'il faudra évaluer l'incidence, en aval, des projets hydroélectriques sur le régime glaciologique et les niveaux de crue.

T. Milne Dick
Chef de la Division de l'hydraulique

TABLE OF CONTENTS

1.0 INTRODUCTION

The Grand River Study is part of a long-term field research program initiated in 1979. The objective of the program 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.

At the present time, observations are carried out in two reaches, one on the Lower Thames River from Thamesville to the mouth; the other on the Upper Grand River from Leggatt to West Montrose (see Figure 1). The two study reaches have different characteristics. The Lower Thames River has a fairly uniform slope of approximately 0.2 m/km, and carries an average discharge of 55.2 m^3/s at Thamesville. The study reach on the Upper Grand River has a wide range of slopes and may be divided into five sections with average slopes ranging from 0.73 m/km (at Lake Belwood) to 8.20 m/km (at Elora Gorge) (see Figure 2). The Grand River study reach has an average discharge of 7.70 m^3/s at Marsville.

Observations of the freeze-up and breakup in the Lower Thames River 1979-80 has been documented in a previous report (Beltaos, 1981). The present report gives the results of the first two Grand River observation seasons: December 1980 to February 1981; and December 1981 to April 1982. This report contains: a description of the study reach;

summaries of freeze-up and breakup observations for both seasons; and analysis and interpretation of the recorded data. The two seasons documented in this report were marked by extensive flooding within the study reach. In 1980-81, West Montrose was flooded due to a major jam and residents along the left bank of the river were evacuated. The jam threatened but did not damage the historic covered bridge at West Montrose. In 1981-82, the village of Grand Valley was flooded on the last day of March. The water level rose over three metres within a matter of hours and caused extensive damage to the town.

2.0 DESCRIPTION OF STUDY REACH

The Grand River study reach is 61.74 km long with its upstream boundary at Leggatt and its downstream boundary at West Montrose (see Figure 1). The downstream boundary is not a strict one and observations have been carried out as far downstream as Winterbourne. Leggatt, the upstream boundary, is assigned a chainage of 0.00 km and all locations downstream are measured along the river from this point. Table 1 contains a list of the more important points along the study reach and their respective chainages, as measured on 1:50,000 topographic maps.

Figure 2 is an approximate water surface profile of the study reach. Water surface elevations have been obtained from a series of 1:50,000 topographic maps at the intersections of elevation contours with the stream boundaries. Straight lines have been drawn between points representing successive contour intersections. River crossings and gauge locations are also shown in Figure 2.

The study reach may be divided into five sections as shown in Figure 2. The divisions are based on the average slopes and the ice regimes in the sections. The sections are listed below and their average slopes and lengths are summarized in Table 2.

I Leggatt to Upper Belwood.
II Lake Belwood.
III Shand Dam to Elora.
IV Elora Gorge.
V Inverhaugh to West Montrose.

Ice related problems have been known to occur in only two of the five sections: section I and section V. Section I, which includes Grand Valley, Waldemar and Marsville, is 24.75 km in length and has an average slope of 1.44 m/km. Section V, which includes Inverhaugh and West Montrose, is 12.56 km in length and has an average slope of 1.96 m/km.

Lake Belwood (section II) freezes up early in the winter and acts as a control against spring flooding. The Shand Dam is regulated during the winter months so that the storage in the lake is reduced. This enables the lake to accept the increased flow of water and ice delivered by section I during the spring runoff. The ice is held in the lake and is not allowed to move downstream into sections III and IV. The dam is also capable of controlling, to some extent, the discharge from the lake as in the case of the 1981 West Montrose flooding.

Sections III and IV are extremely steep with average slopes of 3.61 m/km and 8.20 m/km, respectively. This length of river usually stays free of ice during the winter months. There are three weirs in Fergus and Elora, at 40.37 km, 45.75 km and 46.42 km. Short lengths of ice (~1 km) form behind the weirs but the ice usually melts in place and does not cause any problems.

There are three Water Survey of Canada (WSC) gauges and six Grand River Conservation Authority (GRCA) gauges within the study area. Locations of the gauges are noted in Figure 2 and Table 1. River characteristics for the three WSC gauges are summarized in Table 3 for the period 1970 to 1979. At Marsville, the minimum and maximum recorded daily discharges are 0.031 m^3/s (July 1979) and 306 m^3/s (April 1975). The ten-year average discharge is 7.70 m^3/s. At this flow, the average open water width, depth and velocity in the vicinity of this site are calculated as 38.0 m, 0.63 m and 0.56 m/s based on nearby hydrometric surveys. The average river slope is approximately 2.31 m/km and the Manning coefficient of the river bed, n_b, is 0.052 at Q (discharge) = 7.70 m^3/s.

3.0 SUMMARY OF FREEZE-UP AND BREAKUP OBSERVATIONS

3.1 Freeze-up and Winter 1980-81

Ice conditions during freeze-up were first observed on December 17, 1980. In general, the river was still open with stationary border ice and moving frazil slush. Anchor ice could be seen at the Highway 9 crossing. Complete ice cover sections were noticed downstream of the Leggatt crossing, at the 3rd crossing above Grand Valley, and over a 4 km long reach near Grand Valley (see also photographs in Appendix A). Water Survey of Canada gauge records indicated that complete ice cover at Marsville and West Montrose formed on December 23 and December 18, respectively. The corresponding gauge heights were 3.95 m and 13.10 m (see also Table 5).

Ice thickness measurements and hydrometric surveys were performed during January 9-14, 1981. Available ice thickness data are summarized in Table 4. At West Montrose, a slush deposit extending vertically to the stream bed and over about 2/3 of the width laterally, was detected. The thickness values shown in Table 4 apply to the slush-free portion of the stream.

3.2 Breakup 1980-81

Atmospheric Environment's "Monthly Record" for February 1981, indicates that, at Grand Valley, the maximum air temperature rose above freezing (+3.0°C) on both February 10 and 11. This was followed by two cold days but by February 16, the mean air temperature began to exceed 0°C. On February 10, 24 mm of rain was recorded, followed by 6.6 mm on February 16 and more rain on February 22 and 23. Similar weather conditions were recorded at Elora. Due to manpower limitations and simultaneous ice monitoring elsewhere, field observations of ice conditions only commenced on February 20 and continued until February 24. Breakup had already been in progress for some time before February 20 and the study reach (Leggatt to West Montrose) was ice free by February 23. The breakup observations are briefly summarized below (see also photographs in Appendix B).

February 20, 1981:

Average temperature = 3.0°C at Grand Valley; = 3.5°C at Elora.
Rain = 1.0 mm at Grand Valley; Trace precipitation at Elora.
Q = (daily average flow discharge) ≈ 120 m^3/s near Marsville;
Q ≈ 65 m^3/s at West Montrose.

During 1430 h to 1740 h, open water was observed at all river access points between Leggatt and Upper Belwood. Ice blocks, piled on the river banks were observed at several locations. Remnants of major jams (shear walls) were noticed at Leggatt; near the 2nd crossing above Grand Valley; near the 1st crossing above Grand Valley (local residents reported that Highway 25 was flooded at this location during the night of February 19); and near Marsville.

February 21, 1981:

Average temperature = 2.3°C at Grand Valley; = 2.3°C at Elora.
Rain = 0.4 mm at Grand Valley; Trace precipitation at Elora.
Q ≈ 110 m^3/s near Marsville; Q ≈ 44 m^3/s at West Montrose.

Open water was observed from the Marsville crossing to Belwood and from Inverhaugh to a few kilometres above West Montrose. There were sections of intact ice cover through Fergus and Elora. Remnants of major jams were noticed at the Belwood crossing and the Upper Belwood bridge. At the latter site, locals reported that the road was flooded on February 19 which resulted in large ice floes still left on the road. Similar conditions prevailed at and downstream of Inverhaugh.

At 1400 h, the head of a major jam was observed about 3 km upstream of the Highway 86 bridge. The toe of this jam was located about 100 m downstream of the bridge. Downstream of the toe there was relatively intact ice cover with open water side strips to, at least, Winterbourne.

February 22, 1981:

Average temperature = 4.3°C at Grand Valley; = 4.8°C at Elora.
Rain = 9.0 mm at Grand Valley; Rain = 7.6 mm at Elora.
$Q \simeq 102\ m^3/s$ near Marsville; $Q \simeq 34\ m^3/s$ at West Montrose.

The jam packed during the previous night and by 1130 h, its head was 200 m upstream of the Highway 86 bridge. Between 1500 h on February 21 and 1500 h on February 22, the water level at this bridge dropped by about 0.33 m. At West Montrose, the gauge height reached a minimum of 12.86 m at about 2130 h on February 22 (Figure 3).

February 23, 1981:

Average temperature = 4.0°C at Grand Valley; = 4.8°C at Elora.
Rain = 7.8 mm at Grand Valley; Rain = 7.6 mm at Elora.
$Q \simeq 163\ m^3/s$ near Marsville; $Q \simeq 140\ m^3/s$ at West Montrose.

The gauge record in Figure 3 shows a sharp rise to 13.89 m at about 0520 h and continued but slower rise to 14.00 m by 1000 h. Locals reported that the ice started to move at about 0530 h and subsequently jammed against the intact ice and the piers of the covered bridge. Residents of the low lying left river bank at West Montrose were evacuated during the early morning. To ease the problem, blasting operations commenced at 1040 h, in a reach between 1.0 and 1.5 km downstream of the covered bridge. The jam began to move at 1109 h but stopped five minutes later. This event was followed by a sharp stage rise of 0.45 m at the gauge site, resulting in a peak breakup stage of 14.46 m. An explosion at 1311 h was followed by the final release of the jam. The stage dropped to 13.15 m at 1351 h and reached a minimum of 12.74 m at 1505 h. Subsequently, the stage rose but under open-water conditions. A new peak of 13.30 m was reached at 2200 h, followed by continuous drop over the next few days.

3.3 Initiation of Breakup 1980-81

At the Marsville gauge site, there was already open water when observations commenced in the afternoon of February 20. The gauge record, provided by Water Survey of Canada, shows a steady stage value of 3.86 m during February 15 and 16. The stage began to rise in the morning of February 17 and by 2100 h on February 18, the stage was at 4.50 m. Shortly afterwards, the record exhibited spikes that can only be attributed to broken ice effects. Thus the time of breakup initiation is estimated as 2200 h, February 18; the corresponding stage, H_B, is between 4.60 and 4.85 m. A maximum breakup stage of 5.49 m was reached at 0145 h on February 19. The duration of this peak was only 30 minutes which suggests that it was caused by an unstable ice jam. Several lesser peaks were attained subsequently but disappeared by noon of February 20.

At West Montrose, the sheet ice cover was still in place in the afternoon of February 22. This implies that a peak of 13.58 m, reached at 1600 h on February 20 (Figure 3), was not sufficient to initiate breakup. Based on earlier considerations, breakup initiation occurred at about 0530 h, during the associated sharp water level rise. It follows that H_B should be less than 13.96 m (see Figure 3).

3.4 Ice Jams 1980-81

In addition to observations carried out on the West Montrose jam, photos were taken of shear walls at upstream locations and used for later surveys. Such photos enable approximate determinations of ice top elevations and local jam thicknesses. For the West Montrose and Marsville gauge sites, ice top levels obtained from photographs were found to be in fair agreement with corresponding peak gauge heights. Shear wall heights were 1.65 m at a location below Leggatt and 1.50 m at Upper Belwood.

3.5 Freeze-up and Winter 1981-82

Observations of ice conditions during freeze-up were carried out on December 16, 1981. This was early in the season and most reaches had some border ice but were open in the centre. Frazil slush was flowing freely in the river. Lake Belwood by this date was completely ice covered and the ice cover had progressed toward the Upper Belwood crossing.

Complete ice cover also formed at the small weir in Grand Valley (Photo C1 in Appendix C) and progressed 0.67 km upstream to the Amaranth St. crossing. "Hummock" ice formed at these locations resulted from the frazil floes packing against the ice cover boundary. The rough appearance of this type of ice cover is shown in Photo C2 in Appendix C. Using gauge records from the Water Survey of Canada and the Grand River Conservation Authority, the times of the formation of complete ice cover and the corresponding gauge heights were determined for Marsville, Upper Belwood and West Montrose. The data are listed in Table 5.

By March 16, 1982, sections I, II and V were completely ice covered. The steeper sections of the study reach (sections III and IV) were open except for short lengths of ice (~ 1 km) behind the weirs in Fergus and Elora.

