Fenco MacLaren

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007097

28 March 1995

Newfoundland Department of Environment
Confederation Complex, 4th Floor
West Block, P.O. Box 8700
Prince Philip Parkway
St. John's, Newfoundland A1B 4J6

Attention: Dr. Wasi Ullah
Director, Water Resources Management Division

Re: Exploits River Ice Modelling

Dear Dr. Ullah:

We are pleased to submit the enclosed copies of our final report on the above titled project. Our pleasure is principally derived from knowing that our earlier hydrotechnical study (in 1985) has proven beneficial to your Department in carrying out its work in flood damage reduction.

We are also pleased that this report and its additional analyses will allow you to continue your ice and flood forecasting at Badger for many years to come. The central focus of this project has been to:

- provide an overview of the flooding problem and the earlier study;
- review the data collection and modelling;
- present an overview and details about applicable, recent ice models; and
- give a series of recommendations to improve flood/ice forecasting for the Badger area.

All aspects of the work have been completed and are contained within the main body and appendices of this volume.

We have enjoyed working on this project with members of your team, and we particularly wish to thank you, Mr. Picco and Dr. Abdel-Razek for the considerable assistance and constructive comments we received throughout the course of the study.

We look forward to being of service to you again in the near future.

Yours very truly,

Fenco MacLaren Inc.

Douglas, B. Hodgins, P.Eng.
Senior Vice President

DBH/pj

encl.

River Ice Modelling
Exploits River at Badger

Report to

Newfoundland Department of Environment

March 1995

007097

Fenco MacLaren Inc.

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EXPLOITS RIVER ICE MODELLING

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EXECUTIVE SUMMARY

E.1 Introduction

In February 1983, an ice jam caused the Exploits River to spill over its banks and flood the Town of Badger. Flood damages were high and there was significant potential for loss of life from this flood and six similar floods which preceded it.

The Department of Environment, Water Resources Division, recognized that similar flooding could occur in the future and joined with Environment Canada to conduct a hydrotechnical study under the Canada-Newfoundland Flood Damage Reduction Program. That study was published in 1985 and delineated the flood risk area in Badger as part of a series of steps to inform all people that there is a risk of flooding in certain areas of the town.

Flooding in Badger is caused by frazil ice jams and, as a result, the 1985 study focused on several methods to determine and confirm ice jam flood levels at Badger. One method involved development of a numerical model which was used to project river ice volumes and the progression of the frazil ice accumulation as it moved upstream from Goodyear's Dam to Badger. The model provided an ice and flood forecasting capability which was not available until that time and it was recommended that the model (or a similar one) be used for early warning of possible flood conditions during subsequent winters. Among other things, it was also recommended that ice conditions and water levels be regularly monitored to provide additional forecasting capability.

The Province adopted these recommendations and has continued its commitment to flood damage reduction in Badger over the past 10 years through its ice observation program, installation of water level recorders, collection of meteorological data and ice modelling for flood forecasting. In that there has been this additional data collection and experience of "real time" use of the current ice forecasting model, and given that the model was largely based on ice observations conducted in a single season, it is timely to re-examine the ice modelling tool now in use for Badger.

In 1993, the governments of Canada and Newfoundland joined in a new program respecting water resources management. One element of the new program identifies the importance of flood forecasting and specifically includes the Exploits River at Badger as a location where flood forecasting can be beneficial. The enclosed study was initiated in 1994 as part of this federal-provincial program to provide an updated approach for flood forecasting at Badger, and to recommend a strategy for the collection of data which could be used to update the forecasting procedure.

The objectives of the enclosed study were to:

- evaluate the data collection program and ice modelling which has been conducted since 1984 on the Exploits River;

- review the available data as compared to the needs of available, recent ice models (or analytical approaches) and assess the practicality of these models; and

- recommend revised/updated approaches to improve flood/ice forecasting for Badger (if found necessary) based on modelling, field data collection or other.

The approach was not initiated as one which would put in place a new model. Instead it was one which would evaluate that possibility and other practical approaches based on the review of existing data and current ice modelling practices.

E.2 Data Collection and Monitoring

The ongoing ice observer program has been reviewed and found to provide a significant quantity of baseline data for assessing past and future ice conditions at Badger. In that a considerable volume of baseline data has been collected for certain elements (i.e., ice thickness), it is recommended that the program be modified to focus on providing:

- detailed mapping of the upstream progression of the frazil ice accumulation until such time as the complete ice cover is upstream of Badger/Three Mile Island.

- increased frequency of ice progression observations in the period when the ice cover is upstream of the Big Bend (upstream of Badger Chute). This could include observations every second or third day during this period and should include rapid (i.e., faximile or telephone) transmission of the data to the Province.

- increased frequency of staff gauge readings when the readings (remotely obtained) indicate rapidly falling or rising levels. This set of readings by the observer is simply to confirm the readings given by the automatic recorder.

Review of the ongoing ice observer monitoring program also indicated that it can now be simplified to:

- eliminate ice condition observations on Junction Brook and Little Red Indian Brook;

- eliminate ice thickness measurements at all locations except the Exploits River near the stadium. These measurements need only be taken until two weeks after the ice cover has reached Badger and has continued upstream past Three Mile Island;

- eliminate the staff gauge readings at Junction Brook.

It is recommended that the current compilation of historical streamflow, water levels and meteorological data (most of which has been compiled for ice progression modelling) be continued into the foreseeable future. It provides the basis for future analysis and, in that these analysis may eventually be based on hourly variations, it is recommended that hourly data files be kept.

The Provincial engineer responsible for the program at Badger has correctly observed that snowfall has an influence on frazil ice production. Similarly, it is recognized that wind direction (particularly if along the axis of the river channel) increases surface water cooling and the potential for frazil ice production. Both of these meteorological factors have potential application for refined flood forecasting and should now be included in the meteorological data base. As time permits, the hourly records of these parameters from previous years should be added to the above mentioned hydrometric (flow) data base.

The water level recording data from the Badger Stadium location was not available for the 1985 study and has been found to provide a new set of extremely valuable data for flood forecasting at Badger. The importance of this information cannot be overstated and it is strongly recommended that the Stadium gauge be maintained and viewed as the primary source of information for flood forecasting.

Water temperature is an important element in the forecasting of ice production in the Exploits River upstream of Badger and is included as a sampling parameter in ongoing provincial water quality monitoring programs. As a result, it is recommended that water temperatures from existing programs be reported to the ice modeller and that water temperatures be taken twice monthly at the outlet of Exploits Dam and at Badger for use in enhancing flood forecasts.

E.3 Analysis and Modelling

Analysis of water level recording data from the 1987 to 1995 period (and particularly the 1990-91 period) provides a strong indication that:

- decreases in water levels in the range of 2 m are indicative of unusually significant frazil ice blockages downstream of Badger. In 1990-91, these decreases were followed in about 24 hours by similar and larger increases in flood water levels.

- remote monitoring of water levels, which are likely to reflect decreases during the frazil-producing night hours, should be closely monitored for water level decreases during the period when the ice front is in the Big Bend/Badger Rough Waters area.

- similarly, rapid increases in levels should continue to be closely monitored - in conjunction with reports from the ice observer, tracking of meteorological conditions and modelling of projected frazil ice volumes.

Analysis of water level data showed a number of oscillations in water levels which may be related to changes in streamflow or ice conditions. In that early knowledge about ice-induced changes in water levels is imperative, it is also recommended that an open water stage-discharge relationship be prepared for the Badger Stadium gauge site. This relationship, when coupled with ice observer reports, will provide a valuable indication of the downstream location where frazil ice blockages begin to contribute to elevated water levels at Badger. This relationship should also provide data on the volume of water which is being transformed into ice and assist in future refinements to the ice observation and modelling work.

A number of river ice models were analyzed as part of this study to determine if any recent (1983-1995) models would be applicable to improve water level forecasting from frazil ice accumulations. The non-proprietary models (the Ice Cover Evolution Module of RIVICE and RIVJAM) are recommended for testing to determine if they can enhance the information provided by the existing ice progression model. These models are not, however, recommended for immediate application to replace any portion of the existing flood forecasting model. RIVJAM and the ice cover evolution module of RIVICE are suggested for review because they appear to hold potential for providing additional insight into the processes of ice cover thickening, transport, stability and erosion in the area downstream of Badger. The existing model should, however, be retained to account for other conditions such as heat balance, open water ice generation, ice cover initiation, etc. Certain refinements can be made (and have been as part of this study) to the existing model, but there is no compelling reason to recommend a broad change in the modelling approach.

The existing ice modelling approach employed by the Province was also reviewed as part of this study and was found consistent with that developed by the authors of the model in 1985. Realistic flood forecasts were provided in this period but it is recommended that the range of the adjustment parameters (provided in Appendix A) be employed as a guide for future flow forecasting modelling.

The existing ice model uses river water temperature as an input to the assessment of ice progression data. It was found that the current model should be modified to use water temperatures which are measured during the winter, and this modification was completed in the model to enhance the forecasting capability in future applications. Similarly, as future applications may employ hourly meteorological data, consideration should be given to modifying several of the subroutines which employ daily values.

E.4 Flood Hazard Analysis

Ice modelling results for the most recent nine years were analyzed to determine if recent information would alter the current approach to forecasting flood levels. The recent observations and simulations confirmed that:

- there is a direct relationship between the frazil ice generation rate and freeze-up flood elevation;
- this relationship can be used to forecast potential flood situations.

Analysis of the recent modelling results (in concert with historical information) confirms that the 100-year flood level at Badger is 100.36 m (Badger Stadium). There are strong indications that the 20-year flood level (99.48 m) should be slightly higher, but this change cannot be advanced until completion of additional years of monitoring.

Analysis of the recent modelling (and re-analysis of the 1985 simulations) indicated that exceptionally high volumes of frazil ice generation on a single day may contribute to water levels which are higher than would normally be forecast at Badger. As a result, it is recommended that forecasted elevations be increased by ~0.7 m when single-day frazil ice generation rates exceed 2.9 million m^3 during the period when the ice cover is between Badger Chute and Badger.

Overall, it is concluded that flood forecasting can continue with increased confidence for Badger. Water level fluctuations (particularly significant reductions) at the gauge in Badger can now be added as a new tool for forecasting subsequent and equally significant rises in water levels. The existing ice progression model can also continue to be used for estimating flood levels. The model has been updated to allow for inclusion of water temperature inputs, and the relationship between ice production and water level has been revised to enable more accurate projection of these levels.

1.0 INTRODUCTION

In 1985, Fenco Newfoundland Ltd. presented its final report on a hydrotechnical study of the Badger and Rushy Pond areas of the Exploits River system to the Canada-Newfoundland Flood Damage Reduction Program (FDRP). This comprehensive study included the determination of river stages during winter ice conditions to establish the 20-year and 100-year winter water levels.

Three approaches were used for determining ice effects on water levels at Badger. One of these approaches included an ice progression model which identified the factors regulating ice conditions in the Exploits River upstream of Grand Falls, and used the frequency of occurrence of these factors (and historical observations) to determine the return period of various flood levels.

This ice progression model appeared to hold promise for providing a forecast/advanced warning of potential flood hazards at Badger and, as a result, has been used by the Province for this purpose. The model, however, was recognized as having limitations. It was largely based on ice observations conducted for a single season, required ice observer information and was based on incomplete physical data describing the channel in the remote area between Badger Chute and Badger.

The value of being able to forecast ice-related water levels at Badger is recognized by the Province and, in order to improve these forecasts, the Province initiated the following study. Its purpose is to examine the current procedure and recommend improvements, if warranted, to the current approach.

The following report is a technical report designed for the technical reviewer who has some familiarity with ice engineering, river hydraulics and surface heat exchange.

1.1 Background

The history of flooding on the Exploits River between Badger and Grand Falls was drawn together from a variety of sources for the Fenco Newfoundland Hydrotechnical Study of the Badger area (1985). Overall, there are at least twenty reports or documents which refer to past flood and river conditions of interest, and review of these reports showed that flooding or high water levels have occurred in the study area on eight occasions since the turn of the century:

Report of Flooding at Badger		
1916-18	1945-46	1977
1937	1957	1983
1943		1991

Study of these incidents indicated that flooding at Badger has only occurred during formation of the ice cover on the Exploits River in January (or February 1983 during reformation). River discharge during these events ranged from about 100 to 200 m^3/s (3600 to 6900 cfs) and averaged approximately 150 m^3/s (5300 cfs) at the Exploits Dam.

Evidence from 1983 photographs taken during field surveys suggested that flooding occurred in that year when the Exploits River ice cover was just reaching Badger. It was also clear from local residents, ice observers and field surveys (and historical photographs) that this ice cover was mostly composed of frazil slush (also referred to locally as "slob") which accumulated to form a frazil ice jam that obstructed a large portion of the channel.

Problematic floods in the past were thought (in 1984) to have been caused by:

(a) a frazil ice cover which thickened and obstructed openings beneath the ice cover as a result of heavier frazil run;

(b) a compression or "shove" in the Badger ice cover brought about by periods of relatively warm weather which weakens the ice cover; and

(c) grounding or compression of the ice cover due to upstream flow changes.

Although past studies and the historical data base provided information which suggested these various causes of flooding in the study area, there was also almost no physical information describing the river hydraulics, the ice cover and the topography of the overbank areas. This information was required to isolate the causes of floods and develop flood level estimates, and was gathered through a number of comprehensive field surveys launched in early January 1984. Following break-up, a second series of surveys were carried out in the summer of 1984.

The data from these surveys and analysis of other information (e.g., river flow) supported a further set of findings about approaches which could be employed to determine flood stages at Badger:

- All of the past flooding in Badger (to 1984) has taken place in January or February. There have been no floods in open water months since the turn of the century and, hence, the flooding potential in the open water months is low.

- Past flooding problems at Badger have only occurred when discharge on the Exploits River has been at values close to the 2-year winter flow rate. At flood flows as low as about the 20-year winter flow rate, the cover has been swept downstream without incident (e.g., March 1979); and at higher flow rates the ice cover has not been able to advance into the Badger area (e.g., January 1978). This structural inter-relationship between discharge and the ice cover suggested that flooding is related to the supply of ice entering the Badger area or arises from thick or obstructive frazil ice jams which can only form in the low flow range.

- The thick ice cover on the Exploits River at Badger contributes to high water levels in the community, but field surveys in 1984 showed that the controlling problem is a blockage by frazil slush in the area of Badger Rough Waters and/or further downstream.

- The timing of Badger flood events is also of interest as it appears that ice jam floods nearly coincide with the appearance of the ice cover as it progresses upstream past the town. At that time, the subsurface channels which later erode this thick ice cover to form open water leads have not fully developed. The cover is at its thickest, and the full extent of any downstream blockages are felt. These blockages include partially developed hanging dams (e.g., Badger Chute) and anchor ice, which should occur on the bottom of the river at many locations between Badger and Badger Chute.

Subsequently, the problem was clearly linked to the volume of frazil slush which is generated above Badger and the rate of progression of the ice cover through the Badger area. There was sufficient data to simulate this condition (in the 1985 study) and tie this causal factor to observed water levels.