3.6 Breakup 1981-82

Breakup in the study reach occurred between March 16 and April 1, 1982. During this time, there formed numerous small jams and one large jam which flooded the village of Grand Valley on March 31. The observations are summarized below (see also photographs in Appendix D).

March 16, 1982

Average temperature = 2.3°C at Grand Valley; = 1.8°C at Elora.
Rain = 5.4 mm at Grand Valley; Rain = 6.2 mm, Snow = 1.9 cm at Elora.
$Q \approx 7.20\ m^3/s$ near Marsville;
$Q \approx 4.3\ m^3/s$ at West Montrose.

At most access points in section I, the ice was intact with water running over ice along the banks.

Short open leads and open patches were observed at the 1st crossing upstream of Grand Valley, at the Main St. crossing in Grand Valley, and at the 1st crossing upstream of Waldemar.

Cracks extending along the length of the river were visible at Leggatt, at the 3rd crossing upstream of Grand Valley, at the 2nd crossing upstream of Grand Valley, and at the 2nd crossing upstream of Waldemar. Photographs of these cracks are shown in Photos D1 and D2 in Appendix D.

At Waldemar and Upper Belwood, the inflows from creeks above the two bridges caused large open patches and large areas with water over the ice.

Lake Belwood (section II) was ice covered.

The short lengths of ice behind the weirs in Fergus and Elora were intact.

The ice cover in section V extending from Inverhaugh to West Montrose was still intact.

March 17-25, 1982

Average temperature for nine-day period = -0.9°C at Grand Valley; = -0.4°C at Elora.
At Grand Valley, rain = 0.8 mm, snow = 0.4 cm on March 21.
snow = 6.2 cm on March 25.

At Elora, rain = 1.0 mm on March 20.
rain = 0.3 mm on March 21.

Average discharge for nine day period = 9.2 m^3/s near Marsville;
= 7.3 m^3/s at West Montrose.

The deterioration of the ice cover continued over the nine day period and ice conditions at the end of this period are noted below.

By March 25, the river was open at Leggatt and for 1 km downstream of this point. Starting from 500 m downstream of the 1st crossing upstream of Grand Valley, a 3 m wide open lead meandered down the river for approximately 1 km. At the Main St. bridge in Grand Valley a 4 m wide lead ran downstream of the bridge for 1 km. Apart from these three locations, the ice from Leggatt to Waldemar remained intact but appeared weak. There were numerous cracks and the water had risen above the ice at several locations.

The inflow from Willow Brook aided the breakup process at and downstream of Waldemar. Breakup initiation had occurred at numerous locations between Waldemar and Upper Belwood. The ice movements at these locations resulted in small surface jams which were held back by intact ice cover sections. Photo D7 in Appendix D shows a small jam at the 2nd crossing downstream of Marsville.

At Marsville, the ice immediately below the bridge was intact and a 550 m long jam piled up behind the ice sheet. At 1025 h on March 25, the ice sheet broke and the jam moved approximately 200 m and came to rest with the toe 150 m downstream of the bridge and the head 400 m upstream of the bridge. The movement of the jam caused a sharp rise in the water level and this can be seen in the gauge height versus time graph in Figure 4. The water level remained high as the jam remained in place over the next several days.

Lake Belwood remained ice covered.

The ice behind the weirs in Fergus and Elora remained intact.

In section V, the 1st and 2nd crossings downstream of Inverhaugh were open. At Highway 86, the ice was intact with an open channel along the right bank where a small creek fed into the river. The ice cover remained intact at West Montrose.

March 26 to 29, 1982

Average temperature for 4-day period = -6.8°C at Grand Valley,
= -5.9°C at Elora.

Rain = 0.2 mm at Grand Valley, no precipitation at Elora.

Average discharge for 4-day period ≈ 17.2 m^3/s near Marsville;
≈ 29.0 m^3/s at West Montrose.

The low temperatures between March 26 and 29 caused the breakup process to slow down significantly. There was little visible change in ice conditions during this time.

March 30, 1982

Average temperature = 1.0°C at Grand Valley; = 3.2°C at Elora.

Rain = 25.0 mm at Grand Valley; rain = 20.4 mm at Elora.

Q ≈ 17.5 m^3/s near Marsville; Q ≈ 35.0 m^3/s at West Montrose.

This date marked a noticeable change in the weather conditions. The cold spell ended and the deterioration of the ice continued throughout the morning and the afternoon. The rain which caused the final movement of the ice began at 1940 h.

The study reach was observed from the air by using a small aircraft betwen 1030 h and 1120 h. The observations are summarized in the following paragraphs and in Figures 5 and 6 and in Photos D3 to D14 in Appendix D.

In Section I, the ice was weak but still in place between 1 km downstream of Leggatt and Willow Brook which is 350 m upstream of Waldemar (see Figure 5). Open leads were observed at the 1st crossing upstream of Grand Valley (Photo D3) and at the Main St. bridge in Grand Valley.

From Waldemar to Upper Belwood, there were a number of ice jams with open water between them (see Figure 5). A 600 m long jam was located at Marsville (Photo D5). At the 1st crossing downstream of Marsville, a jam extended from 200 m upstream to 30 m downstream of the bridge (Photo D6). At approximately 500 m upstream of the 2nd crossing downstream of Marsville, a 200 m jam was located. Another 150 m long jam was located 300 m downstream of the same crossing (Photo D7). The toe of a 600 m jam was above the confluence of a small creek 300 m upstream of the Upper Belwood crossing (Photo D8). The head of another jam was 600 m and the toe was 1.5 km downstream of the same bridge. This jam rested on the ice cover which extended into Lake Belwood.

In section II, Lake Belwood was ice covered but the ice was deteriorating in the upper portion of the lake. The ice conditions at the Belwood crossing are shown in Photo D9.

The ice behind the weirs in sections III and IV was still intact. Aerial photographs (Photo D10, D11) were taken in Fergus and Elora.

In section V, a 100 m long jam was located at the mouth of Carroll Creek which is about 1.5 km upstream of Inverhaugh. Ice remained intact in the left channels at the 1st crossing downstream of Inverhaugh and just downstream of the crossing (Photo D12). Otherwise, the river was open until about 4 km upstream of Highway 86 crossing. There was a jam at this location and from there to the end of the study reach, the ice was still intact. Aerial photographs of Highway 86 and West Montrose crossings are shown in Photos D13 and D14, respectively.

The ice conditions in the study reach remained the same until the rainfall began at 1940 h. The 600 m long jam at Marsville released at 2028 h and the water level dropped 0.53 m within 14 minutes after the release as shown in Figure 4. By 2047 h, the jams at the 1st crossing downstream of Marsville had cleared. The 600 m long jam located 300 m upstream of the Upper Belwood crossing had released and the ice pieces were passing under the right side of the bridge at 2107 h.

31 March 1982

Average temperature = 6.0°C at Grand Valley; = 7.6°C at Elora.
No precipitation.
Q = 155 m^3/s near Marsville; Q = 145 m^3/s at West Montrose.

Approximately 22 mm of rain fell since 1940 h on March 30 and the condition in the study reach changed dramatically. Breakup was initiated at many previously ice covered sections and many of the jams noted on the previous day released overnight.

Section I was inspected between 0640 h and 0742 h and the following observations were made.

The Leggatt crossing, the 3rd crossing upstream of Grand Valley and the 2nd crossing upstream of Grand Valley were open.

The toe of a 125 m long jam was located at the 1st crossing upstream of Grand Valley. Downstream of this bridge, the river was open for 900 m and then jammed.

The ice sheet under Amaranth St. bridge in Grand Valley had moved and shoved onto the left bank of the river.

Large ice sheets were held by the banks 50 m upstream of the Main St. bridge. The downstream side was open for about 500 m and then ice blocks were jammed against solid ice cover.

Small jams were also located at the 1st and 2nd crossings upstream of Waldemar.

The rest of the river in section I was open. The jam downstream of the Upper Belwood crossing was out of sight, i.e., the head was more than 600 m downstream of the bridge.

By 1005 h, the ice at the Amaranth St. bridge in Grand Valley moved and at 1029 h, the jam at the 1st crossing upstream of Grand Valley also released. All the ice joined the large jam which had its toe at the mouth of Boyne Creek, 900 m downstream of the Main St. bridge in Grand Valley. The water levels behind the jam rose sharply and flooding was experienced throughout the village of Grand Valley. Figure 7 shows the water level versus time at the Main St. and Amaranth St. bridges. Photos D15, D16, D17 and D18 show the extent of the flooding in Grand Valley at various times during the day.

By 1147 h, the jam at the 1st crossing upstream of Waldemar had released and by 1258 h, the jam at the 2nd crossing upstream of Waldemar had also cleared. The only remaining ice in section I was the jam in Grand Valley.

By 1422 h, the latter jam extended from Boyne Creek, 900 m downstream of the Main St. bridge, to about 500 m upstream of the same bridge. The jam released at 1600 h and the surge and the ice that followed ran unobstructed into Lake Belwood.

No observations were made in any of the other four sections on this date.

1 April 1982

Average temperature = 0.3°C at Grand Valley; = 1.4°C at Elora.
No precipitation.
Q ≈ 171 m^3/s near Marsville; Q ≈ 137 m^3/s at West Montrose.

The river was open at all access points in the study reach.

Remnants of the ice jam at Grand Valley are shown in Photo D19 to D20.

The ice behind the weirs in Fergus and Elora had cleared.

Ice blocks along the banks indicated that there had been a jam between West Montrose bridge and Highway 86 crossing. The Water Survey of Canada gauge records showed that the jam was in place until 2000 h on March 31.

4.0 DATA INTERPRETATION AND ANALYSIS

4.1 Initiation of Breakup

Earlier work on the lower Thames River (Beltaos 1981, 1982a) has shown that, at a given site, the breakup initiation stage, H_B, depends on the maximum (daily average) freeze up stage, H_F, as well as on the ice thickness at the time of breakup, h_i. The stage is usually associated with the time of formation of a complete ice cover across the stream and thus provides a measure of the ice cover width, W_F. Similarly, the stage H_B is a measure of the water surface width that is available for movement of the ice cover, W_B. Beltaos (1981, 1982a) argued that the ratio W_B/W_F should depend on h_i/W_F as well as on several other dimensionless parameters that reflect the driving force of the water, ice strength and channel geometry. Because W usually varies as a power of Y (= average flow depth), the ratio W_B/W_F can be replaced by Y_B/Y_F. Considering also that ΔH (= stage in excess of stage at zero discharge) is a rough measure of Y, Y_B/Y_F can be approximately replaced by the more convenient parameter $\Delta H_B/\Delta H_F$.

The available data for 1980-81 and 1981-82 seasons are listed in Table 5. H_F and H_B were deduced from observation notes and from gauge records provided by Water Survey of Canada and by Grand River Conservation Authority. The ice thickness measurements listed in Table 4 enable ice growth patterns to be established for the three gauge sites. The ice thickness is related to the degree-days of frost after freeze-up and estimates of ice thicknesses at the time of break up are listed in Table 5. These values are consistent with measurements of ice left on the banks after breakup (e.g. in 1980-81, h_i = ~49 cm at West Montrose).

Figure 8 shows $\Delta H_B/\Delta H_F$ plotted against $100h_i/W_F$, along with a data range applicable to the Thames River at Thamesville. It is seen that the data points for Marsville and Upper Belwood are in fair agreement with the Thames River data but those for West Montrose are not. This discrepancy may be due to local slush accumulations that were detected during both seasons. Detailed observations during the 1982-83 freeze up revealed that, initially a slush jam formed and caused high water levels. The maximum daily freeze up stage H_F was thus associated with the formation of this jam. Subsequently, however, the stage dropped relatively fast, leaving crusty and porous ice accumulations on the river banks, as illustrated in Figure 9. These accumulations slowly disappeared during the winter while the final solid ice cover formed at a lower stage than the assumed H_F. It appears, therefore, that in such instances, a meaningful value of H_F can only be established on the basis of insitu observations.

Another interesting finding in Figure 8 is that the 1981-82 Grand River data points are low relative to those for 1980-81. This could be attributed to the fact that the 1980-81 breakup was of the "premature" type, i.e., it took place after a February thaw and rainfall with little time for the ice cover to deteriorate. In contrast, the 1981-82 breakup was preceeded by several days of mild weather and considerable weakening of the ice.

4.2 Ice Jams

Based on theory and field data, Beltaos (1983) has shown that the water depth, h_j, caused by a floating, equilibrium jam can be approximately determined from the following relationship

$$\eta = h_j/WS = f(\xi) \qquad (1)$$

in which W = channel width; S = channel slope; $h_j = h + s_i t$ = total water depth; h = depth of flow under the jam; t = jam thickness; and s_i = specific gravity of ice ≈ 0.92. The parameter ξ is a dimensionless discharge defined by

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

in which q = Q/W; Q = discharge; and g = acceleration of gravity. The function f is depicted in Figure 10 as a band of which the upper and lower limits envelope the available field data. It must be emphasized that Eq. 1 and Figure 10 apply to equilibrium jams, i.e., jams in confined channels which have attained a steady state condition and contain a uniform flow depth and jam thickness reach. The depth h_j applies to the latter reach and can be shown to be the maximum possible for breakup jams in ordinary streams (Beltaos 1983). If a jam is still in the process of evolution or if it rises above the channel banks with water and ice spreading laterally on the flood plain, the stage would be less than that indicated by Eq. 1.

Observations of the breakup process for both seasons have noted the presence of a number of small ice jams in the study reach. The jams were usually short (in the order of 100-300 m in length) and did not cause significant increases in the water surface elevations. These jams were documented but no further analyses were performed.

Four larger ice jams were documented and analysed. These are: West Montrose (1981), Marsville (1981), Marsville (1982) and Grand Valley (1982). Jam characteristics such as the state of the jam, gauge height and estimated flowrate are listed in Table 6. Estimates of the average river width, slope and depth of flow were obtained from cross-sections taken at the jam locations. These parameters together with the calculated values of η and ξ are also listed in Table 6. The latter two parameters for each jam are plotted in Figure 10.

The stage-time curve at West Montrose (1981) in Figure 3 shows that the jam did not reach an equilibrium state and that the peak stage of 14.46 m occurred at ~1100 h on 23rd February 1981. At this time, the flowrate estimated from the gauge/flow records at Shand Dam and at Salem (on Irvine Creek) was approximately 120 m^3/s. At this stage and flowrate, it is estimated that $W = 58$ m; $S = 1.00$ m/km; $h_j = 3.2$ m; $\eta = 55.0$ and $\xi = 131$. The latter two parameters are plotted in Figure 10 where the corresponding data point, 81WM, is seen to fall beneath the equilibrium range. This can be attributed to lack of equilibrium due to unsteadiness and considerable overbank flooding that prevailed at the time. It is estimated that, had formation of an equilibrium jam been possible (e.g., if a dyke adjacent to the left river bank had been in place), the stage at a value of $Q = 120\ m^3/s$ would have reached 15.1 m, i.e., about 0.6 m higher than what actually occurred.

The Marsville (1981) jam did not attain a steady state condition. The peak gauge reading of 5.49 m occurred at 0145 h on February 19. The peak gauge reading translates to a geodetic elevation of 438.87 m, which compares well with three nearby ice top elevations obtained from post-breakup photographic evidence (average elevation = 439.15 m). The discharge was deduced from Water Survey of Canada flow records to be 59 m^3/s at this time. Using four cross-sections near the Marsville gauge site, it was calculated that W = 41 m; S = 2.31 m/km; h_j = 2.15 m; η = 22.7 and ξ = 48.7. The data point representing this jam is below the equilibrium range in Figure 10. As in the case of West Montrose (1981) jam, a steady state condition was not achieved and the data point should fall beneath the equilibrium range.

At Marsville (1982), breakup started at 1025 h on March 25 1982, and a 600 m jam remained at this location from this time until 1900 h on March 30 when the jam broke. The stage-time curve for this period (Figure 4) shows a sharp increase in stage at breakup initiation, reaching a maximum value of 5.49 m at 1430 h on March 25. The level then gradually declined over the next five days until the release of the jam when the gauge reading sharply dropped by ~0.8 m and came back up within a few hours.

Using daily discharge values from Water Survey of Canada, ice jam parameters were calculated for two occasions (82M(25) and 82M(26)) and are listed in Table 6. The 82M(25) data point in Figure 10 represents the characteristics of the jam at the peak stage under ice conditions. This occurred on March 25. The 1982M(26) data point in Figure 10 represents the characteristics of the jam when the stage was fairly steady throughout the entire day on March 26. Analyses were not done on the data after March 26 because the ice blocks may have frozen together and produced a cohesion effect which is assumed to be negligible during break-up.

In Figure 10 the data point 82M(26) is just below the equilibrium range while the 82M(25) point is within the range. The reverse should be true because the 82M(26) data point represents a jam which was at steady state and the 82M(25) point represents a jam which was evolving. The discrepancy may be attributed to uncertainty in the flowrate records which shows an increase of 13.5 m^3/s to 21.0 m^3/s from 25th to 26th of March, in spite of a decrease in temperature and lack of rainfall over that time period. The ξ parameter depends on $Q^{2/3}$ and seems to be overestimated for the 82M(26) data point.

For Grand Valley (1982), the toe of the 1.4 km jam was located at the Boyne Creek confluence which is approximately 900 m downstream of the Main St. bridge. Reports from the Grand River Conservation Authority stated that there was very thick ice at the Boyne Creek location and that the toe was probably grounded. Figure 7 shows water level elevations measured at Main St. bridge and Amaranth St. bridge during the formation and release of the jam. The figure shows that at Main St. the water level rose 3.2 m within a 19 hour period, from 2100 h on March 30 to the release of the jam at 1600 h on March 31. The flowrate at the time of release was estimated to be about 80 m^3/s.

Although the jam did not attain a steady state condition and the river did overflow its banks, an equilibrium analysis was performed. The jam parameters are listed in Table 6. The resulting data point falls at the lower end of the equilibrium band in Figure 10. If an equilibrium jam had formed at this location, the upper limit of the range drawn in Figure 10 indicates that η could have been as high as 34 which translates to a water level about 0.65 m higher than what actually occurred.

5.0 DISCUSSION AND SUMMARY

Observations of two ice seasons on the Upper Grand River have been described and partly interpreted in the previous sections.

In the 1980-81 season, the freeze up process began in mid-December. The study reach produced a large amount of frazil and, in general, the ice cover was formed by a combination of the formation of border ice and the accumulation of the frazil ice particles. Warm weather and rainfall in mid-February caused a "premature" breakup, i.e., breakup with strong ice cover. Ice jams developed at numerous locations in section I and the water overflowed the banks at some of these locations. A major ice jam occurred at West Montrose where the ice level had risen to the base of the historical covered bridge. The jam, however, cleared with no damage to the bridge.

In the 1981-82 season, freeze up began in mid-December and the breakup process took place between March 16 and April 1. Most of the field observations were done in section I where there were a number of small jams and one major jam in the town of Grand Valley. The (possibly) grounded toe of the major jam caused a rapid increase in water level resulting in extensive flooding in Grand Valley. The jam released at 1600 h on March 31.

The Upper Grand River study reach is smaller and steeper than the study reach of the Lower Thames River. Therefore, documentation of the ice seasons of the Grand River provides important information required to test existing theories on breakup initiation and equilibrium floating ice jams. The field work on the Grand River provides a data base which is different from the previously documented results from the Thames River and other rivers in Alberta (Beltaos 1981).

Analysis of breakup initiation levels showed that for Marsville and Upper Belwood there exists a relationship between $\Delta H_B/\Delta H_F$ and $100h_i/h_F$ that is similar to the relationship deduced from the Thames River data (Beltaos 1981). The data point representing the breakup initiation at West Montrose, however, did not compare well with the other points. The actual value of $\Delta H_B/\Delta H_F$ for the given value of $100h_i/W_F$ is well below the predicted zone (see Figure 8). The discrepancy may be due to freeze up ice jams which cause artificial high values of H_F thereby producing low $\Delta H_B/\Delta H_F$ factors. In such instances, the maximum daily freeze stage may not be representative of the ice cover width owing to the precipitous drop in stage after the formation of the jam; the solid ice cover then forms at a lower stage and therefore has a smaller width than that which is associated with the maximum stage. The determination of H_F may require careful visual monitoring at sites of significant slush jams (e.g. West Montrose).

The dimensionless parameters η and ξ derived from the present ice jam measurements were used to compare with the existing theory on equilibrium floating jams. Values for the parameter ξ for the Grand River jams are smaller than those calculated for the Thames River jams; ξ = 18.5 - 131 for Grand River, ξ = 290 - 1766 for Thames River. Four jams were analyzed and the data points representing three of the four jams were lower than the equilibrium zone established by other river data. The jams on the Grand River were not suited for this type of analysis because a number of assumptions were not satisfied: the jams were not in equilibrium; the jams were relatively short in length; overflow at the banks took place along the length of the jam. The analysis, however, did show that, as expected, the maximum water elevations predicted by the theory were not exceeded.

Flowrate values used in the ice jam analyses were taken from daily flowrate records provided by Water Survey of Canada. The daily estimate is only an approximation and thus the flowrate should be measured as frequently as possible in future field work.

6.0 CONCLUSIONS

Ice conditions in the study reach on the Grand River were recorded for two seasons, 1980-81 and 1981-82.

Interpretation of the observations indicated the following:

(i) The data base for small, steep rivers such as the Grand River is limited. Continuation of this type of field work is needed.

(ii) The existing theory on break up initiation applies fairly well to the data collected from Marsville and Upper Belwood. At sites of significant slush jams as at West Montrose, careful visual monitoring is required in determining the value of H_F.

(iii) The maximum water elevations predicted by the theory of equilibrium floating jams were not exceeded in any of the four major jams that were documented in 1980-81 and 1981-82. This is in agreement with expectation given that three of these jams did not attain equilibrium while the fourth appeared to be associated with overestimated flow discharge.

(iv) Better flowrate measurements are needed during the documentation of spring ice jams.

7.0 ACKNOWLEDGEMENTS

Acknowledged with thanks is the valuable assistance provided by the Grand River Conservation Authority and the Water Survey of Canada; these organizations worked with our field crew in providing important field notes and reports on river conditions.

Messrs. W.J. Moody and F. Dunnett of the Hydraulics Divison provided valuable assistance with both field work and data processing. Review comments by Dr. T.M. Dick and Dr. Y.L. Lau are appreciated.

REFERENCES

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

Beltaos, S. 1982a. Initiation of River Ice Breakup. Proceedings from the Fourth Northern Research Basin Symposium Workshop, Ullensvang, Norway, March, pp. 163-177.

Beltaos, S. 1983. River Ice Jams: Theory, Case Studies and Applications. Journal of Hydraulic Engineering, ASCE, Vol. 109, No. 10, October, pp. 1338-1359.

TABLES

TABLE 1. Important Locations In Study Reach

Description	Chainage (km) distance from Leggatt
Leggatt bridge (GRCA gauge site)	0.00
3rd crossing u/s of Grand Valley	3.96
2nd crossing u/s of Grand Valley	4.64
1st crossing u/s of Grand Valley	7.39
Amaranth St. bridge; east end of Grand Valley	10.21
Dam in Grand Valley	10.88
Main St. bridge in Grand Valley	11.11
Mouth of Boyne Creek	12.55
2nd crossing u/s of Waldemar	13.26
1st crossing u/s of Waldemar	15.09
Mouth of Willow Brook	16.09
Canadian Pacific Railway bridge	16.14
Waldemar bridge (GRCA gauge site)	16.24
Hwy 9 bridge	17.46
Marsville bridge (WSC and GRCA gauge site)	19.84
1st crossing d/s of Marsville bridge	21.54
2nd crossing d/s of Marsville bridge	22.96
Upper Belwood bridge (GRCA gauge site)	24.75
Belwood bridge	29.57
Shand Dam (GRCA gauge site)	36.56
Shands Bridge (WSC gauge site)	37.71
Scotland St. bridge in Fergus	40.24
Mill Dam in Fergus	40.37
St. David St. (Hwy 6) bridge in Fergus	41.05
Tower St. bridge in Fergus	41.30
Canadian National Railway bridge	43.72
Dam in Elora	45.75
High St. bridge in Elora	46.26

TABLE 1. (continued)

Description	Chainage (km) distance from Leggatt
Dam in Elora	46.42
Mouth of Irvine Creek	46.69
Bridge in Elora	46.74
Elora Gorge Park bridge	49.18
Mouth of Carroll Creek	51.03
Mouth of Swan Creek	51.69
1st crossing d/s of Inverhaugh	53.33
2nd crossing d/s of Inverhaugh	56.26
Canadian Pacific Railway bridge	60.32
Hwy 86 bridge	60.87
West Montrose covered bridge (WSC and GRCA gauge site)	61.74
Winterbourne	65.22