1.2 Ice Progression Modelling

The model which was developed to simulate ice conditions on the Exploits River combined a number of existing model approaches (from the 1960's and 1970's) with the data obtained from the detailed winter survey of 1983-84.

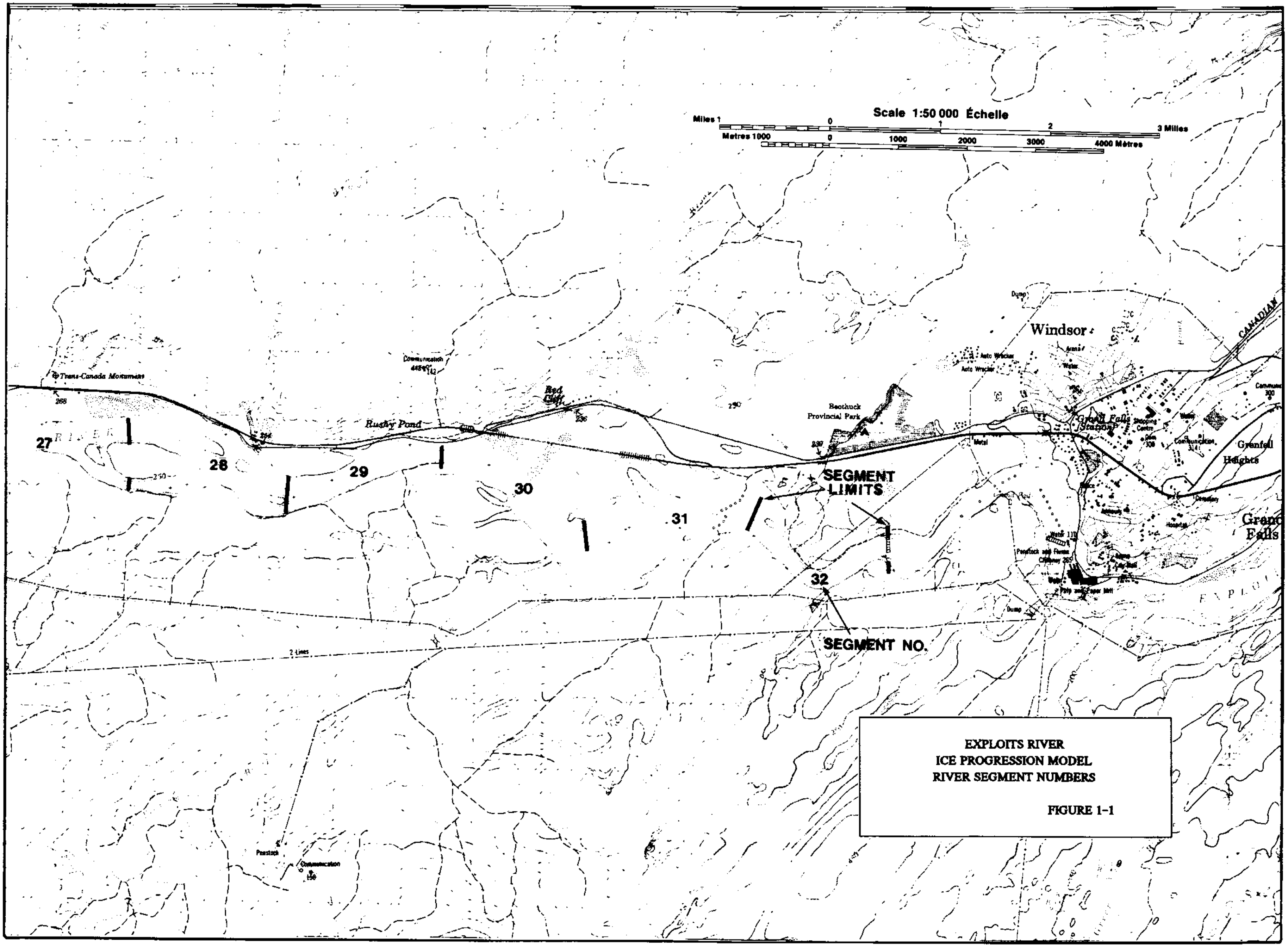
In brief, the original model subdivided the river into 32 connected segments which are described in Appendix A and shown in Figure 1-1. The water temperature in each segment was initially simulated on the basis of meteorological data and discharge information from Environment Canada records and Abitibi Price files. When air and water temperatures in a segment fell to below freezing, frazil ice slush was generated in that segment, combined with that of other segments and was carried downstream. The slush passed over Goodyear's Dam until it was blocked by border ice growth at the dam or by the ice boom just upstream. Once the downstream progression was stopped, the slush from upstream segments began to accumulate in segments upstream of Goodyear's Dam. Gradually (or rapidly), the ice cover grew in an upstream direction from the dam until it passed Badger and moved on up to Three Mile Island and beyond.

The model was calibrated and verified in our 1985 study - relying heavily on 1983-84 ice observations and local observations (historical) - and then employed to simulate over 30 years of ice conditions on the river. This set of information showed that the clear difference between the flood and non-flood years at Badger was the rate at which the ice cover approached Badger.

The flood years of 1982-83, 1976-77 and 1936-37, for example, stood out from the rest because of the massive volume of ice forming the ice cover as it moved through the Badger area. Years in which high water levels were noted but not problematic (e.g. 1956-57 or 1950-51) showed somewhat higher rates of ice production than many, and years without flooding showed a range of lesser rates.

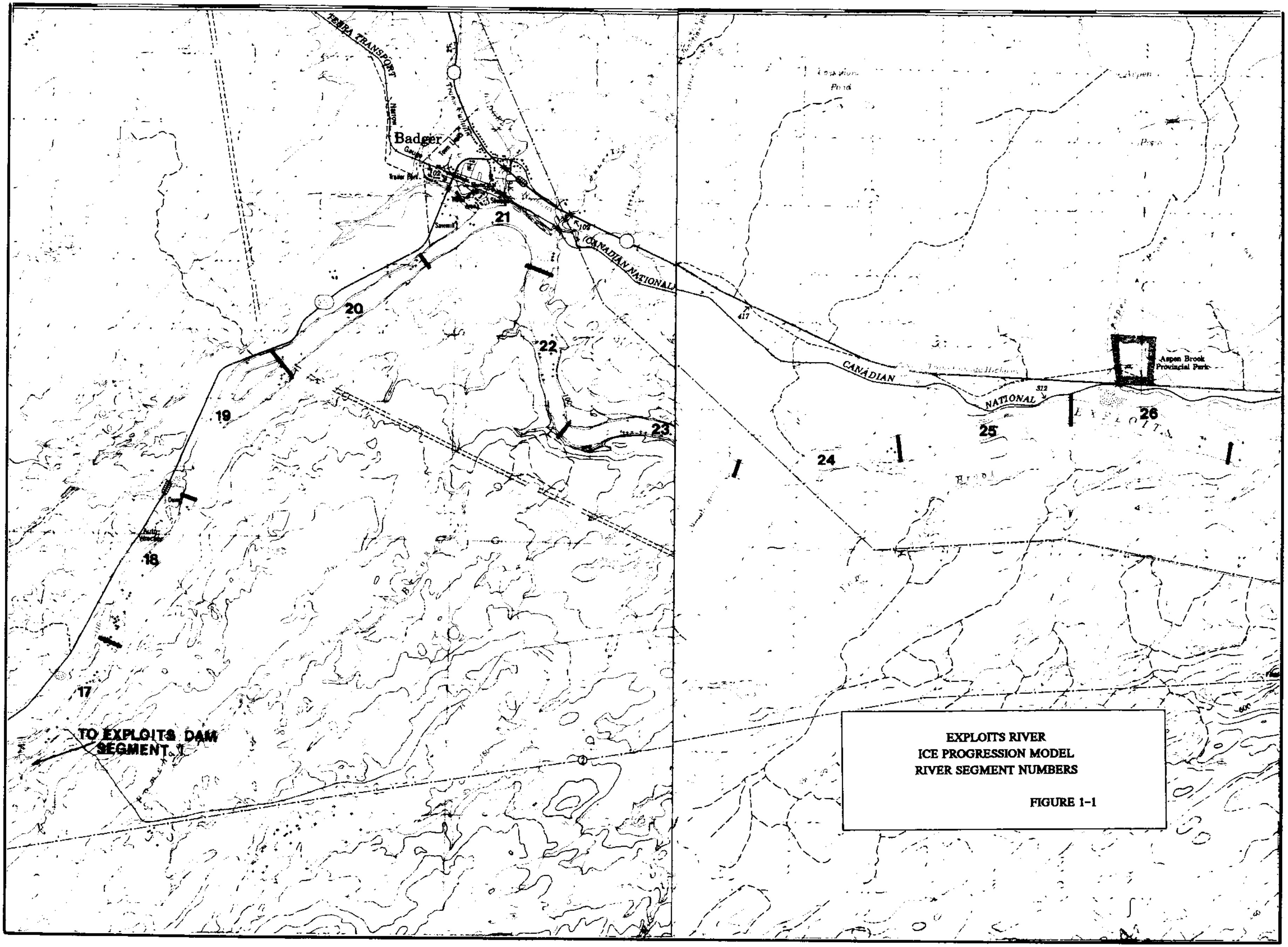
Analysis of the frazil slush generation rate was then linked to water levels at Badger as shown in Figure 1-2. Figure 1-2 compares the volume of ice produced to the geodetic elevation at freeze-up for all the years in which levels were known or estimated (up to 1984).

This linkage made it possible to add additional elements to the provincial flood warning system. Prior to 1983, flood forecasting for the Badger area was conducted using daily discharge records



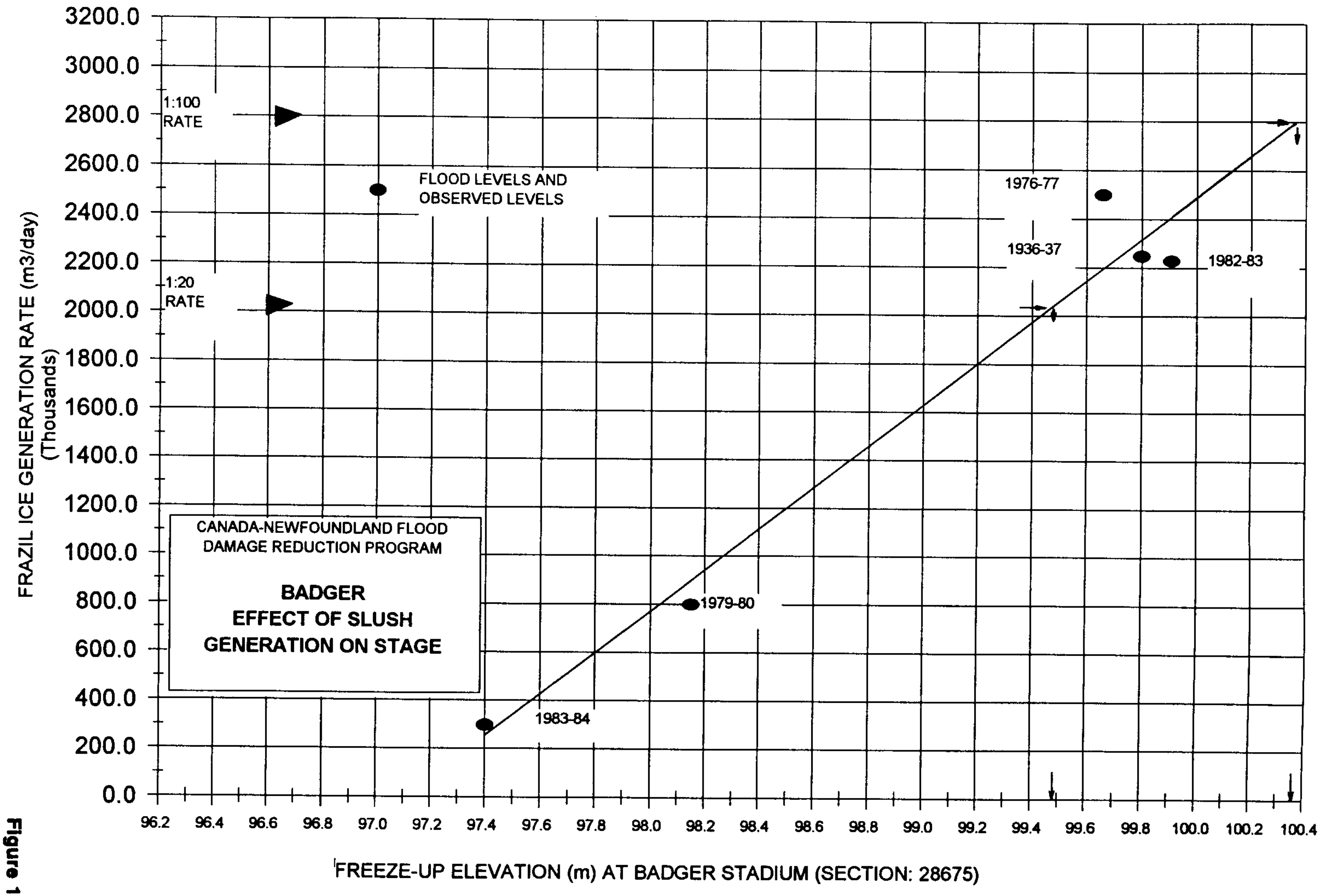
EXPLOITS RIVER
ICE PROGRESSION MODEL
RIVER SEGMENT NUMBERS

FIGURE 1-1



EXPLOITS RIVER
ICE PROGRESSION MODEL
RIVER SEGMENT NUMBERS

FIGURE 1-1


CANADA-NEWFOUNDLAND FLOOD DAMAGE REDUCTION PROGRAM
BADGER
EFFECT OF SLUSH GENERATION ON STAGE
FRAZIL ICE GENERATION RATE (m3/day) (Thousands)
FREEZE-UP ELEVATION (m) AT BADGER STADIUM (SECTION: 28675)
1:100 RATE
1:20 RATE
FLOOD LEVELS AND OBSERVED LEVELS
1976-77
1936-37
1982-83
1979-80
1983-84
3200.0
3000.0
2800.0
2600.0
2400.0
2200.0
2000.0
1800.0
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
96.2
96.4
96.6
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99.4
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99.8
100.0
100.2
100.4

Figure 1-2

at Grand Falls. During the winter, these records showed reductions in discharge at Grand Falls which could not be explained by flow reductions at Exploits Dam. These "losses" represent channel storage made available by upstream ice production and water level increases caused by the presence of the ice cover or ice jams. When the losses become a large portion of the streamflow and/or extend over a long period, teams were sent into the field to evaluate the seriousness of the problem and the potential for flooding (e.g., 1980).

The first additional element to that flood forecasting procedure was initiated by the Province through its use of ice observers to monitor, record and report ice conditions from Grand Falls to Badger and upstream. This was followed by the establishment of a hydrometric station below Noel Pauls Brook (about 20 km upstream of Badger), several staff gauges at Badger and a water level recording station at Badger.