TABLE 2. **Grand River Sections**

Section	Location		Average Slope (m/km)
I	Leggatt to Upper Belwood	(0.00 to 26.01)	1.44
II	Lake Belwood	(26.01 to 36.56)	0.73
III	Shand Dam to Elora	(36.56 to 45.78)	3.61
IV	Elora Gorge	(45.78 to 49.18)	8.20
V	Inverhaugh to West Montrose	(49.18 to 61.74)	1.96

TABLE 3. **Minimum, Maximum and Average Flow (m^3/s) (1970-79)***

Gauge / Year	Grand River near Marsville Drainage Area = 694 km^2			Grand River below Shand Dam Drainage Area = 800 km^2			Grand River at West Montrose Drainage Area = 1,170 km^2		
	Min.	Ave.	Max.	Min.	Ave.	Max.	Min.	Ave.	Max.
1970	.201** Aug.	6.60	161 Apr.	1.08 Jan.	7.77	98. Apr.	1.56 Jan.	12.2	120 Apr.
1971	.116 Oct.	5.99	194 Apr.	.946 Oct.	6.69	120 Apr.	2.36 Oct.	10.7	176 Apr.
1972	.057 Sep.	6.95	264 Apr.	2.11 Mar.	8.11	368 Apr.	3.51 Oct.	12.9	507 Apr.
1973	.099 Oct.	8.36	143 Mar.	1.64 Nov.	9.83	110 Mar.	3.34 Nov.	14.6	156 Mar.
1974	.170 Sep.	7.38	178 Apr.	1.84 Feb.	9.22	188 May	3.17 Dec.	13.6	379 May
1975	.314 Jun	7.12	306 Apr.	2.31 May	7.77	125 Apr.	3.54 Jan.	12.0	234 Apr.
1976	.255 Jun.	9.08	289 Mar.	1.67 Jan.	10.5	153 Mar.	2.49 Jan.	15.3	211 Mar.
1977	.136 Jun.	8.47	243 Mar.	1.27 Jan.	9.89	118 Mar.	1.50 Jan.	13.6	183 Mar.
1978	.459 Sep.	7.29	174 Apr.	1.56 Mar.	7.38	152 Apr.	2.29 Mar.	11.8	197 Apr.
1979	.031 Jul.	9.72	197 Apr.	1.84 Feb.	11.8	239 Apr.	1.54 Sep.	16.5	315 Apr.
Average		7.70			8.90			13.32	

* Data from Water Survey of Canada publication "Historical Streamflow Summary, Ontario, to 1979"

** Flowrates are in m^3/s

TABLE 4. Ice Thickness Data

Location	Date of Measurement	Average Ice Thickness (cm)	Range of Ice Thickness (cm)
	(1980-81)		
Marsville*	Jan. 15	24.1	15-28
West Montrose*	Jan. 16	29.6	26-32
West Montrose*	Feb. 16	50.5	38-59
Near 1st crossing u/s of Grand Valley	Jan. 9-14	24.3	14-32
	(1981-82)		
Marsville*	Feb. 3	28.0	5-41
West Montrose*	Jan. 22	32.0	12-60
West Montrose*	Feb. 11	43.0	28-50
Near 1st crossing u/s of Grand Valley	Jan. 13	34.0	23-51
Near Marsville	Jan. 13-19	22.0	9-43
Near Upper Belwood	Jan. 13-19	27.0	14-35
Near Hwy 86 crossing	Jan. 13-19	20.0	11-30
Near West Montrose	Jan. 13-19	24.0	9-40

* From data provided by Water Survey of Canada, Guelph. At West Montrose, significant slush deposits under the solid ice cover were present; thicknesses apply to the slush free portion of the channel.

TABLE 5. Selected Characteristics of 1980-81 and 1981-1982 Seasons

Location	H_F (m)	Date of H_F	Probable H_B (m)	Approx. time of H_B	Estimated h_i at time of H_B (cm)	H_{max} (m)	Time of H_{max}	Estimated discharge at H_{max} (m /s)
Marsville Gauge	3.95	Dec. 23 1980	4.60 to 4.85	2200 h. Feb. 18 1983	32	5.49	0145 h Feb. 19, 1981	59
West Montrose Gauge	13.10	Dec. 18 1980	>13.58	1600 h Feb. 20 1981	50	14.46	1100 h Feb. 23, 1981	120
			<13.96	0600 h Feb. 23, 1981				
Upper Belwood	1.43	Dec. 14 1980	1.77	2100 h Feb. 18 1981	42	>3.05	0300 h to 1000 h Feb. 19,	>59
Marsville Gauge	3.79	Jan. 7 1982		1025 h Mar. 25, 1982	35	5.27	1430 h Mar. 25, 1982	14
West Montrose Gauge	12.45	Jan. 6	12.48	1800 h Mar. 30, 1982	47	13.33	0300 h Mar. 31, 1982	73
Upper Belwood	1.14	Dec. 18 1981	1.37 to 1.46	2000 h March 24, 1982	44	1.97	0700 h Mar. 25, 1982	>14

TABLE 6. Characteristics of Major Ice Jams on Grand River Study Reach (1980-81, 1981-82)

Ice Jam	Time/ Date	State of Jam	Peak Gauge height (m)	Ave. Gauge height (m)	Estimated Flowrate Q (m^3/s)	Average Width W (m)	Average Slope S(m/km)	Average Depth h_j(m)	η	ξ
West Montrose (1981)	1000 h Feb.23 1981	Unsteady	14.46	-	120	58	1.00	3.2	55.0	131
Marsville (1981)	0145 h Feb.20 1981	Unsteady	5.49	-	59	41	2.31	2.2	22.7	48.7
Marsville (1982M(25))	1600 h. Mar. 25 1982	Unsteady	5.49		14.3	41	2.31	2.2	22.7	18.5
(1982M(26))	Mar. 26 1982	Steady	-	5.10	21.0	39	2.31	2.1	23.1	20.7
Grand Valley (1982)	1600 h Mar. 31 1982	Unsteady	452.61	-	80	57	2.45	4.1	29.4	31.1

FIGURES

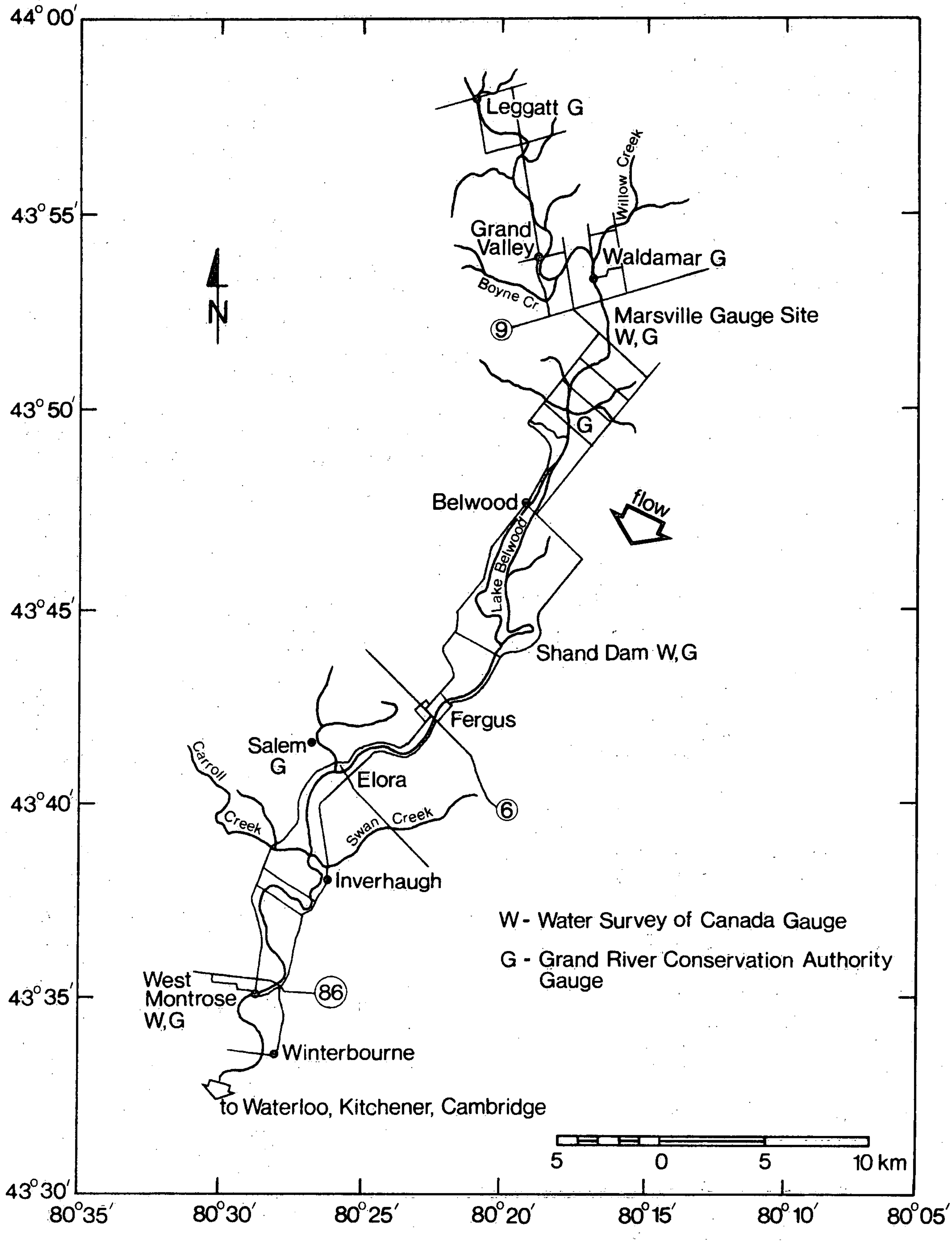
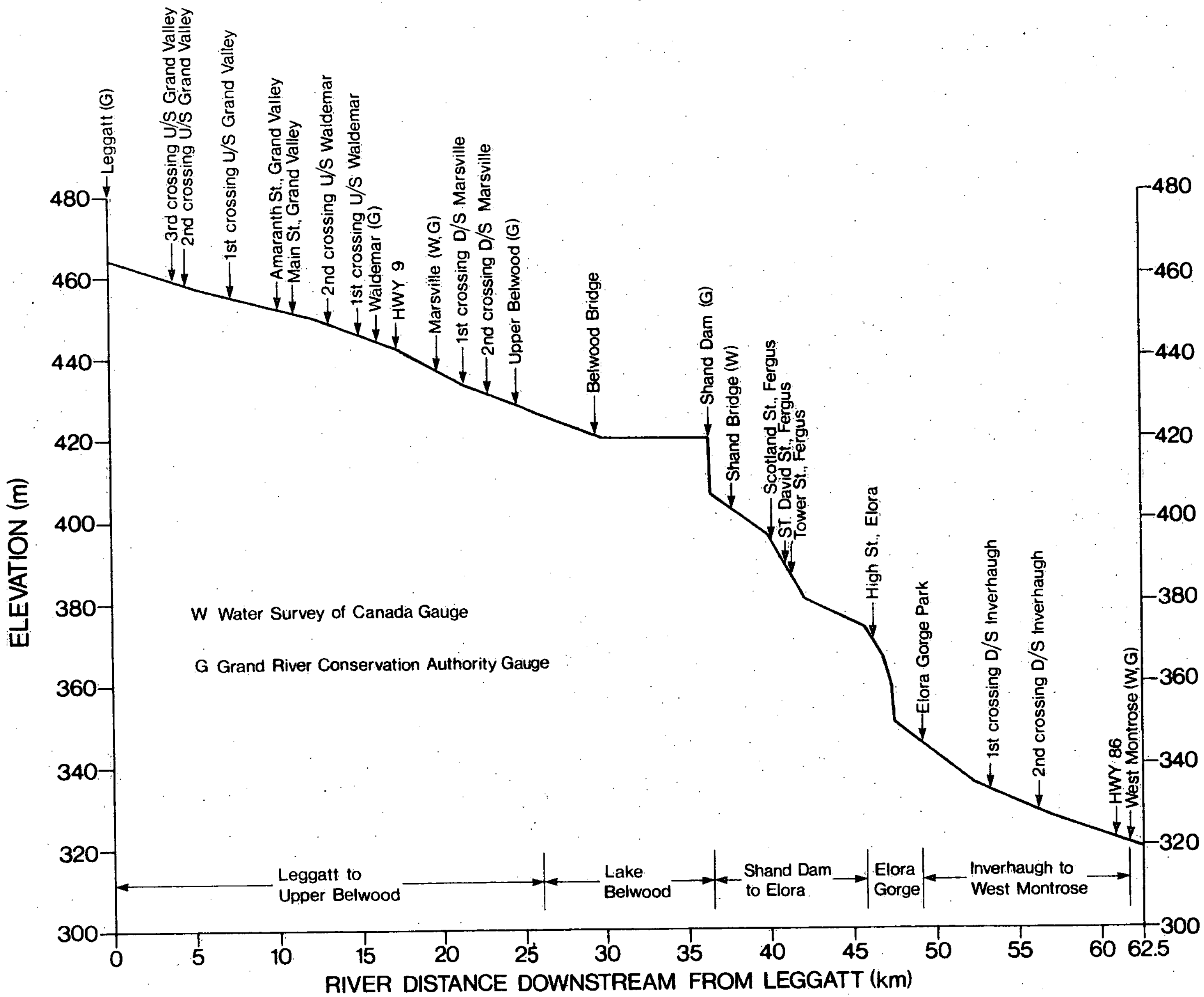