This additional element was set in place to give maximum lead time between "normal" winter water levels approaching Badger and abnormal conditions associated with flood-producing ice accumulations. As shown in Figure 1-3, these abnormal conditions should be readily detected because water levels rise about 2.5 m to 3.0 m above normal winter conditions. A water level recorder was installed near Badger Stadium in 1987/88 and upgraded in 1991 to provide hourly observations (which can be accessed by telephone).

The third element, provision of an ice observer at Badger and ice observations along the river in the Grand Falls area, provided an abundance of practical records of ice data (about 10 years duration) which has assisted in ice forecasting - and which can assist in reformulating an ice forecasting model.

In 1984, the Province also initiated the above-mentioned hydrotechnical study (Fenco Newfoundland, 1985) which added flood forecasting capability through development of an ice progression model. The current model provided good estimates of the ice front location on the Exploits River (for years up to 1984) and was established to be adjusted "interactively" to the observed conditions of a particular year on the basis of climate and river flows, observed ice front location and projected flows and temperatures.

Overall, the Province embarked on a commitment to flood damage reduction in Badger over a decade ago. This procedure is being continuously improved but may have the appearance of being outdated as (in part) it includes an ice modelling tool which embodied technology which

WATER LEVELS – BADGER STADIUM

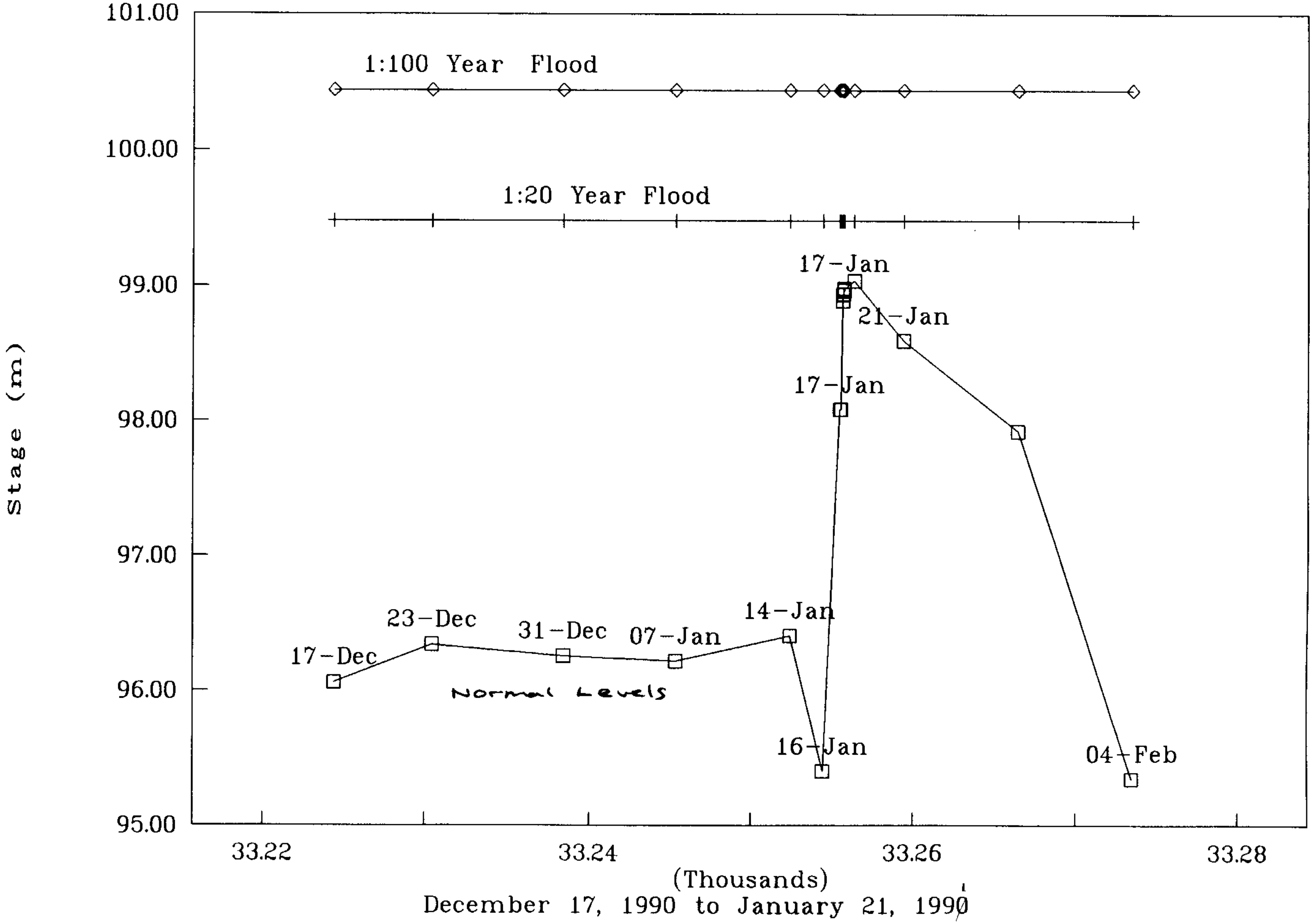

Figure 1-3

is now over 15 years old, and which was based on good - but limited - field data. In the years since 1984, there has been additional data collection, the experience of "real time" use of the current forecasting model (through subsequent studies) and a number of advances in the technology of ice modelling. Given the Province's water resources mandate and responsibility for providing flood warning where possible, it is timely to re-examine the ice modelling tool now in use for Badger.

This current study continues this work to provide an updated approach for flood forecasting at Badger, and a strategy for the collection of data which could be used to update the forecasting procedure.

1.3 Study Approach

The previous section provided a simplified summary of the ice processes at work during early winter months in the Exploits River. More specifically, the ice formation processes involve generation and transport of: frazil ice, anchor ice, frazil slush, snow slush, border ice and sheet ice. Their accumulation involves formation of hanging dams, juxtaposition of floes, frontal progression, progression and thickening by packing, shoving and jamming to equilibrium thickness, and hydraulic resistance from the time of generation/production of frazil and anchor ice to its contribution to an ice blockage. These aspects are further complicated by non-steady flow conditions, surge-like transients and meteorological variability which contributes to rapid warming with snowmelt and rainfall runoff.

The progressive, upstream movement of ice accumulations on the Exploits River is periodically stopped by break-up processes (such as snowmelt/rainfall runoff). As a result, the above-described ice formation processes are intertwined with a similar set of break-up, melt and ice clearing processes.

The total picture is one of apparent and real complexity. However, recent (i.e., about 10 years) data from the water level recordings, observers and modelling of the Exploits River system removes one layer of this complexity. Knowledge about observed features of the problem removes another, and new data from water level monitoring removes others.

Very simply, the approach to this study is to:

- evaluate the data collection program and modelling since 1984;

- review the available data as compared to the needs of available, recent ice models (or analytical approaches) and assess the practicality of these models; and

- recommend revised/updated approaches to improve flood/ice forecasting for Badger (if found necessary) based on modelling, field data collection or other.

The approach was not initiated as one which would put in place a new model. Instead it was one which would evaluate that possibility and other practical approaches based on the review of existing data and current ice modelling practices.

2.0 EXISTING CONDITIONS AND APPROACH

To reiterate, since inception of the first ice study of the Exploits River (1985), there are:

- additional flow data from gauging of the Exploits River near Noel Pauls Brook;
- remote/telemark water level data from Badger;
- a revised series of historical daily discharges from Red Indian Lake and at Grand Falls;
- additional observations of ice conditions and ice movement in the river from the Grand Falls area to Badger;
- more detailed meteorological data;
- information on ice conditions at Badger; and
- a series of ice forecasting model simulations.

The first step in the following study was to review this new and revised data against the information available for the earlier study (1985), and to assess the current ice and flood forecasting approach which has evolved over the past 10 years.

This initial phase involved refamiliarization with the current model (partially revised from the original model), discussions with Environment staff involved in ice forecasting, an overview of ice and river conditions (1985-1995), discussion and data collection from Abitibi Price staff, field observations of ice conditions in the winter of 1993-94, and field observations of ice-free conditions in the summer of 1994.

2.1 Review of Recent Data Collection (1985 to 1994)

The principal information which has been gathered at Badger and in the Exploits River area over the past nine winters provides new insight into ice processes affecting Badger. The recent data includes:

- ice observer reports and their ice progression mapping;
- water level recordings and observations of levels;
- extended hydrometric records;
- an extended meteorological data base; and
- ice regime modelling (nine additional winters).

2.1.1 Ice Observer Reports and Ice Progression Mapping

The local ice observers at Badger have provided important qualitative and quantitative data to the understanding of ice processes in the area and to the capability to forecast flood levels. Tables 2.1 to 2.4 (1983-84 to 1986-87) were assembled as part of this study to illustrate the progression in detail provided by the observers. Tables 2.5 to 2.11 (provided later in this report) give similar information for the years from 1987 to 1994.

TABLE 2.1: ICE OBSERVATION (1983-84)

EXPLOITS RIVER	
Date	**Observations**
Dec 18/83	- ice cover close to Goodyear's Dam
Dec 21	- ice cover probably beyond Aspen Bk (~5500 to 6000 cfs)
Dec 28	- solid ice to Badger Chute; frazil moving past Badger
Jan 10-12	- ice cover progression through Badger*
~Jan 15/84	- ice cover to Three Mile Island (still ~5500 to 6000 cfs)

* conditions observed and reported in previous FDRP study (Fenco Newfoundland, 1985)

TABLE 2.2: ICE OBSERVATIONS (1984-85)

Date	Observations[1]	Staff Gauge
Dec 9/84	- first run of frazil observed	--
Dec 16	- ice front to North Angle	--
Dec 17	- ice front near Rushy Pond (model section 30)	--
Dec 27	- ice front near upstream end of model section 26	--
Jan 3/85	- ice front at Badger Chute (model section 24)	--
Jan 6	- ice front to Badger	--
Jan 7	- ice front near three Mile Island (mid model section 20)	--
Jan 10	- ice front nearly to Red Indian Falls	--
Jan 30	- ice front ~20 km upstream of Red Indian Brook bridge - slush moving downstream, ~15 m border ice both banks - lead open ~70 m from E bank, downstream of Rough Waters* and along E bank at Rough Waters	--
Jan 31	- solid ice cover	

* ice thickness cross-sections taken (sect. 3, 31, C4, 6, 7, B, A)

[1] hydrometric station established at Noel Pauls Brook (~20 km upstream)

TABLE 2.3: ICE OBSERVATIONS (1985-86)

Date	Observations[1]	Staff Gauge
Jan 25/86	- 10-12 m wide central channel at Badger	--
Feb 1	- wide central channel - little border ice (mild weather)	--
Feb 9	- 30-85 m wide channel - some frazil ice flowing	--
Feb 15	- 15-20 m wide channel; channel frozen across (border ice? at Gull Rocks and likely upstream)	--
Feb 22	- as Feb 15	0661
Mar 2	- as Feb 15, but larger control channel	0663
Mar 8	- similar to Mar 2	0653
Mar 15	- similar to Mar 2, with small pans flowing	0659
Mar 22	- similar to Mar 2	0657
Mar 29	- wide central channel, upstream ice decaying	0648
Apr 5	- completely open water at Badger, is still upstream ice	0635
Apr 15	- most of ice is gone	0663

[1]
- ice cover progression not recorded/mapped
- observations may not have captured ice front progression upstream through Badger
- collected Grand Falls temperatures as gaps in Badger temperature record
- local water level station became operational in mid-February 1986

TABLE 2.4: ICE OBSERVATIONS (1986-87)

EXPLOITS		
Date	**Observations**	**Staff Gauge**
Dec 7, 8/86	- near Tom Joe Brook - upstream end of model section 25	--
Dec 9	- at Badger Chute (mid model section 24)	--
Dec 13	- above Badger Chute (section 23)	--
Dec 15	- upper edge of ice front below Big Bend (in section 23) - open with slush - 10-15' of border ice on banks at Badger	0732
Dec 18	- downstream of Big Bend (in u/s section 23 or d/s section 22)	--
Dec 19	- ice front upstream of Big Bend (model section 22)	--
Dec 22	- open water, good flow at Badger - level rise when upper edge of ice front ~ mid section 22	0956
Dec 23	- ice front upstream of Big Bend (to mid section 22)	--
Dec 24	- ice front just reaching Badger (in section 21) but still is open - ice front just upstream of Beatons Island	--
Dec 29	- upstream edge near Gull Rocks lead ~mid channel from Badger Brook to downstream of Badger Rough waters (ice in section 21)	0956
Dec 31	- ice front near 3 Mile Island (ice upper edge mid section 19)	0956
Jan 1/87	- ice front in upstream portion of section 18	--
Jan 3	- ice front just into section 17	--
Jan 5	- ice front in mid section 17	--
Jan 6	- ice front in downstream portion of section 16 - 5-6" thick near Badger	est 0956
Jan 13	- ice front in area 15; gauge not working	normal
Jan 20	- ice front 1 mile from Falls; small lead at Rough Waters	0705
Jan 30	- ice front at Falls above Badger	0699
Feb 8	- ice front at Falls	0703
Feb 15	- ice cover reported to have reached Exploits Dam	0705
Feb 22	- still small lead at Badger Rough Waters	0695
OTHER READINGS		
Mar 1		0688
Mar 8	- 500' lead at Rough Waters - good record of break-up sequence	0679 0675 to 703

The recent observation program includes:

- staff gauge readings for early input to water level changes and confirmation of recorded data at the Badger Stadium location;
- water level/ice level records at several other sites in the Badger area;
- observations and mapping of the upstream location of the frazil ice accumulation (ice front location) throughout the winter; and
- ice thickness, ice type and condition, and snow cover data.

There has been considerable variation in the type and quality of data provided to the Province through the local observer program. Overview of the information highlights the 1986-87 program for its excellence (in providing exceptional detail on the location and progression of the ice accumulation - see Figure 2-1 and Appendix F) and other years for providing estimates of ice thickness and type. In that the program has now gathered a baseline of ice thickness data, it is recommended that the program now be simplified to focus on the principal elements for forecasting flood levels at Badger:

- Detailed mapping of the upstream progression of the frazil ice accumulation until such time as the ice front (complete ice cover) is upstream of Three Mile Island. Upstream of this point, subsequent ice generation rates and changes in water levels appear to have no effect on flooding potential at Badger.
- More frequent, regular monitoring of staff gauge/recorder elevations during the period when the ice accumulation is within the Badger area. As described in the next section of this report, this monitoring offers enhanced possibilities for flood forecasting.

2.1.2 Water Level Recording Data

The strip chart records, observer readings and digitized water level data provide extremely valuable information.

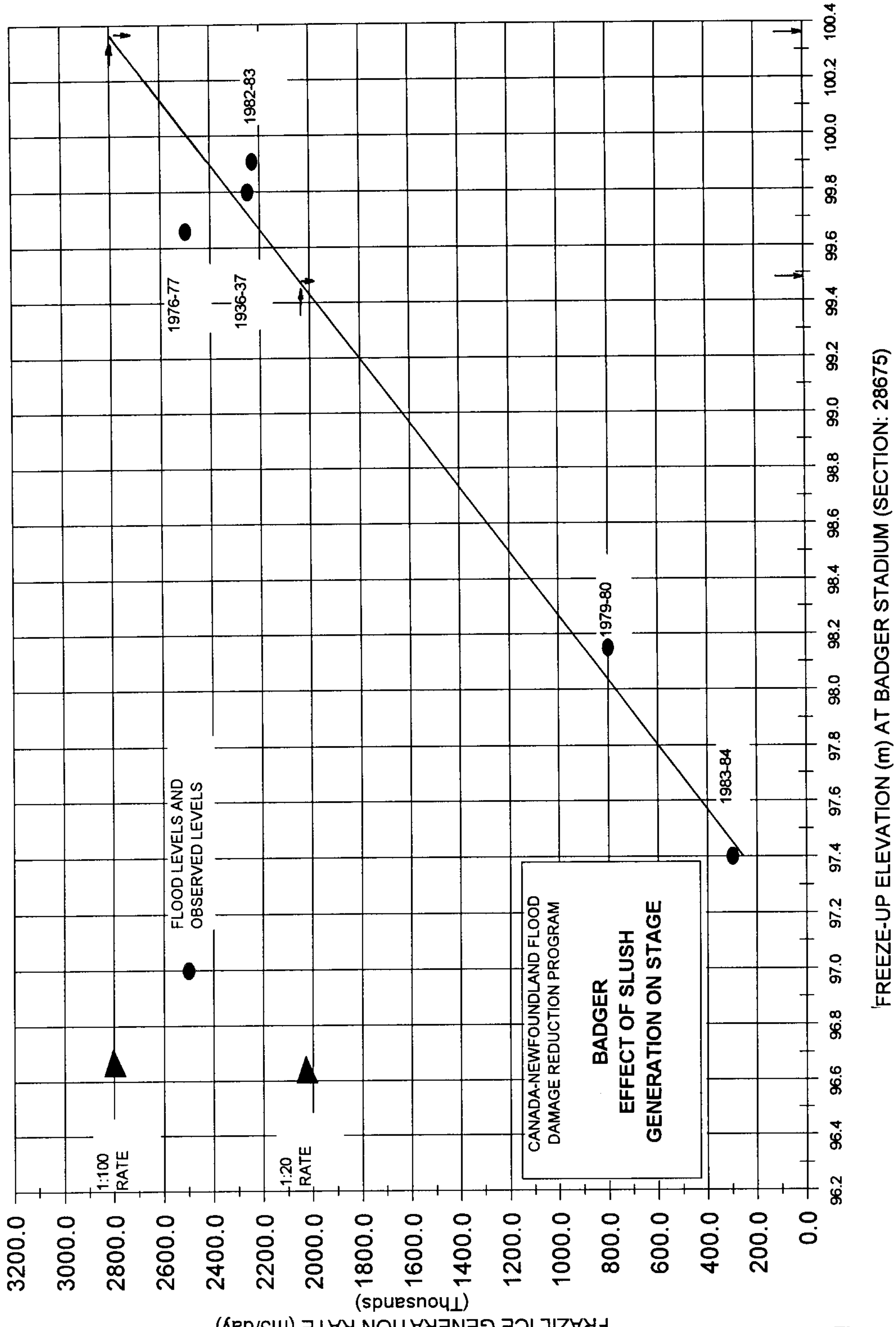
CANADA-NEWFOUNDLAND FLOOD DAMAGE REDUCTION PROGRAM
BADGER
EFFECT OF SLUSH GENERATION ON STAGE
FREEZE-UP ELEVATION (m) AT BADGER STADIUM (SECTION: 28675)
FRAZIL ICE GENERATION RATE (m3/day)
(Thousands)
FLOOD LEVELS AND OBSERVED LEVELS
1:100 RATE
1:20 RATE
1976-77
1936-37
1982-83
1979-80
1983-84
96.2
96.4
96.6
96.8
97.0
97.2
97.4
97.6
97.8
98.0
98.2
98.4
98.6
98.8
99.0
99.2
99.4
99.6
99.8
100.0
100.2
100.4
0.0
200.0
400.0
600.0
800.0
1000.0
1200.0
1400.0
1600.0
1800.0
2000.0
2200.0
2400.0
2600.0
2800.0
3000.0
3200.0

Figure 1-2

at Grand Falls. During the winter, these records showed reductions in discharge at Grand Falls which could not be explained by flow reductions at Exploits Dam. These "losses" represent channel storage made available by upstream ice production and water level increases caused by the presence of the ice cover or ice jams. When the losses become a large portion of the streamflow and/or extend over a long period, teams were sent into the field to evaluate the seriousness of the problem and the potential for flooding (e.g., 1980).

The first additional element to that flood forecasting procedure was initiated by the Province through its use of ice observers to monitor, record and report ice conditions from Grand Falls to Badger and upstream. This was followed by the establishment of a hydrometric station below Noel Pauls Brook (about 20 km upstream of Badger), several staff gauges at Badger and a water level recording station at Badger.

This additional element was set in place to give maximum lead time between "normal" winter water levels approaching Badger and abnormal conditions associated with flood-producing ice accumulations. As shown in Figure 1-3, these abnormal conditions should be readily detected because water levels rise about 2.5 m to 3.0 m above normal winter conditions. A water level recorder was installed near Badger Stadium in 1987/88 and upgraded in 1991 to provide hourly observations (which can be accessed by telephone).

The third element, provision of an ice observer at Badger and ice observations along the river in the Grand Falls area, provided an abundance of practical records of ice data (about 10 years duration) which has assisted in ice forecasting - and which can assist in reformulating an ice forecasting model.

In 1984, the Province also initiated the above-mentioned hydrotechnical study (Fenco Newfoundland, 1985) which added flood forecasting capability through development of an ice progression model. The current model provided good estimates of the ice front location on the Exploits River (for years up to 1984) and was established to be adjusted "interactively" to the observed conditions of a particular year on the basis of climate and river flows, observed ice front location and projected flows and temperatures.

Overall, the Province embarked on a commitment to flood damage reduction in Badger over a decade ago. This procedure is being continuously improved but may have the appearance of being outdated as (in part) it includes an ice modelling tool which embodied technology which

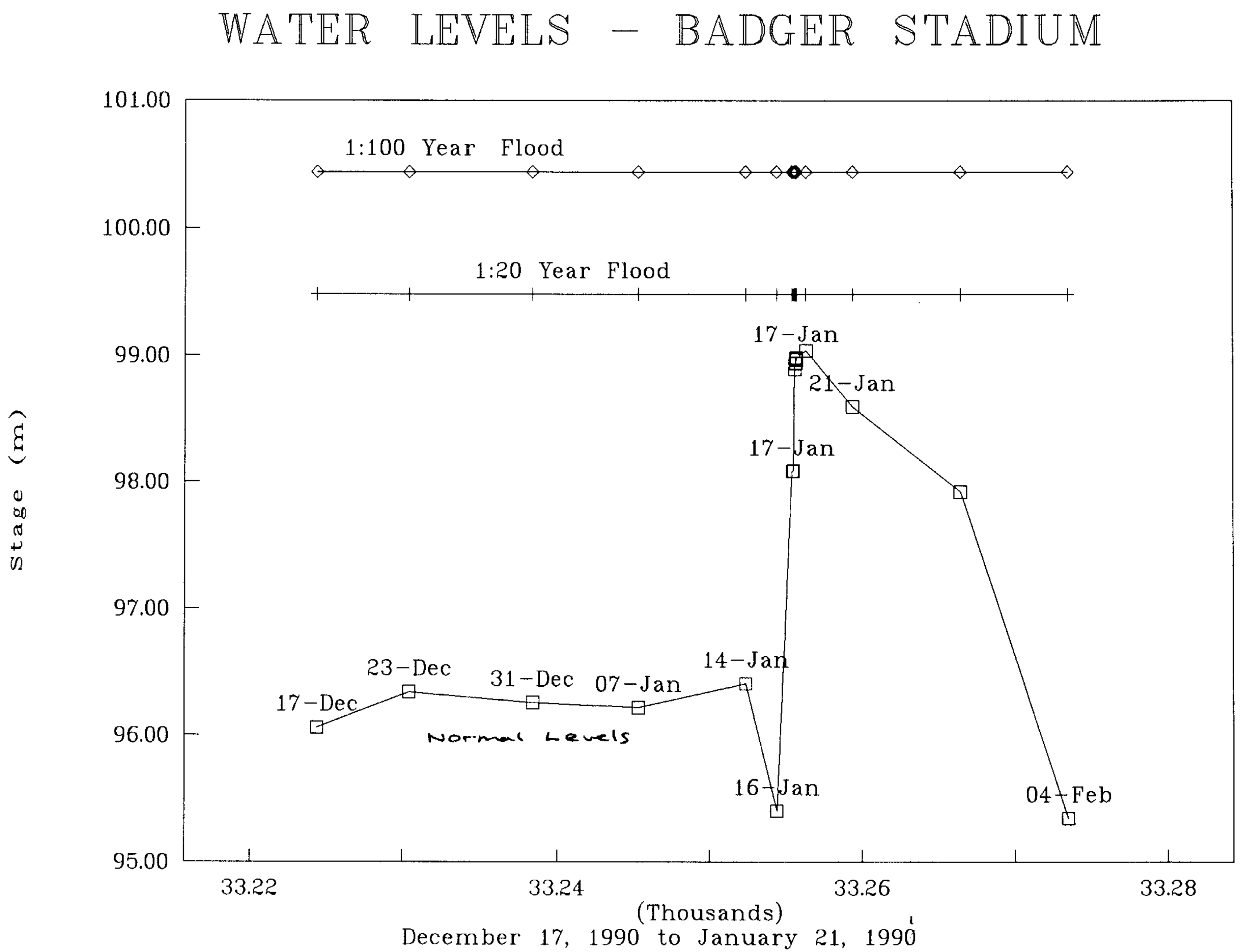
WATER LEVELS - BADGER STADIUM
1:100 Year Flood
1:20 Year Flood
17-Jan
21-Jan
17-Jan
14-Jan
16-Jan
04-Feb
17-Dec
23-Dec
31-Dec
07-Jan
Normal Levels
Stage (m)
101.00
100.00
99.00
98.00
97.00
96.00
95.00
33.22
33.24
33.26
33.28
(Thousands)
December 17, 1990 to January 21, 1990

Figure 1-3

is now over 15 years old, and which was based on good - but limited - field data. In the years since 1984, there has been additional data collection, the experience of "real time" use of the current forecasting model (through subsequent studies) and a number of advances in the technology of ice modelling. Given the Province's water resources mandate and responsibility for providing flood warning where possible, it is timely to re-examine the ice modelling tool now in use for Badger.

This current study continues this work to provide an updated approach for flood forecasting at Badger, and a strategy for the collection of data which could be used to update the forecasting procedure.

1.3 Study Approach

The previous section provided a simplified summary of the ice processes at work during early winter months in the Exploits River. More specifically, the ice formation processes involve generation and transport of: frazil ice, anchor ice, frazil slush, snow slush, border ice and sheet ice. Their accumulation involves formation of hanging dams, juxtaposition of floes, frontal progression, progression and thickening by packing, shoving and jamming to equilibrium thickness, and hydraulic resistance from the time of generation/production of frazil and anchor ice to its contribution to an ice blockage. These aspects are further complicated by non-steady flow conditions, surge-like transients and meteorological variability which contributes to rapid warming with snowmelt and rainfall runoff.

The progressive, upstream movement of ice accumulations on the Exploits River is periodically stopped by break-up processes (such as snowmelt/rainfall runoff). As a result, the above-described ice formation processes are intertwined with a similar set of break-up, melt and ice clearing processes.

The total picture is one of apparent and real complexity. However, recent (i.e., about 10 years) data from the water level recordings, observers and modelling of the Exploits River system removes one layer of this complexity. Knowledge about observed features of the problem removes another, and new data from water level monitoring removes others.

Very simply, the approach to this study is to:

- evaluate the data collection program and modelling since 1984;

- review the available data as compared to the needs of available, recent ice models (or analytical approaches) and assess the practicality of these models; and

- recommend revised/updated approaches to improve flood/ice forecasting for Badger (if found necessary) based on modelling, field data collection or other.

The approach was not initiated as one which would put in place a new model. Instead it was one which would evaluate that possibility and other practical approaches based on the review of existing data and current ice modelling practices.

2.0 EXISTING CONDITIONS AND APPROACH

To reiterate, since inception of the first ice study of the Exploits River (1985), there are:

- additional flow data from gauging of the Exploits River near Noel Pauls Brook;
- remote/telemark water level data from Badger;
- a revised series of historical daily discharges from Red Indian Lake and at Grand Falls;
- additional observations of ice conditions and ice movement in the river from the Grand Falls area to Badger;
- more detailed meteorological data;
- information on ice conditions at Badger; and
- a series of ice forecasting model simulations.

The first step in the following study was to review this new and revised data against the information available for the earlier study (1985), and to assess the current ice and flood forecasting approach which has evolved over the past 10 years.

This initial phase involved refamiliarization with the current model (partially revised from the original model), discussions with Environment staff involved in ice forecasting, an overview of ice and river conditions (1985-1995), discussion and data collection from Abitibi Price staff, field observations of ice conditions in the winter of 1993-94, and field observations of ice-free conditions in the summer of 1994.

2.1 Review of Recent Data Collection (1985 to 1994)

The principal information which has been gathered at Badger and in the Exploits River area over the past nine winters provides new insight into ice processes affecting Badger. The recent data includes:

- ice observer reports and their ice progression mapping;
- water level recordings and observations of levels;
- extended hydrometric records;
- an extended meteorological data base; and
- ice regime modelling (nine additional winters).

2.1.1 Ice Observer Reports and Ice Progression Mapping

The local ice observers at Badger have provided important qualitative and quantitative data to the understanding of ice processes in the area and to the capability to forecast flood levels. Tables 2.1 to 2.4 (1983-84 to 1986-87) were assembled as part of this study to illustrate the progression in detail provided by the observers. Tables 2.5 to 2.11 (provided later in this report) give similar information for the years from 1987 to 1994.