Figure 1 PLAN VIEW OF UPPER GRAND RIVER STUDY REACH



LONGITUDINAL PROFILE OF UPPER GRAND RIVER

Figure 2

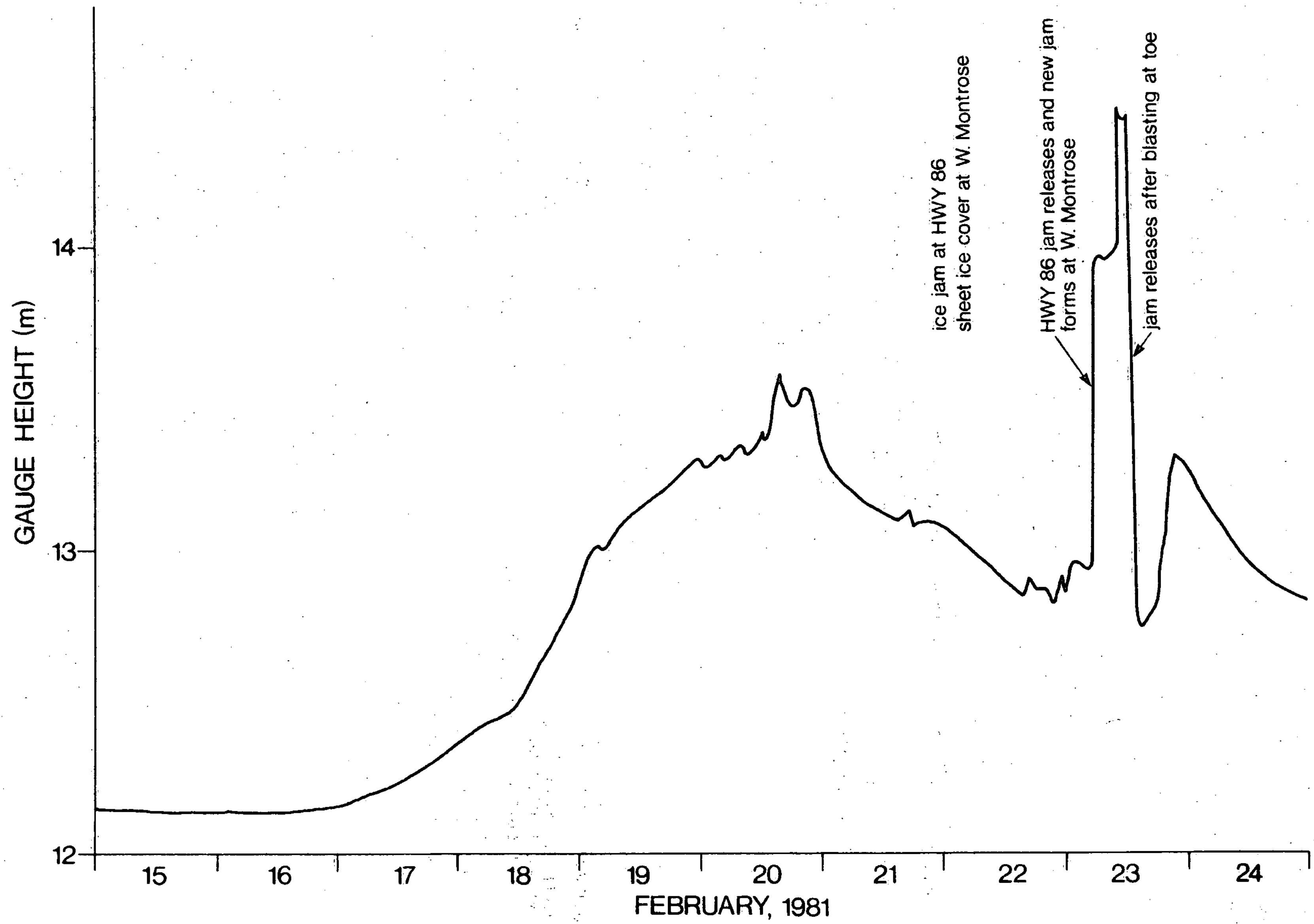


Figure 3 STAGE HYDROGRAPH DURING 1981 BREAKUP AT W. MONTROSE

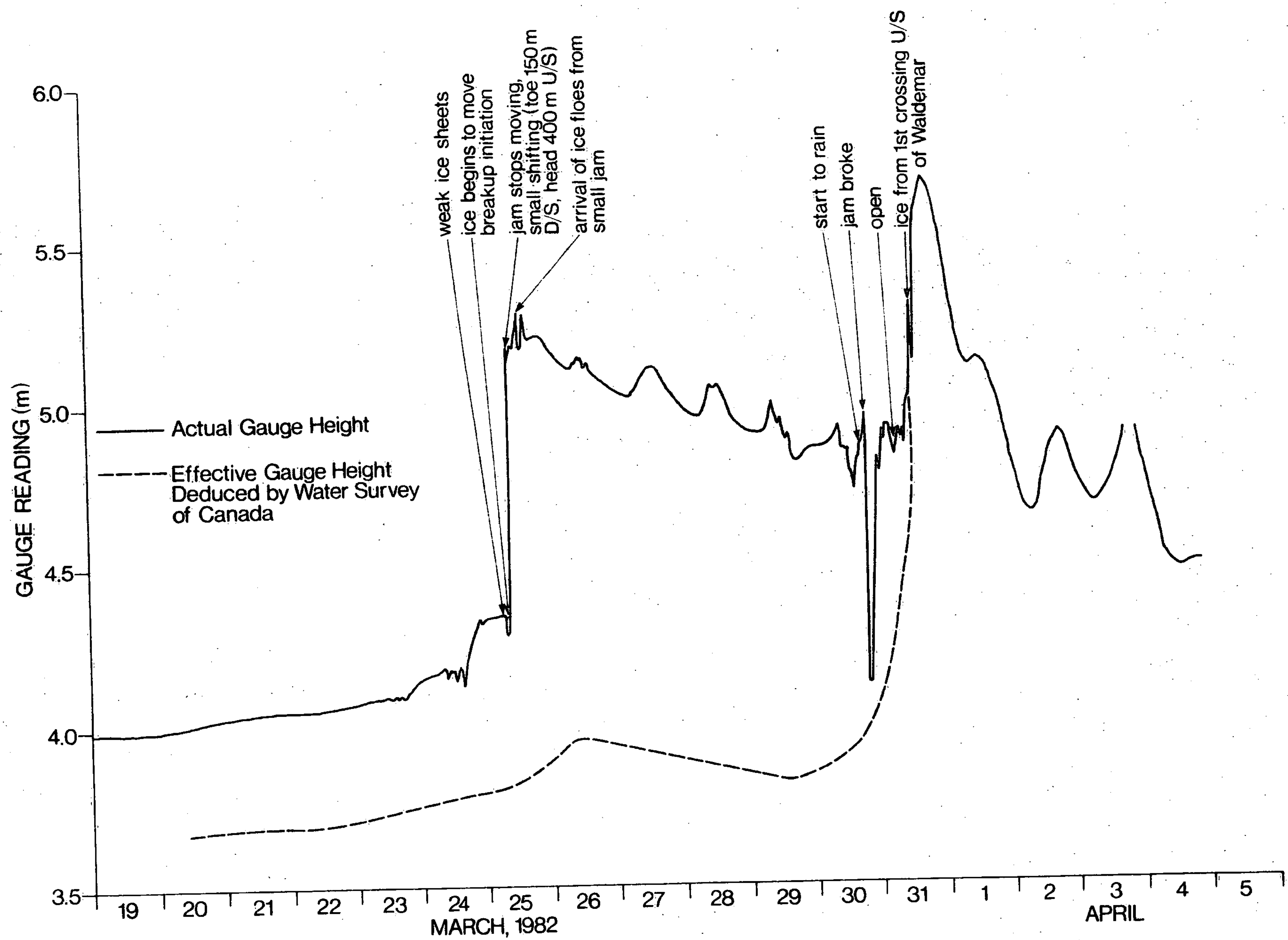


Figure 4 STAGE HYDROGRAPH DURING BREAKUP AT MARSVILLE (1981-82)

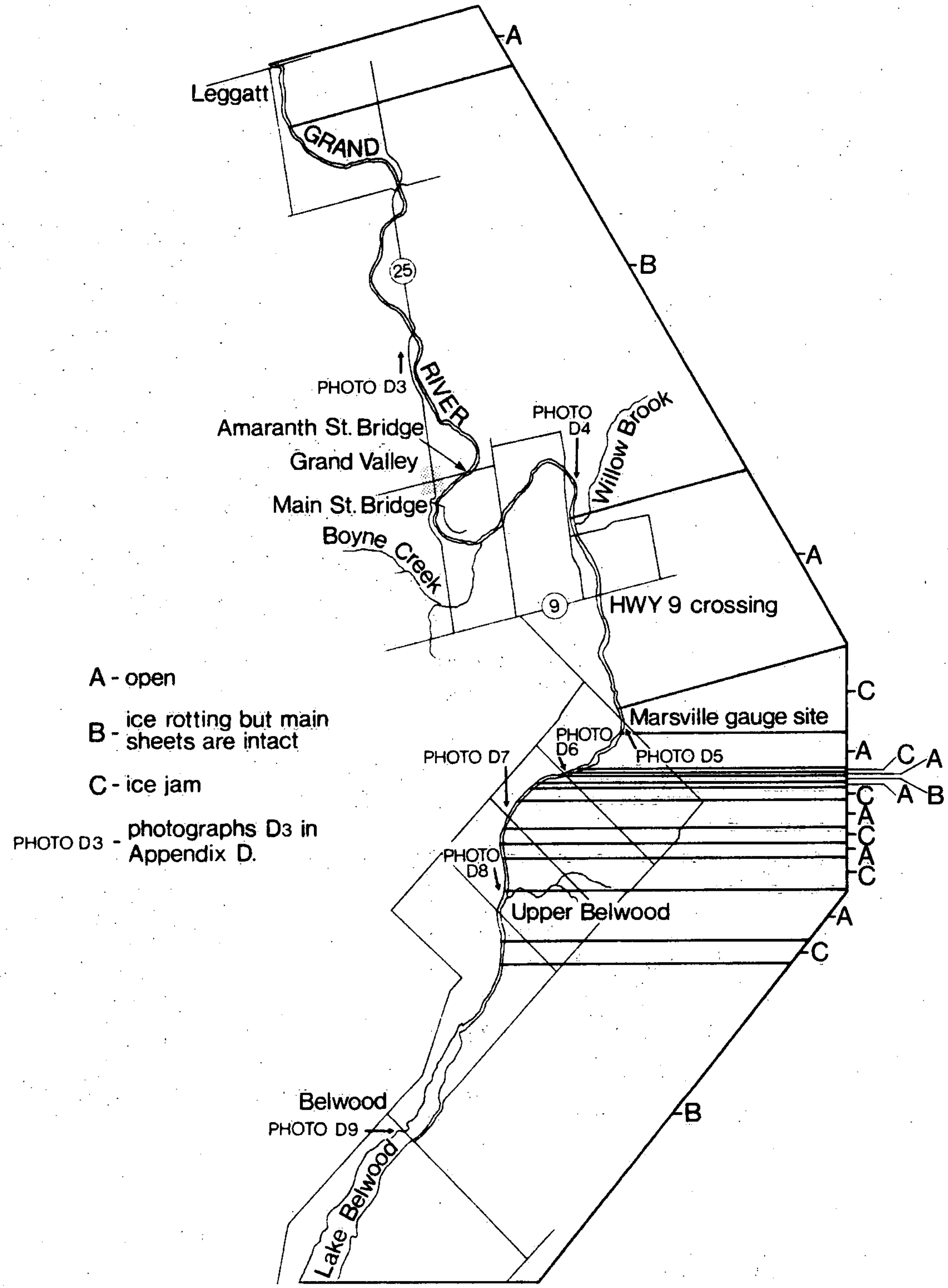


Figure 5 CONDITION OF STUDY REACH AS OBSERVED BY AIRCRAFT ON MARCH 30, 1983. UPPER HALF OF REACH.