TABLE 2.1: ICE OBSERVATION (1983-84)

EXPLOITS RIVER	
Date	**Observations**
Dec 18/83	- ice cover close to Goodyear's Dam
Dec 21	- ice cover probably beyond Aspen Bk (~5500 to 6000 cfs)
Dec 28	- solid ice to Badger Chute; frazil moving past Badger
Jan 10-12	- ice cover progression through Badger*
~Jan 15/84	- ice cover to Three Mile Island (still ~5500 to 6000 cfs)

* conditions observed and reported in previous FDRP study (Fenco Newfoundland, 1985)

TABLE 2.2: ICE OBSERVATIONS (1984-85)

Date	Observations[1]	Staff Gauge
Dec 9/84	- first run of frazil observed	--
Dec 16	- ice front to North Angle	--
Dec 17	- ice front near Rushy Pond (model section 30)	--
Dec 27	- ice front near upstream end of model section 26	--
Jan 3/85	- ice front at Badger Chute (model section 24)	--
Jan 6	- ice front to Badger	--
Jan 7	- ice front near three Mile Island (mid model section 20)	--
Jan 10	- ice front nearly to Red Indian Falls	--
Jan 30	- ice front ~20 km upstream of Red Indian Brook bridge - slush moving downstream, ~15 m border ice both banks - lead open ~70 m from E bank, downstream of Rough Waters* and along E bank at Rough Waters	--
Jan 31	- solid ice cover	

* ice thickness cross-sections taken (sect. 3, 31, C4, 6, 7, B, A)
[1] hydrometric station established at Noel Pauls Brook (~20 km upstream)

TABLE 2.3: ICE OBSERVATIONS (1985-86)

Date	Observations[1]	Staff Gauge
Jan 25/86	- 10-12 m wide central channel at Badger	--
Feb 1	- wide central channel - little border ice (mild weather)	--
Feb 9	- 30-85 m wide channel - some frazil ice flowing	--
Feb 15	- 15-20 m wide channel; channel frozen across (border ice? at Gull Rocks and likely upstream)	--
Feb 22	- as Feb 15	0661
Mar 2	- as Feb 15, but larger control channel	0663
Mar 8	- similar to Mar 2	0653
Mar 15	- similar to Mar 2, with small pans flowing	0659
Mar 22	- similar to Mar 2	0657
Mar 29	- wide central channel, upstream ice decaying	0648
Apr 5	- completely open water at Badger, is still upstream ice	0635
Apr 15	- most of ice is gone	0663

[1]
- ice cover progression not recorded/mapped
- observations may not have captured ice front progression upstream through Badger
- collected Grand Falls temperatures as gaps in Badger temperature record
- local water level station became operational in mid-February 1986

TABLE 2.4: ICE OBSERVATIONS (1986-87)

EXPLOITS		
Date	**Observations**	**Staff Gauge**
Dec 7, 8/86	- near Tom Joe Brook - upstream end of model section 25	--
Dec 9	- at Badger Chute (mid model section 24)	--
Dec 13	- above Badger Chute (section 23)	--
Dec 15	- upper edge of ice front below Big Bend (in section 23) - open with slush - 10-15' of border ice on banks at Badger	0732
Dec 18	- downstream of Big Bend (in u/s section 23 or d/s section 22)	--
Dec 19	- ice front upstream of Big Bend (model section 22)	--
Dec 22	- open water, good flow at Badger - level rise when upper edge of ice front ~ mid section 22	0956
Dec 23	- ice front upstream of Big Bend (to mid section 22)	--
Dec 24	- ice front just reaching Badger (in section 21) but still is open - ice front just upstream of Beatons Island	--
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The recent observation program includes:

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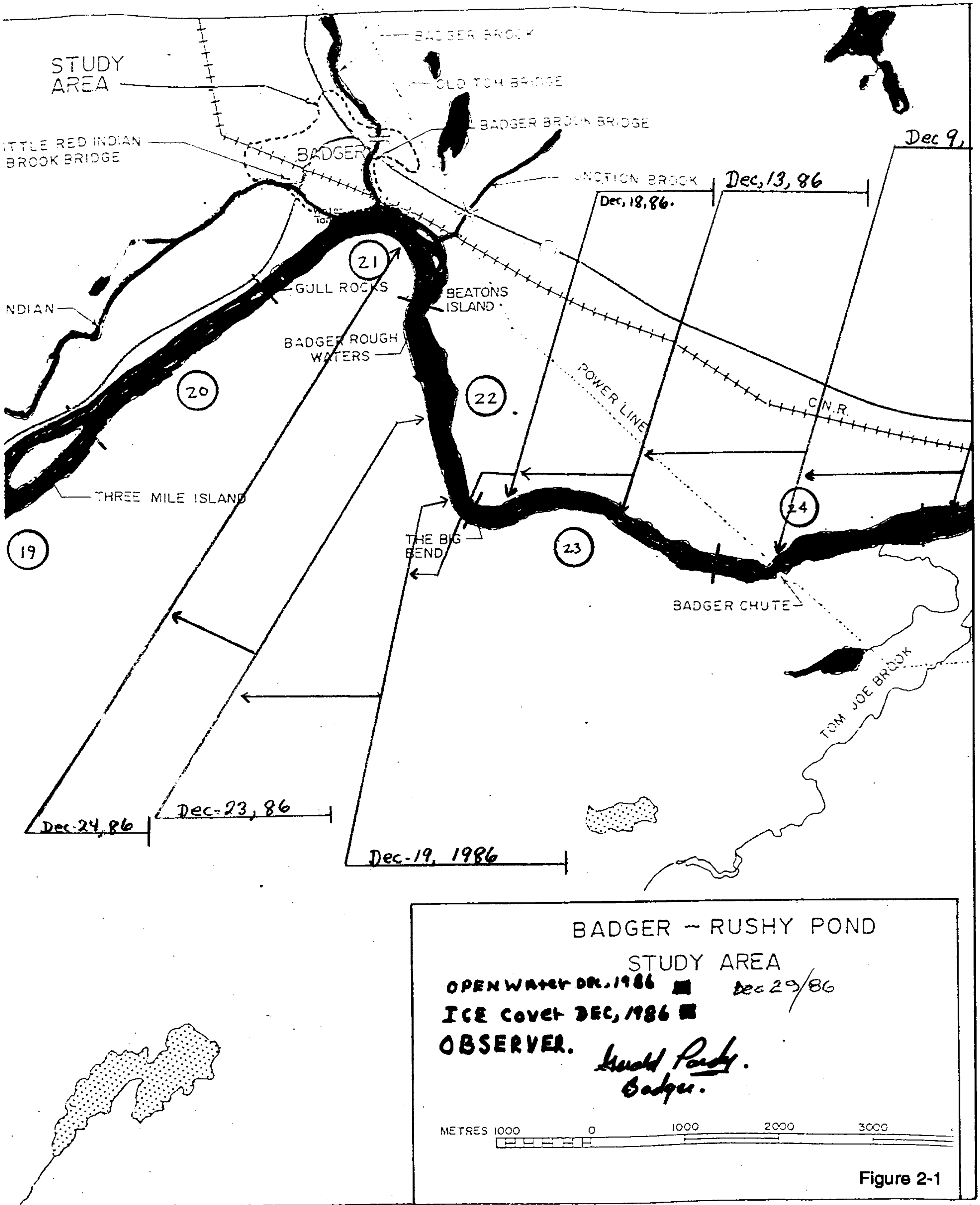


STUDY AREA
BADGER BROOK
OLD TOM BRIDGE
BADGER BROOK BRIDGE
LITTLE RED INDIAN BROOK BRIDGE
BADGER
JUNCTION BROOK
Dec 9,
Dec, 13, 86
Dec, 18, 86.
21
GULL ROCKS
BEATONS ISLAND
INDIAN
BADGER ROUGH WATERS
POWER LINE
C.N.R.
20
22
THREE MILE ISLAND
24
19
THE BIG BEND
23
BADGER CHUTE
TOM JOE BROOK
Dec-24, 86
Dec-23, 86
Dec-19, 1986
BADGER – RUSHY POND
STUDY AREA
OPEN Water DEC. 1986
Dec 29/86
ICE Cover DEC, 1986
OBSERVER.
Badger.
METRES 1000 0 1000 2000 3000

Figure 2-1

In the previous FDRP study, the focus of the work was to determine high water levels (e.g., 100-year). Anecdotal information about the rate of water level rise or the peak level during a flood event was remembered by local residents or recorded on film, as well as the fact that the floods were associated with frazil ice production. This was confirmed by cross-section surveys showing massive frazil ice accumulation from Badger Chute to Badger.

It was surmised in the previous study that compression, shoving and collapse of the frazil ice field accounted for floods in Badger. This was then proven to be linked to the volume of frazil ice generation upstream of Badger through a modelling approach.

The recent water level data illustrate the ice packing/shoving process and provide another forecasting tool for use in flood damage reduction for Badger. The 1987-88 winter water levels were the first recorded on strip charts and were augmented by local observers' readings of a staff gauge and plotting of ice progression (Appendix F). The recordings show changes in levels with flow conditions but, more importantly, show changes specifically brought about by downstream ice conditions. Table 2.5 summarizes observations and notes the oscillation in water levels observed on 14-15 January 1988 when the ice cover was progressing upstream past Badger. On 14 January, the water level fell approximately 0.9 m in six hours (approximately 0.2 m/hour) and then rose 1.2 m in six hours (0.2 m/hour rise). On 16 January, there was another 0.25 m rise in one hour followed by a 0.25 m drop.

The 1988-89 reports from the local ice observer are missing for that year, but the strip chart records from January 10 to 16 illustrate some of the same oscillatory behaviour (Table 2.6).

Table 2.7 reports some of the 1989-90 strip chart results and ice progression is plotted in Appendix F. In the period when the ice cover was thickening and consolidating downstream of Badger, there was a 1.5 m rise in water levels (2 January) followed by a 0.3 m drop in less than an hour. A week later when the cover was well upstream of Badger (and not providing significant frazil volumes to the ice accumulation below Badger), there was a 2 m drop in levels (approximately 0.3 m/hour) and similar rise.

TABLE 2.5: ICE OBSERVATIONS (1987-88)

EXPLOITS RIVER			
Date	**Observations***	**Staff Gauge**	**Water Levels**[1]
Dec 6/87	- open water at Stadium area	0646.2	nr
Dec 13	- open water at Stadium area	0639.2	nr
Dec 21	- open water, slush filled moving downstream - gradual 0.5 m rise and fall in day	--	6.4 m
Dec 27	- open with moving slush	0653.6 at RR bridge	~6.3 m
Jan 3/88	- open with moving slush	0643	6.36
Jan 8	- ice front downstream of Big Bend (in section 22 or 23)	*	6.37
Jan 10	- open with slush moving	0650.8	6.33
Jan 14	- oscillating levels		~6.44
Jan 14-15	- 0.9 m drop in levels in 5 hours, then 1.3 rise in 7 hours (~.2 m/hr change in level)		~5.5-7.7 m change
Jan 15	- open above Gull Rocks (ice in section 21 or 20)	*	7.8 m
Jan 16	- brief 0.2 m rise then fall over 2-hr. period	--	7.80
Jan 17	- ice cover reaches model section 16 (~6 km u/s of Three Mile Island)	0769.4	7.74 m
Feb 7	- 17-24" ice thickness	0750	--
Feb 28	- water cover	0759	--
Mar 6	--	0760	--
Mar 13	- open water along NE banks	0730	--
OTHER READINGS			
Mar 30	Exploits River	0760	
Mar 31	Exploits River	0766	
Apr 1	Exploits River	0761	
Apr 2	Exploits River	0753	
Apr 3	Exploits River	0747	
Apr 8	Exploits River	0667	

[1] Province observations - strip chart record
* very limited observations (local) of ice progression
nr not recorded
\- level not computed from data

TABLE 2.6: ICE OBSERVATIONS (1988-89)

Date	Exploits Observations*	Water Levels[1]
Jan 10/89	- water level rise of 1.2 m in ~14 hours	6.4 - 7.6 m
Jan 13	- water level rise of ~0.3 m in 1 hour followed by ~0.25 m fall in next hour	7.5 - 7.8 m
Jan 16	- water level rise ~0.3 m in 1 hr followed by gradual drop of ~0.3 m in 8 hours	7.4 - 7.7 m

[1] Province observations (strip chart)
* local observer reports are missing

TABLE 2.7: ICE OBSERVATIONS (1989-90)

EXPLOITS		
Date	**Observations***	**Water Level[1]**
Nov 24/89	- ice at Goodyear's Pulpwood Holding Area	~6.36 m
Dec 13 (or 18)	- just upstream of Battle Island (model section mid-27)	--
Dec 18 (or 13)	- ice near mouth of Tom Joe Brook (section 25)	~6.35 m
Dec 24	- ice front just downstream of Badger Chute (model Section 24) - small oscillations begin in water level at Badger	~6.38 m
Dec 28	- ice front just upstream of Badger Chute (~mid Section 23)	~6.42 m
Dec 31	- ice front just upstream of Big Bend (~1/3 into Section 22)	~6.46 m
Jan 1/90	- water levels constant	6.52 m
Jan 2-3	- steady increase in water levels (with minor oscillations (0.25 m reductions)) from 6.44 m to 8.02 m over ~20 hours	8.02 m (max. level)
Jan 3	- ice front at Gull Rocks (upstream end of Section 21) - rapid drop of 0.3 m in less than 1 hour to level 7.7 m	7.8 m
Jan 4	- ice front at Three Mile Island (mid Section 19) - gradual rise in levels to ~8.0 m	~7.92 m
Jan 5	- ice front at upstream end of model section 18	~7.81 m
Jan 7	- ice front at upstream end of model section 17	~7.96 m
Jan 10	- levels drop to ~6.0 m then rise again to ~8.0 m in 12 hour period (~.3 m/hr level change)	~7.50 m

[1] Province observation (strip chart)
* no water level records taken by local observer this year

The 1990-91 observations are particularly significant (Table 2.8) because of the flooding which occurred at three of the lower homes on 17-18 January 1991. Three observations are important:

- The flood levels occurred when the leading edge of the frazil ice accumulation was passing through the Badger area (i.e., approximately Badger Rough Waters to Gull Rocks area).

- It was driven by massive production of frazil ice which arrived at Badger at that time.

- The flood levels were preceded (by a day) by a dramatic decrease in water levels. This was followed by an equally rapid rise.

The magnitude of the decrease in levels, coupled with the other factors, adds considerably to the flood forecasting potential for Badger.

The detailes of water level changes in 1991 are described below.

15 January 1991

- Morning levels (96.5 m) rose to 97.8 m over the day (1.2 m in 24 hours) in a "saw tooth" fashion of rise, slight fall, further rise, slight fall, etc. At 1700 hrs., there was a 0.6 m fall in about half an hour and a subsequent rise to elevation 97.8 m at approximately 0230 hrs. on 16 January.

16 January 1991

- Water levels at 97.8 m at approximately 0230 hrs.
- Rapid reduction in levels (2 m drop) to 95.8 m by 0830 hrs. This includes a very rapid reduction from 97.7 m to 96.0 m (1.7 m in 2 hours) - suggesting the release and downstream motion of a frazil ice blockage downstream of Badger.
- Water levels remained at about 96 m for 4 hours.
- Levels then rose rapidly to 98.74 m by 1630 hrs. (2.94 m rise in 8 hours (approximately .37 m/hr)).
- Levels fell again 0.6 m in less than one hour at about 1700 hrs. ("saw-toothing").

TABLE 2.8: ICE OBSERVATIONS (1990-91)

Date	Exploits River		
	Observations**	Staff Gauge	Stage (m)
Dec 13/90	- brief frazil ice blockage to Goodyear's, then cleared until 28 Dec		96.64
Dec 17	- open	6494	~96.49
Dec 22	- open	6776	~96.8
Dec 28	- ice front at Goodyear Dam (model section 32)	--	96.78
Dec 31	- open	6690	96.66
Jan 2/91	- slush to Aspen Brook (middle of model section 26)	--	96.5
Jan 7	- slush moving	6653	96.65
Jan 9	- ice front just downstream of Badger Chute (mid model section 24)	--	96.6
Jan 14	- open water with slush observed (ice front ~section 21)	6481	96.48
Jan 15	- ice front just below Badger Rough Waters (~mid section 22) - water level rise ~1.2 m as ice front passed through Badger	--	97.70
Jan 16	- **ice up to Gull Rocks (upstream end section 21)** - 2 m drop in levels over 6-hour period in morning of 16th - steady levels for 4 hours then - 2.94 m rise in 8 hours	5839	95.8 am
Jan 17	a.m. reading p.m. peak (**peak level @ 2130 hrs**)	8523 9420	98.8 m 99.5 m
Jan 18	am/pm? flooding in Badger - some evacuation of homes - threat ended by 24 Jan - 3 homes threatened on River Road on Thursday (17th) when Exploits rose nearly 10' - Millertown Dam closed - water began to rise on Wednesday 16th and began to recede Friday 18th a.m.	9474	99.47
Jan 21	**frazil cover almost complete** (small open area mid-stream)	9031	98.9 m
Jan 28	~14" ice	8356	97.92 m
Feb 4	12-24"	5780	95.3 m
Feb 11	12-18"	7772	nc
Feb 18	12-24"	7730	nc
Feb 25	12-24"	7484	nc

TABLE 2.8: ICE OBSERVATIONS (1990-91) (continued)

Date	Exploits River		
	Observations**	Staff Gauge	Stage (m)
Mar 4	12-24"	--	nc
Mar 11	12-24"	7442	nc
Mar 18	open water along NE bank, Badger Brook to Junction	7294	nc
Mar 25	12-16"	7359	nc
Mar 31	open water Badger Brook and downstream on east bank	7163	nc
Apr 11	open/slush	6059	nc

-- no observation
* missing observation
** ice progression mapping not provided
nc not computed

17 January 1991

- Levels rose approximately 0.9 m in one hour (approximately 1200 to 1300 hrs.) to 99.4 m.
- Maximum level, 99.5 m, occurred at approximately 2130 hrs.
- Levels subsequently declined.

Noteworthy is that similar reductions and increases in levels were monitored on January 23, 24 and 28 in association with downstream ice cover weakening and massive frazil production. However, these oscillations occurred when the ice front was upstream of Badger and supporting itself against downstream motion.

The 1991-92 water level record (Table 2.9) is similar to the 1987-88 and 1988-89 record in that there were no large fluctuations. The largest was about 0.34 m in one hour when ice was in the Badger area.

The 1992-93 record is similar (Table 2.10) and showed a 0.9 m drop in levels in 3 hours (0.3 m/hr) when the ice front was at the Big Bend (and not at Badger).

TABLE 2.9: ICE OBSERVATIONS (1991-92)

Date	Location	Observation	Staff Gauge	Water[1] Level (m)
Dec 16/91	Exploits	- open - ice front at model section 32	6064	95.9
	Junction	- ~5″ ice thickness	--	--
Dec 18	Exploits	- ice front at Battle Island (model section 28)	--	96.1
Dec 19	Exploits	- ice front in middle of model section 27	--	96.0
Dec 20	Exploits	- ice front at mid Eleven Mile Island (in model section 26)	--	95.9
Dec 21	Exploits	- ice front upstream of Eleven Mile Island (in model section 26)	--	96.1
Dec 23	Exploits	- floes reported in open water	5594	95.9
	Junction	- ~6″ ice	0048	--
Dec 30	Exploits	- border ice both banks 10-15 ft floes in open water	5948	95.9
	Junction	- ~9″ ice	0072	--
Jan 3/92	Exploits	- ice front downstream of Badger Chute (mid section 24)	--	96.1
Jan 6	Exploits	- broken blocks. **Cover reached chute, then collapsed/compressed down to below the chute**	5991	96.0
	Junction	- ~8″ ice	0070	--
Jan 13	Exploits	- border ice 12′ wide both sides; open	6056	96.0
	Junction	- ~6″	0092	--
Jan 19 (est)	Exploits	- ice front moved upstream past Badger	*	~96.0
Jan 20	Exploits	- ice at 3 Mile Island at 5 pm (section 19). Frazil cover at Badger - 1.3 m rise in level in 8 hours, then level	7424	97.48
	Junction		0074	--
Jan 27	Exploits	- ~12″ ice thickness	7203	--
	Junction	- ~8″	0018	--
Jan 28	Exploits	- 12-18″ ice	5681	--
	Junction	- white ice	0080	--

TABLE 2.9: ICE OBSERVATIONS (1991-92) (continued)

OTHER STAFF GAUGE READINGS	
Date	**Exploits**
Feb 10/92	5681
Feb 17	7162
Feb 24	7127
Mar 3	7084
Mar 9	7020
Mar 16	6962
Mar 23	6852 (open water NE bank Exploits)
Mar 30	7079 (open water NE bank Exploits)
Apr 6	6902 (open water NE bank Exploits)
Apr 13	--

-- no observation
* missing observation
1 Province observations (digital recording)

TABLE 2.10: ICE OBSERVATIONS (1992-93)

Date	Location	Observation	Staff Gauge	Water[1] Level (m)
Dec 20/92	Exploits	- open water	5957	96.3
	Junction	- ice cover	0107	--
Dec 22	Exploits	- ice front at Goodyears Pit (model section 30)	--	96.4
Dec 27	Exploits	- ice front at Battle Island (model section 28)	--	96.4
Dec 28	Exploits	- ice front at or near Badger Chute (model section 24 or 25) slush	*	96.4
	Junction	- ice covered	0105	--
Jan 4/93	Exploits	- moving slush ice	6113	96.6
	Junction	- ~8" ice thickness	0006	--
Jan 6-7	Exploits	- water level oscillating; questionable rise of 1.1 m in 1 hour, drop of 1.4 m in next hour, then rise 0.85 m in 5 hours followed by drop of 0.9 m in 3 hours (max. elevation 97.3 m)	--	97.3
Jan 10	Exploits	- mix of moving slush and open water, and border ice from Beatons Island to Badger Brook	6092	96.4
	Junction	- ~8" ice	0002.2	--
Jan 12	Exploits	- ice front at Badger Rough Waters (upstream end section 22) - level rise ~0.5 m during day (0.15 to 0.3 m oscillation)	*	96.9
Jan 13	Exploits	- ice front at Gull Rocks (upstream end section 21) - level rise relatively steady	*	98.1
Jan 14	Exploits	- ice front upstream of 3 Mile Island (upstream end section 19)	*	98.1

TABLE 2.10: ICE OBSERVATIONS (1992-93) (continued)

OTHER STAFF GAUGE READINGS	
Date	**Exploits**
Jan 17/93	7654
Jan 24	7443
Jan 31	7243
Feb 7	6342
Feb 14	7224
Feb 21	7069
Feb 28	7006
Mar 7	7033
Mar 15	7038
Mar 21	7041
Mar 28	6973 (Exploits 10-15′ open on S bank)
Apr 4	6019 (Exploits all open water)
Apr 11	5977 (Exploits all open water)

-- no observation
* missing observation
[1] Province observations

The 1993-94 water level record (Table 2.11) during the period of ice cover progression past Badger shows the "saw tooth" pattern of level change which typifies non-flood years. In the January 17-18 period, there were rapid 0.2 m rises and falls in levels mixed with a more gradual 0.8 m rise and rapid 0.5 m fall.

TABLE 2.11: ICE OBSERVATIONS (1993-94)

Date	Location	Observation	Staff Gauge	Water[1] Level (m)
Dec 1993	Exploits	- no local observations recorded - high flows flushed ice from river	--	--
Jan 9/94	Exploits	- slush ice	6042	95.8
	Junction	- frozen to island at junction	0150.2	--
Jan 16	Exploits	- moving slush - ice upstream of Badger Chute (model section 23)	5981	95.8
	Junction	- frozen to island at junction	0135	--
Jan 17-18	Exploits	- **water level oscillations** begin at night; rise of 0.2 m in 1 hour followed by 0.2 m drop in next hour. On 18th, gradual 0.4 m rise, rapid 0.3 m drop, gradual 0.8 m rise, rapid 0.5 m drop	--	95.8 to 96.8
Jan 20	Exploits	- ice cover at ~Gull Rocks (model section 20)	*	98.07
Jan 21	Exploits	- highest water level	*	98.12
Jan 23	Exploits	- ice cover at ~model segment 18	--	98.12
Jan 24	Exploits	- ~9" thick at Badger, fairly smooth cover	8026	97.8 avg
	Junction	- ~10" thick	0139	--

OTHER STAFF GAUGE READINGS	
Date	**Exploits**
Jan 30/94	8002
Feb 7	7755
Feb 13	7658
Feb 20	7638
Feb 28	7566
Mar 6	7525
Mar 14	7648
Mar 20	7696

\+ water over ice
-- no observation
* missing observation
[1] Province observations

In 1994-95, water levels rose steadily from February 5th to February 9th (when they peaked at 98.83 m) before gradually declining to a level of about 97.2 m by the end of the month (Table 2.12). The period of rising levels was in response to the second largest single day of frazil ice production in the past nine years, yet water levels did not reach flood stage because the rate of frazil production declined by the time the ice front reached Badger.

TABLE 2.12: ICE OBSERVATIONS (1994-95)*

Date	Location	Observation*	Staff* Gauge	Water Level (m)
January	Exploits	- mid to late January levels relatively constant - front of ice cover remained at Badger Chute for an extended period before initiating steady upstream progression	--	95.7
Feb 5	Exploits	- levels begin gradual rise in the afternoon	--	95.85
Feb 7	Exploits	- ice front reached Badger, accompanied by continuously rising levels	--	96.40
Feb 9	Exploits	- water levels peaked in late afternoon, and then gradually began to decline	--	98.83
Feb 22	Exploits	- declining water levels	--	97.4

* preliminary data for 1994-95 winter season (local observer data not available)

Water levels during the rising period (February 5 to 9) dropped gradually by about 0.2 m over 16 hours on the 6th and 7th, fell 0.32 m in one hour on the 7th and dropped 0.11 m, then re-rose 0.13 m on the 8th. Overall, however, the water level changes were modest and typical of the "saw tooth" pattern which occurs in non-flood years.

Overall, the fluctuations in water levels at Badger provide important flood forecasting information. Modest changes in level are typical by-products of the "normal" ice progression process in the Badger area. However, rapid and large decreases in level (coupled with the ice front being at Badger and significant frazil volumes) may offer a 24-hour warning of flood levels at Badger.

It is strongly recommended that the current water level monitoring program be continued, and that the range of water level decreases be considered equally important as the increases. Water level data can be taken from this gauge by remote means, but because of its importance during the few days that the ice front is moving past Badger, there will be a requirement for continued (and enhanced) reporting from the local observer.

2.1.3 Additional Hydrometric Records

The projection of water levels at Badger has again been substantially improved by the installation of a water level recording and transmitting platform about 20 km upstream of Badger (Exploits River below Noel Pauls Brook). This station provides flow data on the river in the area which contributes frazil ice and flood flows to Badger. The principal benefit of this station, in terms of ice-related flooding, is that the flow data can be obtained in real time (prior to flows reaching Badger) and can be analyzed for ice production in the reach between the station and Badger.

To this end, it is also recommended that an open water stage-discharge relationship be prepared for the Badger Stadium gauge site. The relationship can be initially developed by using flow data from the station below Noel Pauls Brook and water levels at Badger Stadium (during periods when there is relatively insignificant flow from intervening catchment areas). This stage-discharge relationship should provide data on the volume of water which is being transformed into ice and assist in future refinements to the ice observation and modelling work. This stage-discharge relationship, when coupled with ice observer reports, will also provide a valuable indication of the downstream location where frazil ice blockages begin to contribute to elevated water levels at Badger.

Another ice-production index is water temperature, which is taken periodically as part of the provincial water quality monitoring program at Exploits Dam. Water temperature is also an important element in the forecasting of ice production in the Exploits River upstream of Badger. As a result, it is recommended that water temperatures from existing programs be reported to the ice modeller and that water temperatures be taken twice monthly (December 1st to February 28th) at the outlet of Exploits Dam. A twice monthly program is suggested to provide information on the cooling processes in the river between Exploits Dam and Badger. In that there is a reasonable thermal reserve within Red Indian Lake (particularly beneath the ice cover), it is unlikely that outflow temperatures will fluctuate and that their decay can be accurately tracked with a measurement every two weeks. This monitoring augments ongoing provincial work and could be undertaken by the ice observer or through an agreement with Abitibi Price.

At the same time, it would be valuable to measure water temperatures of the Exploits River at Badger (twice monthly until the river is ice covered). This information at Badger need only be gathered for a year or two to provide data which could be used to verify the existing (or future) ice models. This process would include water temperatures taken regularly at the gauge below Noel Pauls Brook and any other stations downstream of Badger.

The river is turbulent over much of its length and can be assumed to be well mixed. Hence, measurement of the flowing water at any location (e.g., near the river banks below the water surface) would be appropriate.

2.1.4 Extended Meteorological Data Base

Daily meteorological data for the winter period has been assembled and coded for modelling use (winter seasons 1986-87 to 1993-94). The data set includes mean daily air temperature, dew point temperature, wind speed and hours of bright sunshine. Precipitation and wind direction which are available and have an effect on frazil ice production are not employed in the present ice forecasting model.

In general, meteorological data has been taken from the automatic gauge at Badger as it best represents the region of study. Periodically, however, data gaps have been filled by data from other representative locations.

Overall, the current compilation of historical streamflow, water levels and meteorological data (most of which has been compiled for ice progression modelling) should be continued into the foreseeable future. It provides the basis for future analysis and, in that these analysis may be based on hourly variations, it is recommended that hourly data files be kept.

The Provincial engineer responsible for the program at Badger has correctly observed that snowfall has an influence on frazil ice production. Similarly, it is recognized that wind direction (particularly if along the axis of the river channel) increases surface water cooling and the potential for frazil ice production. Both of these meteorological factors have potential application for refined flood forecasting and should now be included in the meteorological data base. As time permits, the hourly records of these parameters from previous years should be joined with the above mentioned hydrometric (flow) data base to determine the nature of these factors relating to flood forecasting.

3.0 ICE REGIME MODELLING REVIEW

Modelling was employed in the 1985 Flood Damage Reduction Program study of the Exploits River to assist in evaluating and forecasting ice conditions on the Exploits River. Subsequently, the Province has employed the same model to assist in annual forecasting of potential ice problems in the Badger area. One of the objectives of the enclosed study was to assess the merit of making revisions to the modelling portion of the forecasting procedure including the use of:

- analytical modelling methods;
- sophisticated numerical modelling methods; and
- a compromise approach involving both methods.

The most appropriate selection for today's application is the latter compromise approach which was the conclusion reached in 1985. However, in order to determine the practical level of compromise for future applications, the current technology in ice modelling was reviewed.