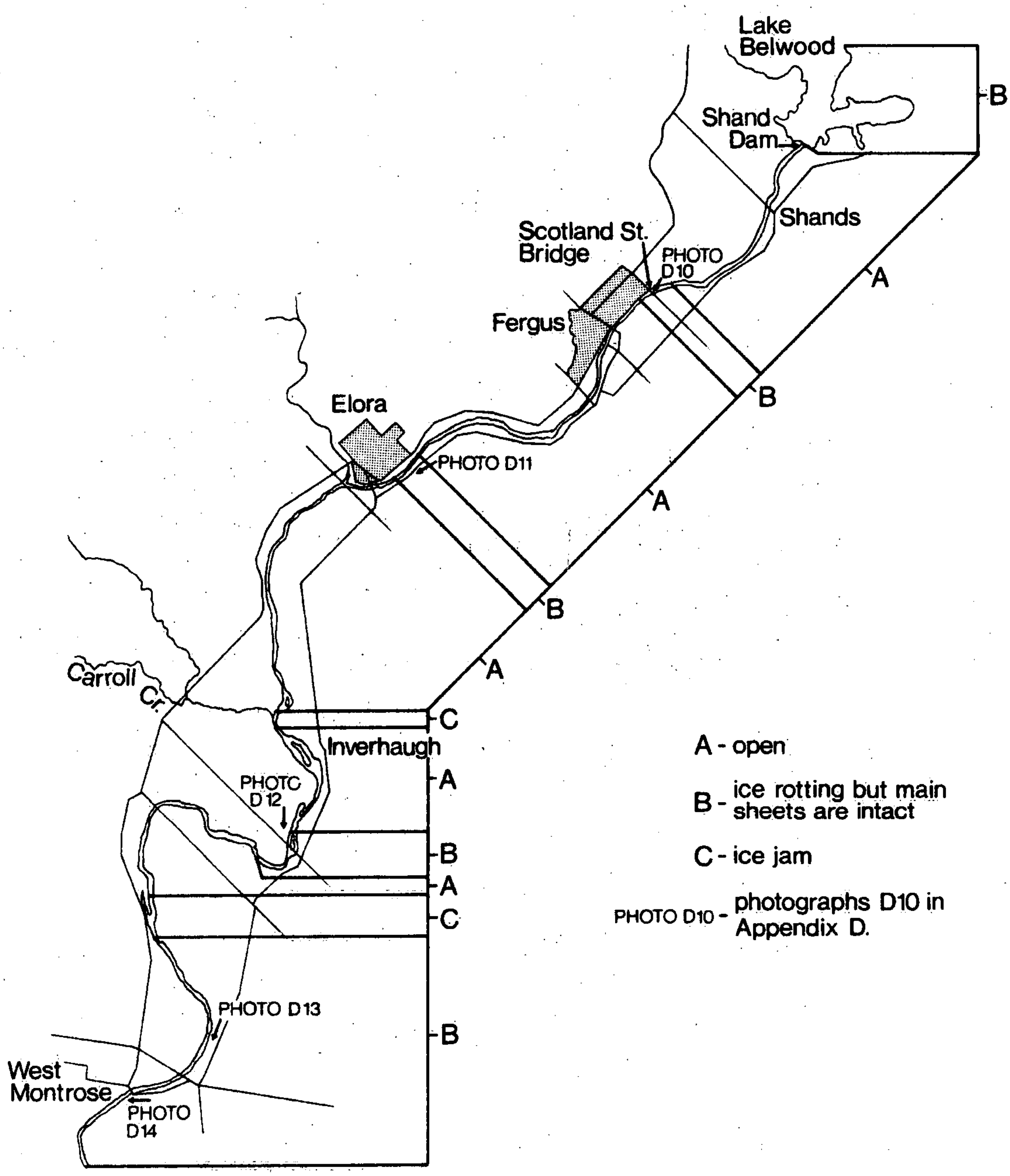


Figure 6 CONDITION OF STUDY REACH AS OBSERVED BY AIRCRAFT ON MARCH 30, 1983. LOWER HALF OF REACH.

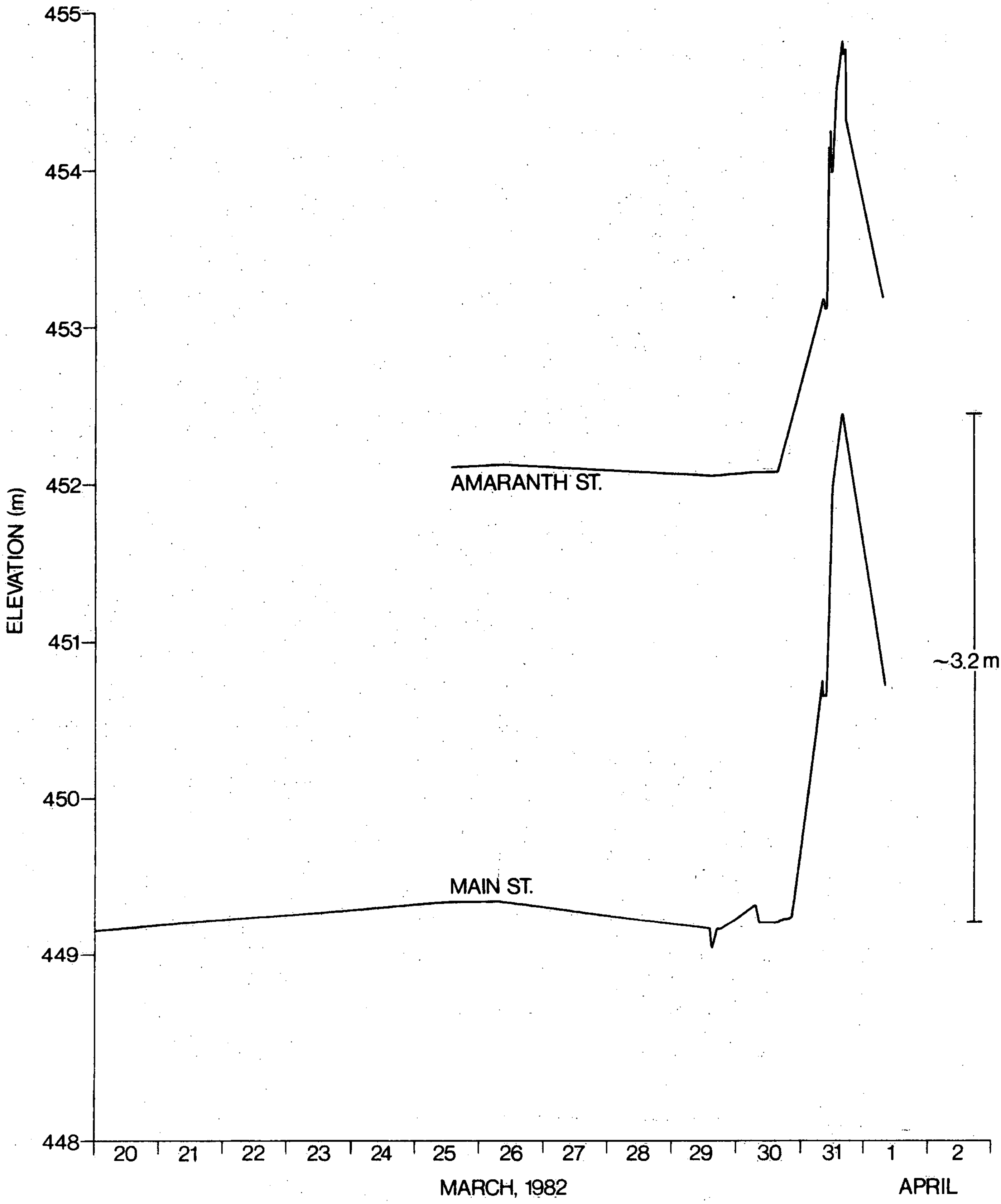


Figure 7 WATER LEVEL ELEVATION DURING 1981-82 BREAKUP AT MAIN ST. BRIDGE AND AMARANTH ST. BRIDGE IN GRAND VALLEY.

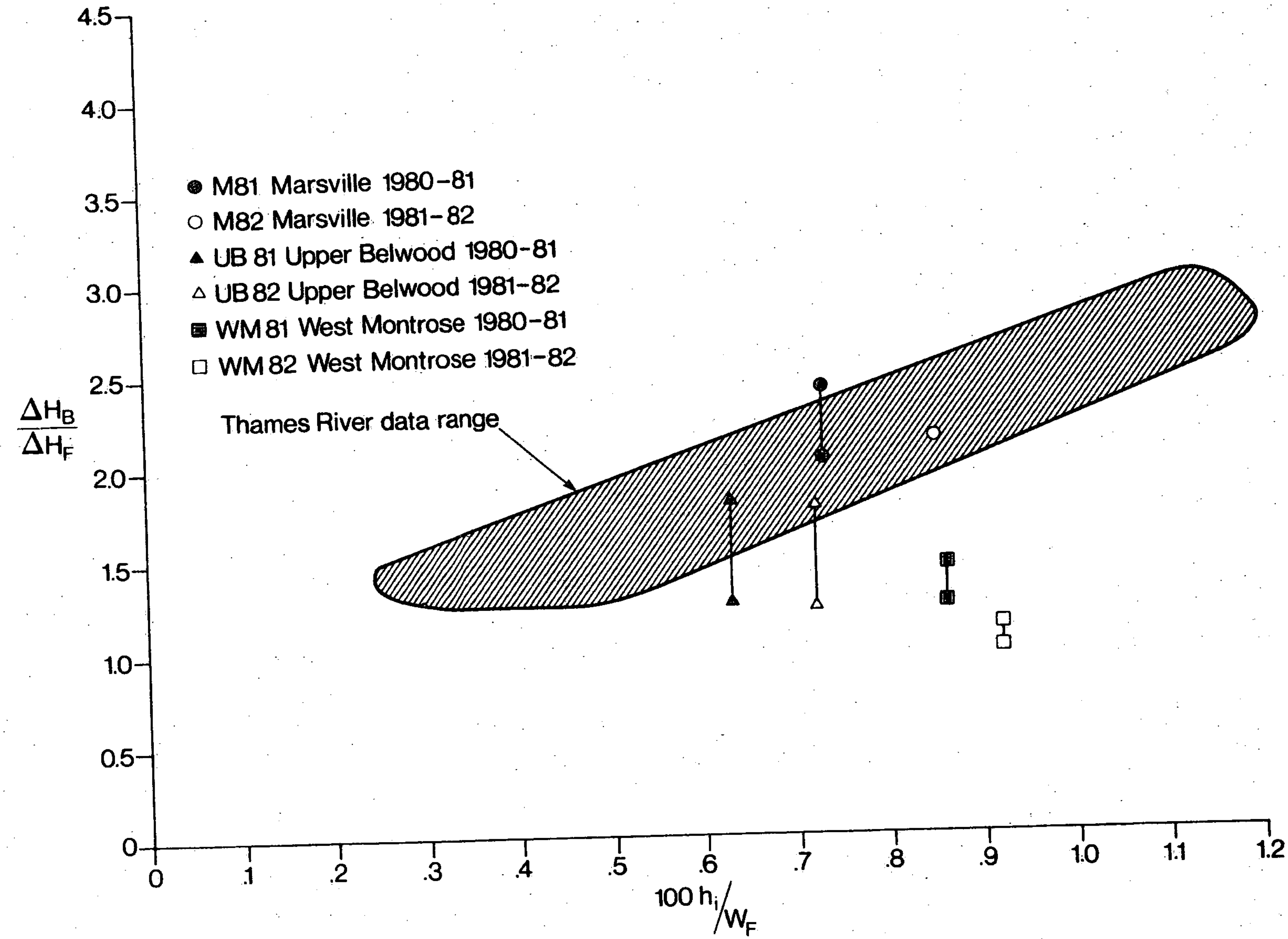


Figure 8 DIMENSIONLESS BREAKUP AND INITIATION STAGES VERSUS DIMENSIONLESS ICE THICKNESS. GRAND RIVER AT MARSVILLE, UPPER BELWOOD AND WEST MONTROSE.