This step began by a computer/literature search of available models, an initial screening, discussion with the authors of the models, and acquisition of model synopses of:

ICESIM	ICEROUTE	SIMGLACE	COVER
RICE	RHIVER	HDAMPAK	HEC-ICE
CCLH2	MENVIQ	IOWAICE	RIVJAM
CCREL89	RIVICE	JJT	GLOBICE

These and other models (including the existing model) have many commonalities and our review centred upon the derivation/extraction and proven practical application of subroutines within each model. A brief synopsis of the above listed models is given below.

ICESIM is a proprietary model (Atkinson, 1973) initially developed in 1968 for use in studies of ice break-up on the Nelson River. It has subsequently been used to evaluate ice conditions in a number of hydro-electric projects but, because it is proprietary and fundamentally similar to other models using the work by Pariset *et al* (1966), it was not selected for use on the Exploits River. The ICEROUTE model (Girling, 1991) is an enhancement of ICESIM and is used by

Manitoba Hydro to route flows through reservoirs which have had significant stage rises resulting from downstream ice jams.

SIMGLACE was initially developed in 1977 (Rousseau, Sauvé, Warren Inc., 1983) for evaluation of ice conditions at a diversion for the La Grande River complex. It was subsequently used (with some modification) by B.C. Hydro on the Peace River. The authors note that there are a number of limitations to the model and adjustments (e.g., to the channel geometry) which must be made by the user to account for the two-dimensional variability in ice cover conditions across most channels. Given these limitations and that the model is proprietary mitigated against its selection for the Exploits River.

The ice model COVER (described in Shen and Chiang, 1984) may be viewed as a useful subroutine or subcomponent of river ice models which must account for thermal growth and decay of a solid ice cover (thickening, melting) over the course of a winter. These thermal processes are not significant during frazil ice jamming at Badger and this model was not chosen for further investigation.

The computer model RICE (Lal and Shen, 1991) was initially developed in 1984 to simulate ice cover progression in the upper St. Lawrence River. Noteworthy is that the model applies more sophisticated and comprehensive formulations of river ice processes than many earlier models (e.g., SIMGLACE) which use various degrees of simplification. RICE is not advanced herein for use on the Exploits River, however, because of its complexity, its specific application (10-year development for the upper St. Lawrence) and its assumption of laterally-averaged ice conditions.

RHIVER was conceived and developed for Hydro-Québec (Marcotte, 1984) with a focus on evaluating thermal exchange and the development of anchor ice and frazil ice in the Lake St. Louis area, St. Lawrence River. It was subsequently revised in the mid-1980s by others to the extent that the original model code was compromised. Considerable recent work (as part of the RIVICE approach) may have restored this model but, given that a more sophisticated approach is currently used for the Exploits River, there is no reason to advance this model for use at Badger.

HDAMPAK is an acronym for the hydrodynamic ice packing modelling framework developed by the US Army Corps of Engineers, Cold Regions Research and Engineering Laboratory

(Ferrick and Mulherin, 1989). This model and CRREL89 relate only to dynamic ice break-up by regulating flow releases from hydropower dams and neither are applicable to the ice formation concerns at Badger.

HEC-ICE and CCLH2 (Hydrologic Engineering Centre, 1990; CCL, 1986) involve application of the US Army Corps of Engineers HEC-2 backwater program with the ice-cover option. The program has serious limitations for use at Badger (ice processes are not considered and ice cover characteristics are arbitrarily specified) and cannot be advanced to improve ice forecasting on the Exploits River.

MENVIQ, an acronym for numerical modelling at the Ministère de L'Environnement du Québec, has its roots in three publications by Tanguy (1986 a, b, c). Currently, MENVIQ has been calibrated for application on the Mille Isles River and is being verified. However, until promulgated and proven for general use, it cannot be recommended for the Exploits River.

The IOWAICE program (the University of Iowa) is in the process of developing an extremely sophisticated ice modelling tool following the advanced work of Uzuner and Kennedy (1976). Although the model is still in the development stage, it is being supported by a series of physical modelling research projects which may lead to a numerical ice model of benefit to ice forecasting at Badger. The development of this modelling tool should be followed closely but, until it is developed (perhaps in the next five to ten years), it is not recommended for use at Badger.

The JJT model was developed in the late 1980s to evaluate ice conditions on four Finnish rivers (Huokuna, 1991). The model appears to perform reasonably well but its theoretical basis (apparently similar to SIMGLACE, etc.) and coding have remained highly proprietary and unavailable for assessment for use on the Exploits River.

GLOBICE (or GLACE91) is a numeric ice generation and build-up model described by Saucet and Beauchemin (1992) for use in ice formation assessments at hydro-electric projects. It focuses on ice formation and build-up, yet appears to employ empirical formulations and is proprietary. As a result of this latter factor, it cannot be advanced for use in ice forecasting at Badger.

Three models emerged from this review as having subroutines, modules or components which could be employed to assist in flood forecasting at Badger:

- the existing model,
- RIVICE (its ice cover evolution model), and
- RIVJAM.

3.1 Existing Model

The existing model is documented in the Technical Appendix of the *Hydrotechnical Study of the Badger and Rushy Pond Areas* (Fenco Newfoundland, 1985). Included is user information, a listing and example output file, a description of inputs and a discussion of the sensitivity of outputs to variation in the input parameters.

The existing model is composed of 21 subroutines designed to:

1) simulate surface heat exchange and cooling of the Exploits River between Red Indian Lake and Grand Falls;

2) produce frazil ice (and border ice); and

3) accumulate the frazil ice in a manner which gives upstream progression of the ice front.

The model is very specific to the Exploits River and specifically designed for freeze-up ice conditions. As a result, no melting or break-up ice conditions are included and the hydraulics are empirical.

3.1.1 List of Principal Subroutines

A) Calculation of Heat Exchange Parameters
B) Equilibrium Temperature and Heat Exchange
C) Ice Volume Accumulation
   C.1 Fully Mixed Temperatures Along the River
D) Ice Production
E) Border Ice Closure
F) Ice Flushing

3.1.2 Discussion

The computational methods employed to provide the three results listed in Section 3.1 are described below.

Heat Exchange and River Cooling

The model simulates the daily sequence of river cooling through the winter months and along the river course from Exploits Dam to Goodyear's Dam. The equilibrium temperature approach presented by Edinger *et al.* (1974) is employed in this computation. The equilibrium temperature (EPT) is defined as the hypothetical water temperature at which the net rate of heat exchange would be zero.

The bulk temperature of the vertically mixed river increases or decreases with time according to whether the sum of its heat inputs (net atmospheric and solar radiation) and heat outputs (evaporation, conduction and back radiation) is positive or negative.

The computation of the water surface/fully mixed temperature draws on meteorological inputs (air temperature, dew point temperature, wind speed and sunshine hours). Solar radiation input is computed following the procedures outlined by Raphael (contained in EPA, 1971) and can be made site-specific using observed sunshine hours.

The evaporative wind speed function of Brady *et al.* (1969) is employed in the computation of the surface heat exchange coefficient. This coefficient is employed in evaluating evaporation, conduction and back-radiation in the equilibrium temperature concept.

The coefficient of surface heat exchange, water temperature in each of the 32 river segments, air and equilibrium temperatures, degree days and total seasonal degree days, and the daily wind chill factor are provided as model output.

Ice Production

Border ice growth is generated in the model using the border ice growth equation developed by Newbury (1968) for the Nelson River, Manitoba, producing growth from air temperature and surface velocity as:

$$B = (M)\ DD \tag{1}$$

$$M = (C\ /\ V^{1.5}) \tag{2}$$

where:

B	=	total width of border ice (m)
M	=	a coefficient to relate freezing degree days to border ice growth (m/°C-day)
C	=	empirical coefficient of growth rate varying between 0.04 and 0.06 (typically 0.054)
V	=	mean velocity (m/s)
DD	=	freezing degree-days (°C-day)

Frazil is generated when air and water temperatures fall below zero from the following relation (Ashton, 1980):

$$V(t) = \frac{CAT}{\rho L}\ t \tag{3}$$

where:

V (t)	=	volume of ice produced per second, $ft^3\ s^{-1}$
C	=	coefficient of surface heat exchange, BTU $s^{-1}\ ft^{-2}\ °F^{-1}$
A	=	open water area producing frazil, ft^2
ρ	=	mass density of ice = 57.2 lbm ft^{-3}
L	=	latent heat = 144 BTU/lbm
T	=	average temperature below 32°F during period of interest, °F
t	=	time, s

Conversion to metric units (m^3 ice volume) follows this calculation.

The volume of frazil ice produced is determined by dividing the ice volume (Equation 2) by the porosity of frazil slush. The porosity is arbitrarily taken to be 0.5, but may be adjusted by an input parameter if it is determined to be too high or too low from observations of the ice progression rate in a given year.

The volume of frazil production is gradually reduced by formation of the ice cover and becomes zero when a river section is completely covered. No reduction in frazil-producing area is made to account for pans of frazil slush in the river.

Ice Progression

The frazil ice generated in early days of the winter season passes downstream until border ice growth closes the river at the downstream segment (Goodyear's Dam), or frazil slush is accumulated at the ice boom at Rushy Pond.

The current version of the model includes the ice boom at Rushy Pond and the current configuration of Goodyear's Dam, and is to be used for recent years when the boom was in place (1974-75 to present). Another version of the model (NEWICE) contained the old configuration of Goodyear's Dam and was used in simulating historical conditions prior to 1974-75.

Closure by border growth is simulated by Equation (1) and closure by accumulation is determined by the Froude number criterion presented by Kivisild (1959). The limiting Froude number is given as:

$$Fr = V / (gH)^{0.5} = 0.154\ (1-E)^{0.5} \qquad (4)$$

where:

V	=	mean velocity in open water upstream of the ice front (m/s)
g	=	acceleration of gravity (m/s^2
H	=	upstream flow depth (m)
E	=	porosity of accumulated ice cover

Work by Fountain (1984) suggests that the critical Froude number is in the range of 0.08 and this simplification is incorporated in the model (along with an adjustment factor which makes it possible to set the Froude number for site-specific conditions).

Once the river is closed by border ice growth or frazil accumulation at Rushy Pond, the ice cover grows upstream on a daily basis at a rate dictated by the volume of frazil slush generated in open stretches of the river each day. The progression rate through each segment is based on observed accumulation thicknesses from field surveys rather than iterative approaches requiring this thickness to be estimated.

Model outputs include estimates of: the total volume of slush generated along the full length of the river, the total generated in the river reach above the Badger Rough Waters and the total accumulation in the river. One to ten day totals of the total ice generated above Badger are also provided.

Appendix A provides additional user information, including a range of "default" values not provided in original documentation.

3.2 RIVICE

The RIVICE model is documented in three reports (Tecsult *et al.*, 1993) which include a user's manual, technical appendices and a programmer's manual. Although not all of the ambitious goals set for the model were completed, ongoing work (1994-95) may place the model in a position for final testing (i.e., currently, the components/modules of model are not linked). It is anticipated that a PC version will eventually be made compatible for the more powerful PCs (such as a Pentium system).

The RIVICE model is composed of 12 modules, each designed to simulate distinct ice processes or control the input/output data and the computation procedure. Each module is semi-independent of the other modules such that:

1) each module can be tested independently with test data;

2) options for different linking of the modules are available to the user to simulate the required ice processes according to the user specified hypothesis without calling other modules which may not be needed in a particular situation; and

3) future changes to the model can be facilitated as improvements in current ice knowledge become available. Also, the user may wish to make changes to the model to adapt it to his particular application.

3.2.1 List of Modules

Given below is a list of the modules that compose the RIVICE model.

A) Input;
B) Output;
C) Hydraulic Modelling Modules:
  C.1 Steady State model;
  C.2 Time-varied model;
D) Heat Balance;
E) Border Ice;
F) Open Water Ice Generation;
H) Initiation of Ice Cover;
I) Ice Cover Evolution during freeze-up:
  I.1 Ice Cover Progression;
  I.2 Ice Cover Thickness Changes;
K) Ice Cover Break-Up;
L) Break-Up Ice Jams.

Of these modules, the one of greatest interest for application on the Exploits River for Badger is module (I): Ice Cover Evolution During Freeze-up, and its sub-modules:

I.1 Ice Cover Progression
I.2 Ice Cover Thickness Changes.

This module is described generally in the following section. Other modules of interest for possible subsequent review for use on the Exploits River include all of those listed above except for the break-up models.

Appendix B includes a technical description of and programming instructions for the ice cover evolution module.

Ice Cover Evolution During Freeze-Up

This module simulates the upstream advancement of an ice cover, changes in thickness due to hydraulic forces and thermal effects, and transport of ice under the cover, including effects of deposition and erosion.

The stability of the leading edge is represented by the classic equation for juxtaposition. A second option which may be invoked by the user is a criterion for progression due to a "train" of closely spaced ice pans, which does not permit entrainment of the ice into the flow under the leading edge of the cover.

Ice is drawn under the leading edge if the juxtaposition limit is exceeded (except in the case of the second option). Passage of the ice under the ice cover is estimated with simulation of deposition at locations where the velocity is low. The criterion for deposition can be selected by the user from one of:

- a direct specification of the velocity below which ice deposition will occur;

- the Meyer-Peter algorithm for sediment transport, with modifications to apply to ice; this requires the user to identify a dominant diameter of the ice particles which must be used in the calculations;

- a user-specified maximum densimetric Froude number of the flow under the existing ice cover. At locations where the densimetric Froude number is less than the maximum, deposition of ice will occur.

Each option has a default value for its parameter which is used if no value is specified by the user. The module tracks the passage of the ice in transport under the ice cover from time period to time period, making depositions where appropriate. Transported ice which escapes from under the cover at its downstream end, without having been deposited, is added to the ice load in the open water reach downstream.

Erosion of the ice cover by high velocity flow is also addressed in the module, according to one of two user specified options:

- a direct specification of the velocity above which ice erosion will occur;

- a maximum tractive force on the ice under-surface. At values exceeding this, erosion of the ice cover will occur.

As for the deposition mode, each option has a default value for its parameter which is used if no value is specified by the user.

Ice which is eroded from the ice cover because of high velocities or tractive forces, is added to the ice in transit under the ice cover. It then becomes a candidate for deposition at appropriately low velocity locations downstream.

Hydraulic forces which are exerted on and by the ice cover are computed:

- hydrodynamic thrust on the leading edge;

- friction drag on the ice under-surface;

- the component of weight of the ice cover and the water held in its interstices, acting along the slope of the channel;

- the resisting forces of the bank on the ice cover and the internal resistance of the ice cover.

At locations where the resultant forces on the ice cover exceed its internal resistance, a shove is simulated. This is done by increasing the ice cover thickness to the stable value. The volume of ice required for this is transferred from the leading edge to conserve the total mass. Thickening of the ice cover in this way is limited by the maximum speed of movement of the ice cover, which is assumed to be equal to the average velocity of the flow.

As noted earlier, a more detailed technical description (and programming instructions) for this module are provided in Appendix B. A diskette is also provided.

It is noteworthy that the current version of the model is not supported by the Canadian Federal Government or any of the River Ice Project Steering Committee members that sponsored its initial development. It is provided in the form received at the conclusion of the project and, as indicated earlier, is currently being modified/revamped for possible completion in 1995.