Figure 9 GRAND RIVER NEAR WEST MONTROSE, LOOKING DOWNSTREAM FROM HWY. 86 BRIDGE. JAN. 1983. NOTE ICE ACCUMULATIONS ON BANKS AND LOWER STAGE OF SOLID ICE COVER.

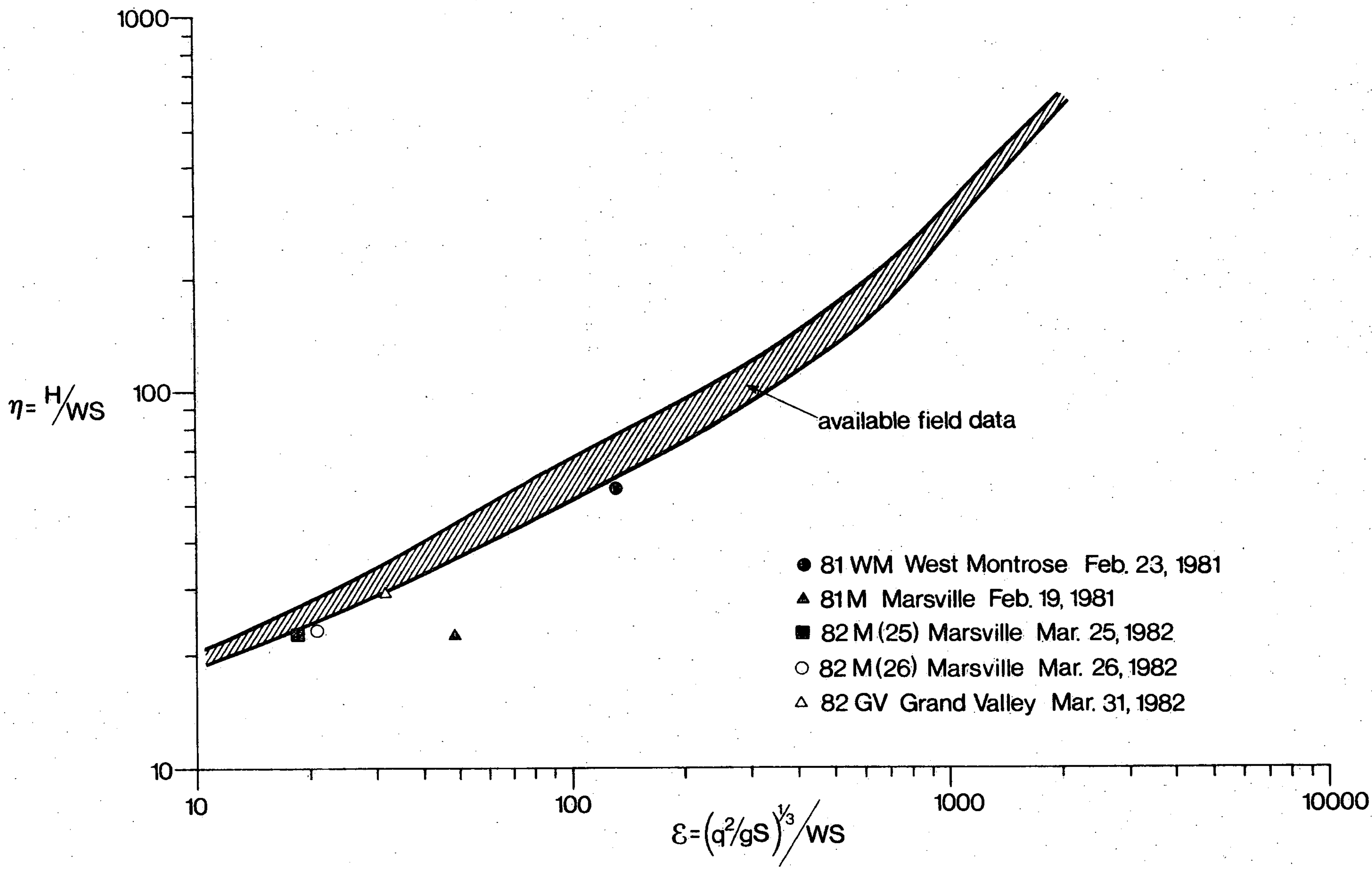
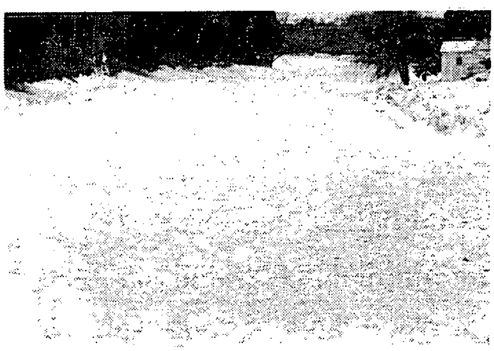


Figure 10 DIMENSIONLESS JAM STAGE VERSUS DIMENSIONLESS DISCHARGE. GRAND RIVER DATA

APPENDICES

APPENDIX A. FREEZE UP PHOTOGRAPHS, DECEMBER 17, 1980

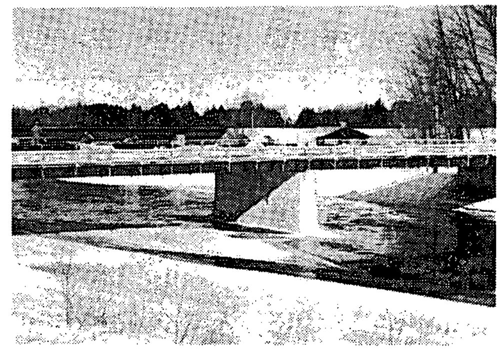

A1 Looking d/s, 1530 h.

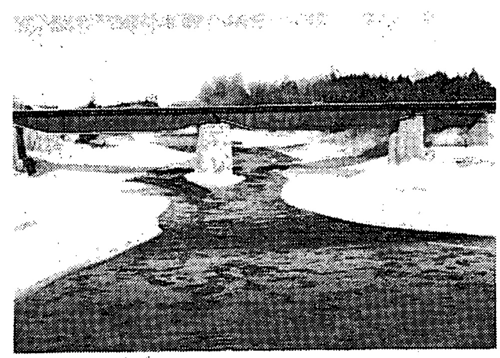

A2 Looking d/s, 1530 h.

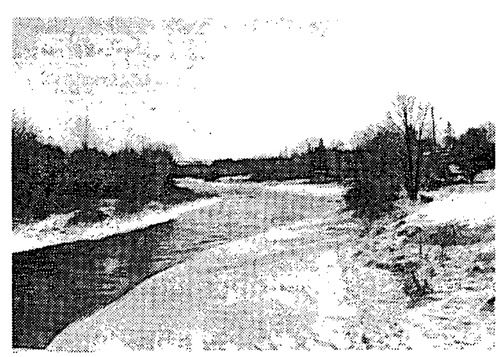

A3 Looking u/s, 1530 h.

↑

A1-A3 Crossing east of Grand Valley. Note rough ice surface.


A4 Looking u/s, 1350 h.

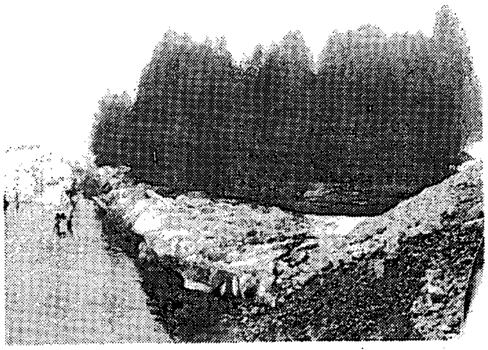

A5 Looking u/s, 1350 h.


A6 Looking d/s, 1350 h.

↑

A4-A6 Waldemar crossing. Note border ice, moving frazil slush.

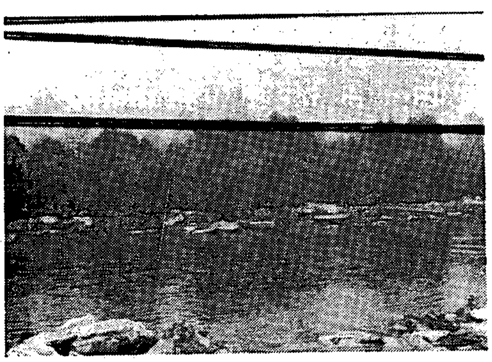
APPENDIX B. BREAKUP PHOTOGRAPHS, FEBRUARY,1981



B1 Leggatt crossing, looking u/s, 0845h, Feb. 21.

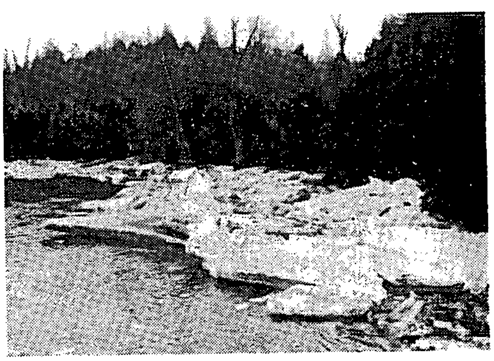
B2 2nd crossing u/s of Grand Valley, looking u/s, 1720h, Feb. 20.

B3 Looking u/s, 0815h. Feb 21. ~0.6km below 1st crossing u/s of Grand Valley.



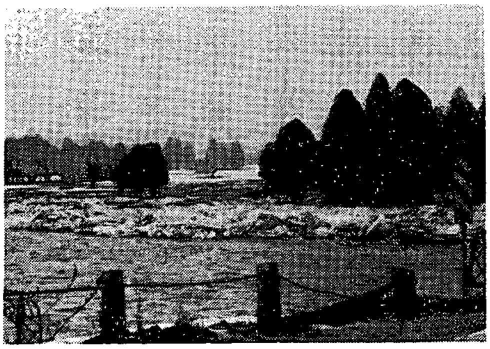
B4 Looking toward left bank, 0810h. Feb. 21. ~1.1km below 1st crossing u/s of Grand Valley.

B5 At Grand Valley. Looking d/s,1645h, Feb. 20.



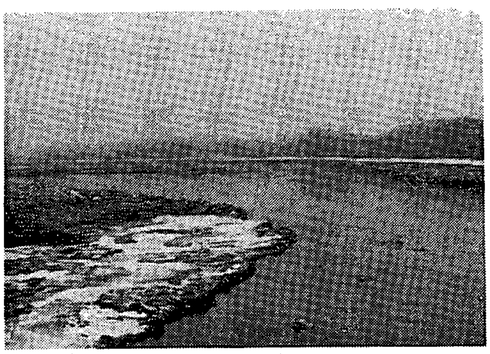
B6 Marsville crossing. Looking u/s,1440h, Feb 20.

APPENDIX B. CONTINUED



B7 Upper Belwood.
Looking u/s,1020h, Feb 21.

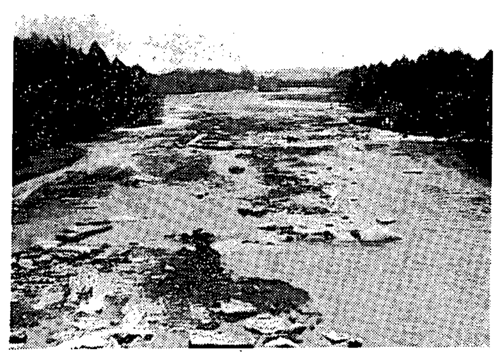
B8 Upper Belwood.
Flooded left bank, 1030h,
Feb. 21.



B9 Belwood crossing. Looking u/s,
1115h, Feb 21.

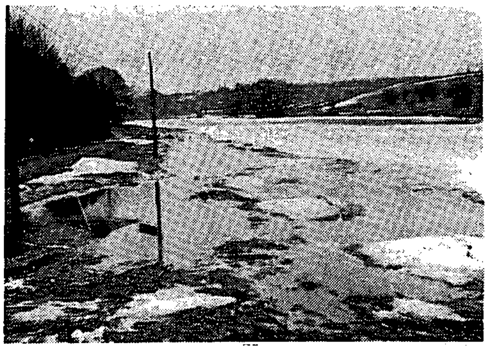
B10 Near 2nd crossing d/s of
Inverhaugh, 1610h, Feb 21.

B11 Ice jam, 1600h, Feb. 21,
~2.8 km u/s Hwy. 86 crossing,
looking toward right bank.



B12 Toe of jams, 1450h, Feb.21.
Looking d/s from Hwy. 86 bridge.

APPENDIX B. CONCLUDED



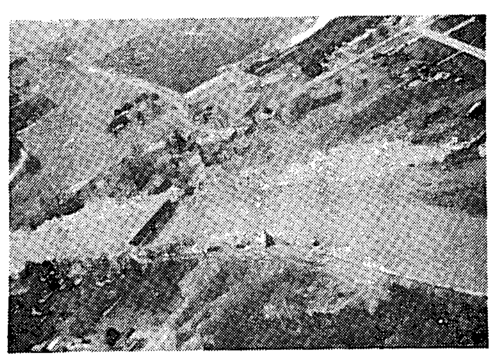
B13 Looking d/s from covered bridge, 1525h, Feb. 21.

B14 Flooding of left bank near covered bridge, 1025h, Feb. 23.

B15 U/s side of covered bridge, ice close to superstructure. 1110h, Feb.23.

B16 Looking u/s from covered bridge, 1115h, Feb 23.

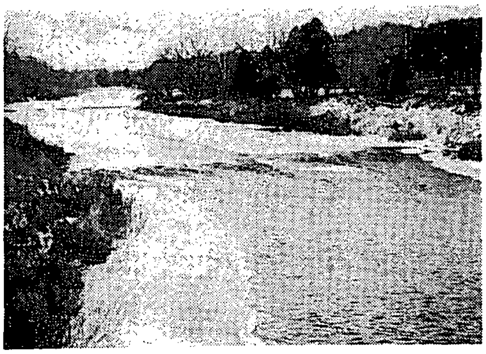
B17 Looking d/s from covered bridge, 1428h, Feb 23. Ice jam remnants on left bank.



B18 Aerial view of covered bridge and vicinity. Looking d/s, 1630h, Feb. 24.

B13-B18 Photographs taken at West Montrose.

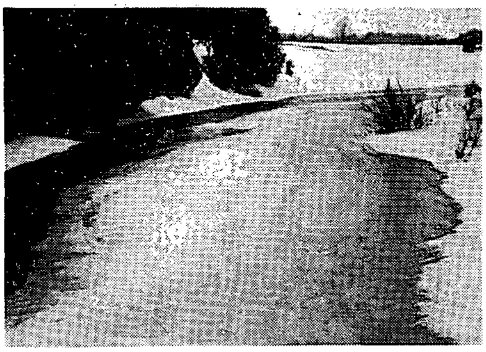
APPENDIX C. FREEZE UP PHOTOGRAPHS, DECEMBER 16,1981



C1 Main St. bridge in Grand Valley. Looking u/s at weir where complete ice cover began.

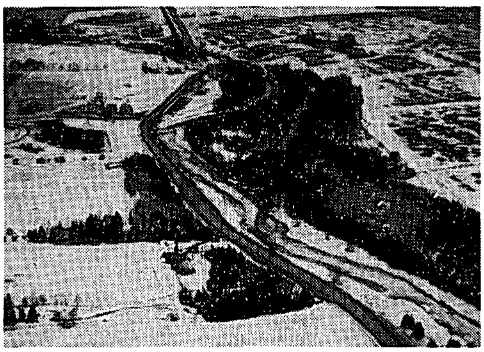
C2 Looking d/s from Amaranth St. bridge in Grand Valley. Note rough appearance of hummocked ice.

APPENDIX D. BREAKUP PHOTOGRAPHS, MARCH and APRIL,1982

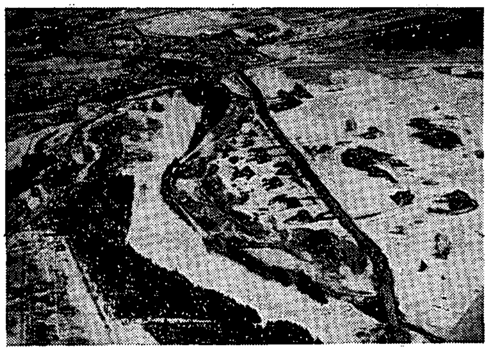


D1 Leggatt looking u/s.
1450h, Mar. 16, 1982.
Note cracks along centre.

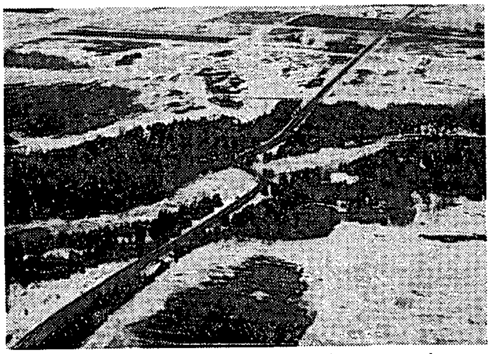
D2 2nd crossing u/s of Waldemar
looking u/s. 1238h, Mar. 25,1982.



D3 1st crossing u/s of Grand Valley.
1030-1120h, March 30, 1982.



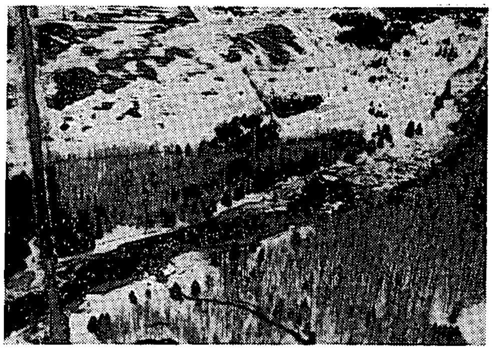
D4 1st crossing u/s of Waldemar
(bottom) and Hwy 9 (top left).
1030-1120h, Mar. 30, 1982.



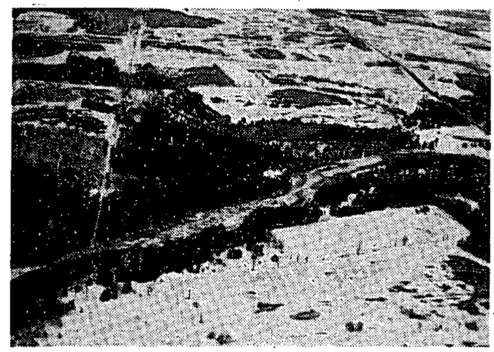
D5 Ice jam at Marsville gauge site.
1030-1120h, Mar. 30, 1982.

D6. 1st crossing d/s of Marsville.
1030-1120h, Mar.30, 1982.

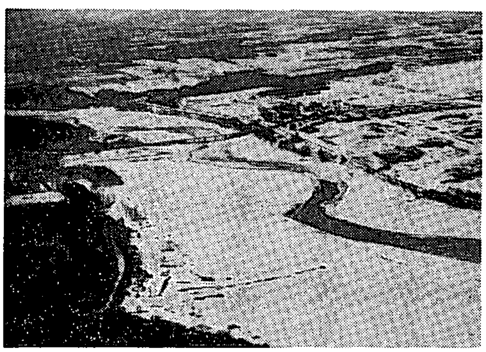
APPENDIX D CONTINUED



D7 2nd crossing d/s of Marsville. 1030-1120h, Mar. 30, 1982.

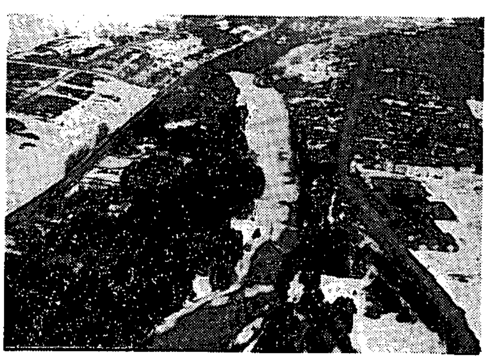


D8 Ice jam just u/s of Upper Belwood crossing. 1030h, Mar. 30, 1982.

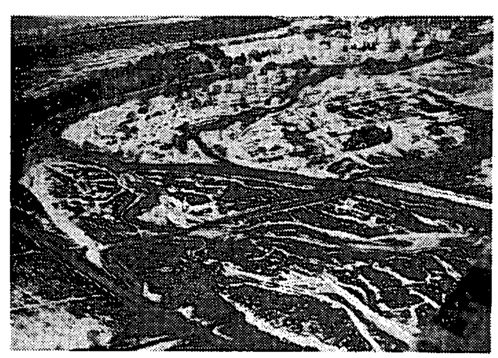


D9 Belwood crossing. 1030-1120h. Mar. 30, 1982.

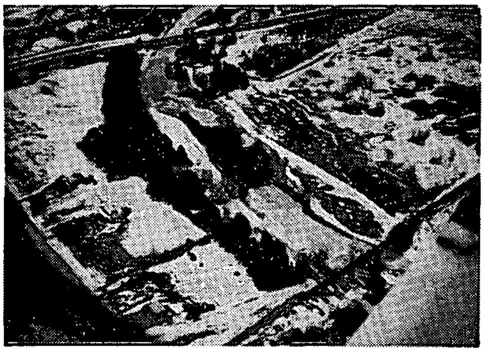
D10 Ice cover behind weir near Scotland St. bridge in Fergus. 1130-1120h, Mar. 30, 1982.



D11 Ice cover behind weir in Elora. 1130-1120h, Mar 30, 1982.

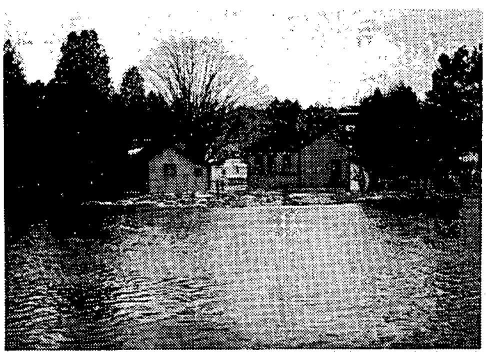


D12 1st crossing d/s of Inverhargh. 1030-1120h, Mar.30, 1982.



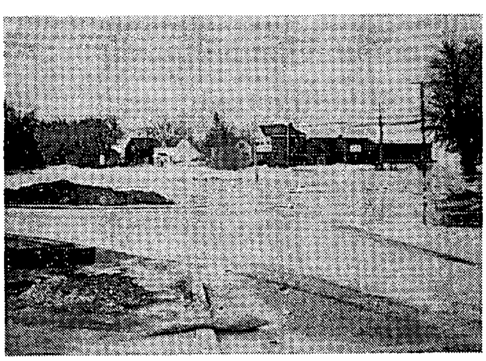
D13 CPR bridge (bottom) and Hwy 86 (top). 1030-1120h, Mar 30, 1982.

D14 West Montrose covered bridge. 1030-1120h, March 30, 1982.

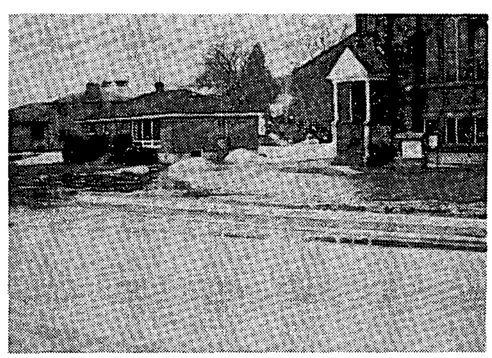


D15 Flooding along right bank u/s of Amaranth St. bridge in Grand Valley. 1456h, Mar. 31, 1982.

D16 Flooding along right bank d/s of Amaranth St. bridge in Grand Valley. 1456h, Mar 31, 1982.

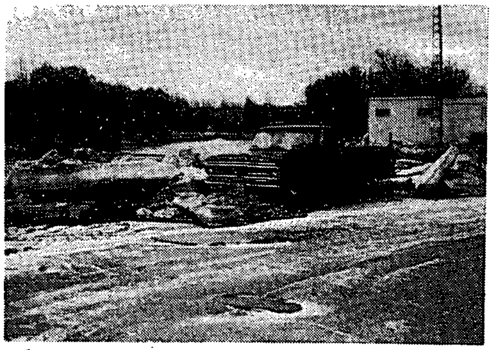


D17 Flooding along Hwy 25 near Main St. bridge in Grand Valley. 1148h, Mar. 31, 1982.



D18 Flooding along Hwy 25 near Main St. bridge in Grand Valley. 1148h, Mar. 31, 1982.

APPENDIX D. CONCLUDED



D19 Ice blocks remaining near Fire Hall in Grand Valley. 0725h. April, 1982.

D20 Ice blocks remaining on Hwy. 25 d/s of Main St. bridge in Grand Valley. 0810h, April, 1982.

9765