3.3 RIVJAM

The RIVJAM model is described in a Canadian Journal of Civil Engineering paper entitled *Numerical Computation of River Ice Jams* (Beltaos, 1993). Its use is also outlined in a series of notes (for internal use by the author) which are not available for publication at this time. However, a diskette of the model is in the public domain and included as part of this report.

RIVJAM was prepared to compute the configuration and water levels created by wide ice jams in natural rivers. The configuration is given regardless of whether or not the ice jam has reached its full equilibrium potential. The model is viewed as having potential for application on the Exploits River because flows are known, cross-section data is generally available, the ice delivery rate is known and the toe of the ice jam affecting Badger can be estimated.

3.3.1 List of Principal Subroutines

The model contains ten subroutines and five pre- and post-processing routines. The main program contains:

A) MAIN - to predict the profile at the toe of an ice jam using

B) DRKGS - solution of first order differential equation,

C) SOLVE2 - simultaneous solution of ordinary differential equations, and

D) PROP - properties of various channel cross-sections.

The pre- and post-processors read in cross-section data and convert it to a RIVJAM file, assigns values and areas to interpolated sections and completes ice volume computations.

3.3.2 Discussion

Rather than reiterating the paper describing this model (Beltaos, 1993) in the text, it has been included as Appendix C.

As noted in the summary of the paper, the model is easy to apply (and well organized) and requires estimation of relatively few parameters. RIVJAM is a one-dimensional numerical model to compute the configuration of "wide" cohesionless ice jams. It can compute in both the upstream and downstream directions, starting at a site of known thickness and water level. Irregular channel bathymetry, typical of natural streams, can be accommodated as a series of surveyed cross-sections with linear interpolation performed by the model between successive sections. A major departure from earlier theoretical work is the consideration of the flow seeping through the voids of the jam. Invariably neglected in the past, this flow could represent a significant portion or even the entirety of the river discharge in cases of thick or grounded jams. Accounting for seepage enables the model to function in the downstream transition leading to the toe of the jam, and to predict grounding in accordance with observations. Neglect of seepage would, at some point, lead to infinitely high velocities for the flow under the jam.

The numerical values of the coefficients required as model inputs are reasonably well known, with the exception of the seepage parameter, λ. For freeze-up application on the Exploits River, however, the author notes that:

- the seepage coefficient, λ, should be set to zero as the jams comprise frazil slush (very small pores/seepage should be negligible).

- the model assumes cohesionless accumulations; cohesion can only be accounted for indirectly, e.g., by increasing the coefficient μ, which is probably acceptable in cases where internal friction is the main source of jam strength. However, if cohesion plays a major role, it would be better to use a different model or to modify the code of RIVJAM itself.

- the model has been designed primarily for jams of relatively limited length, as is the case at break-up. Some difficulty may be encountered with very long jams, due to (a) asymptotic convergence behaviour of equilibrium jams; and (b) extra "jam strength" that may be progressively developing in the upstream direction by freezing of interstitial water (not considered in the model).

Given that RIVJAM has a limited track record and has not been proven in a frazil ice jam condition, it should be applied with caution and, on the Exploits River, with a view only to providing insight into conditions which may lead to elevated water levels at Badger.

The model is provided with the disclaimer that it is furnished by the Canadian Federal Government and is accepted and used by the recipient upon the express understanding that the Canadian Federal Government makes no warranties expressed or implied, concerning the accuracy, completeness, reliability, usability or suitability for any particular purpose of the information and data contained in this program or furnished in connection therewith, and the Canadian Federal Government shall be under no liability whatsoever to any person by reason of any use made thereof. The program belongs to the government. Therefore, the recipient further agrees not to assert any proprietary rights therein or to represent to anyone as other than government program.

3.4 Recommended Approach

Of the many ice-related models which could be applied to assist in flood damage reduction in Badger (through water level forecasting), the existing model, the ice cover evolution module of RIVICE and RIVJAM are applicable for use. However, given that RIVJAM has a limited record of application and is unproven in a frazil ice jam condition, and that the ice cover evolution module of RIVICE is unsupported by any government agency (and is about to be revamped by Environment Canada), there is no compelling reason to adopt a new model for ice jam flood forecasting at Badger.

The existing model appears to perform well in determining daily volumes of frazil ice production on the river in the critical period when the ice front is moving upstream past Badger. These volumes are linked by a graphical procedure to river water levels which, if meterological conditions can be forecasted with any accuracy, should provide one to two days warning of flood conditions.

There are a number of simplifying assumptions within the existing model and certain subroutines, such as the border ice routine, could be updated. The current border ice approach was based on early work by Newbury in 1968 and appears to have provided a source of modelling difficulty in the early stages of model use by the Province. The growth (and failure) of border ice could be assessed by the Province for modification by review of Abdel-Zaher (1990) or Matousek (1984), for example. Although this would elevate the sophistication of this subroutine, the current approach, which uses coefficients to calibrate closure to site-specific data, could be retained without sacrificing the accuracy of the flood forecast.

Another feature of the existing model is that it does not attempt to model the details of the frazil ice jamming processes (accumulation, shoving, surges, etc.). Further understanding of these complex, two- or three-dimensional site-specific processes may be gained by testing of RIVJAM or the ice evolution module of RIVICE. If one or another replicates water level conditions in Badger, that model/module could be considered as a candidate to replace one or more subroutines in the existing model.

It was noted in review of the existing model that it required modification to the way in which it treated upstream boundary conditions for the temperature of river flows from Red Indian Lake. These lake discharges are assumed within the model to be a constant 3° C (± an adjustment factor) for all months of simulation. This is a reasonable, but limiting, assumption that can be corrected to allow for inclusion the results from ongoing water quality surveys.

Overall, the existing model should be retained. It should be examined, however, for inclusion of RIVJAM or RIVICE modules once these have been evaluated and proven in duplicate simulations for use in the Badger area.

It is noteworthy that these two models/modules (RIVJAM and RIVICE) do not account for border ice conditions, heat balance, open water ice generation, ice cover initiation or ice cover break-up. The existing ice progression model appears to account for these sufficiently well (and with a minimum amount of data) for forecasting purposes. As noted above, some of the routines could now be refined (and have been as part of this study), but there is no compelling reason to recommend a broad change in the modelling.

4.0 CURRENT ICE REGIME MODELLING RESULTS

The existing (unrevised) model has been used to simulate the upstream progression of the ice cover from Goodyear's Dam to Exploits Dam since the winter of 1986-87. The basic time-varying input data to the model has consisted of a set of forecasted and actual meterological conditions and streamflow which are input on a daily basis. Computations may be initiated in any month but have generally begun in November or December. Inputs which are not time varying include river segment (reach) number (32 segments are employed) and segment depths, surface area, maximum ice volume (i.e., ice capacity), river mileage and drainage area. The river segments used in the modelling were shown earlier in Figure 1-1 and their physical descriptions are given in Appendix A.

The data described in Section 2.1 have been employed by the Province to calibrate and forecast the progress and severity of ice accumulations on a day-by-day basis for each winter since 1986. The simulation of conditions in most years has been good but, as part of this study, all years were re-examined and re-run using "default" values and calibration factors which were identified (but not published) in the earlier 1985 study. The results of these simulations are discussed below.

1986-87

The local observer's reports about ice progression in 1986-87 were detailed (Table 2.4) and well mapped (Figure 2-1). However, water level observations at the local staff gauge were intermittent and not tied to a geodetic datum.

Figure 4-1 presents a summary of measured and simulated conditions during 1986-87. Observed meteorological conditions (air temperature and associated wind chill factor and cumulative degree days) contributing to frazil ice production in the Exploits River are given in the first three plots. The fourth plot gives the simulated daily volume of frazil ice produced in the river upstream of Badger (model sections 1 to 21 shown in Figure 1-1). The second last plot gives the simulated total volume of frazil slush generated in the river in the December-January period of 1986-87, and the last plot gives the observed water levels at Badger Stadium.

Water levels rose by an estimated ~2 m on December 22. Temperatures and wind chill had oscillated in the period prior to this rise, and total degree days were accumulating steadily. There were also several pulses of frazil ice generation in the period before December 22 - each

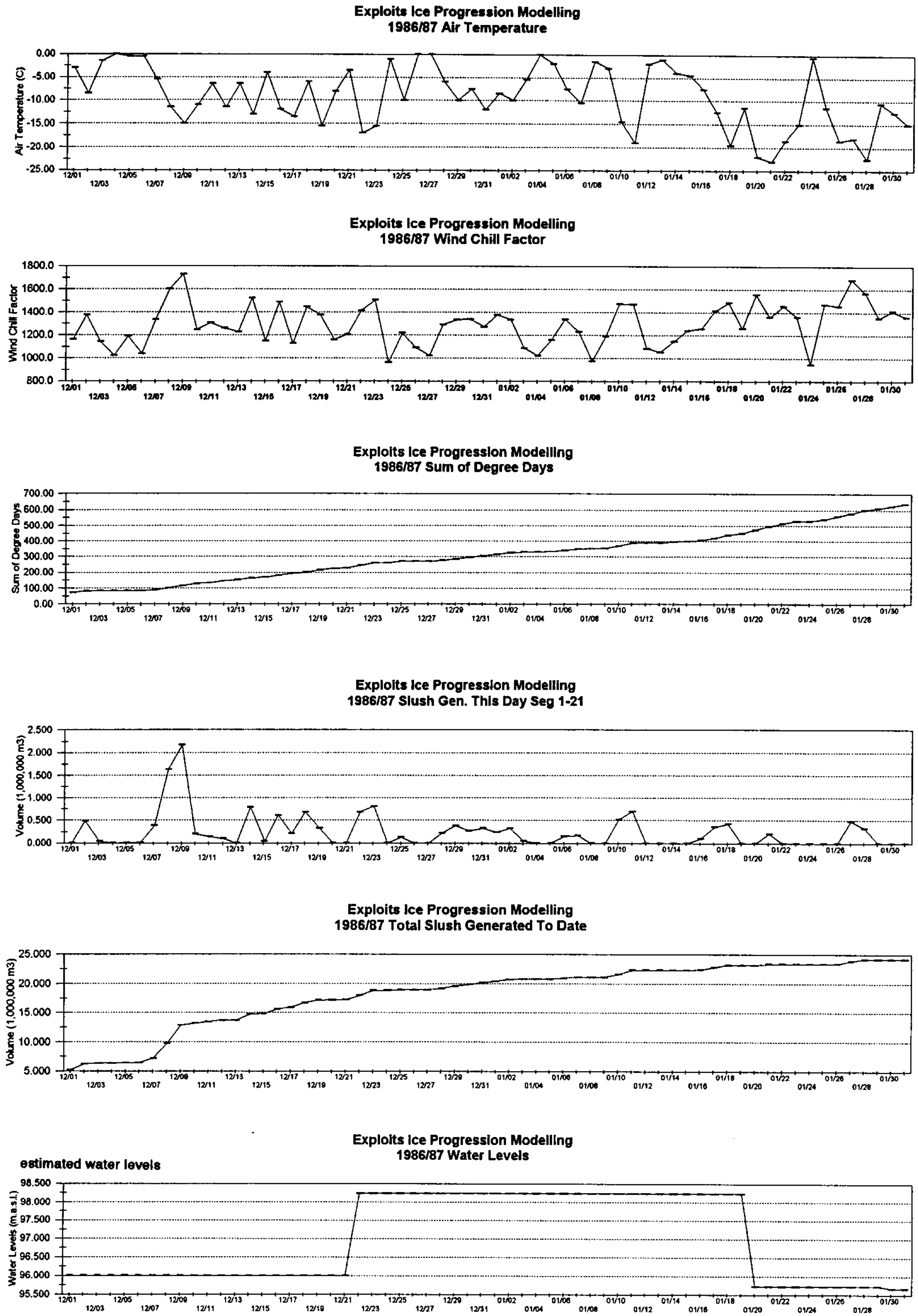

Exploits Ice Progression Modelling
1986/87 Air Temperature
Air Temperature (C)
Exploits Ice Progression Modelling
1986/87 Wind Chill Factor
Wind Chill Factor
Exploits Ice Progression Modelling
1986/87 Sum of Degree Days
Sum of Degree Days
Exploits Ice Progression Modelling
1986/87 Slush Gen. This Day Seg 1-21
Volume (1,000,000 m3)
Exploits Ice Progression Modelling
1986/87 Total Slush Generated To Date
Volume (1,000,000 m3)
Exploits Ice Progression Modelling
1986/87 Water Levels
estimated water levels
Water Levels (m.a.s.l.)

Figure 4-1

corresponding to higher wind speeds and lower temperature occasions. The frazil generation on December 22 and 23 was the highest that year for the period preceding the arrival of the ice cover at Badger (~0.82 x 10^6 m^3/day) and peaked at 0.86 x 10^6 m^3 on 23 December.

1987-88

There were few observations of ice progression during this freeze-up, but strip chart recordings of water levels during the period (Appendix G) provided the first detailed evidence about water level changes during the passage of the ice front past Badger.

The first three plots in Figure 4-2 present a summary of meteorological conditions observed at Badger during December 1987 and January 1988. The fourth plot gives the simulated daily volume of frazil ice production upstream of Badger, and the second last plot gives the simulated total volume of frazil ice produced in the river in the December-January period. The last plot gives the observed water levels at Badger for this ice year. Air temperatures on January 15 were low and wind speed was high, and both contributed to frazil ice production which brought the ice front into the Badger area. The plot of total frazil slush ice generated to date takes a significant upward step on the 15th when 1.39 x 10^6 m^3 of frazil ice was generated. This combined with frazil ice generation during the previous two days to give an average rate of 0.76 x 10^6 m^3/day in the three-day period when the ice front moved past Badger.

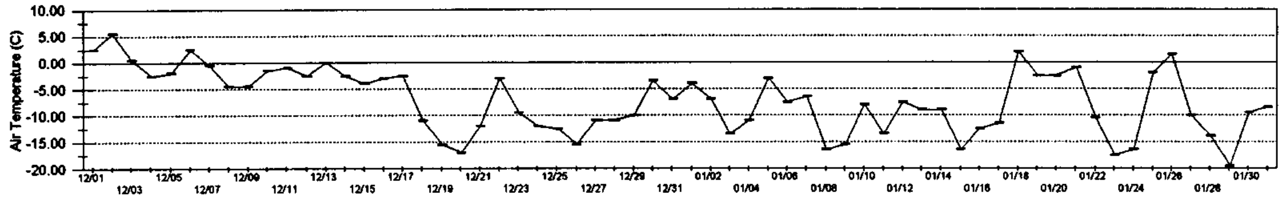
Flooding did not result from conditions during this year. However, the strip chart recordings of water levels were the first record of the water levels oscillation which occur during the ice progression at Badger. During the January 14-15 period, there was a ~0.9 m drop in levels in five hours, followed by a 1.3 m rise in seven hours (~0.2 m/hr changes in levels as a result of ice compressions/shoves in the frazil ice jam).

1988-89

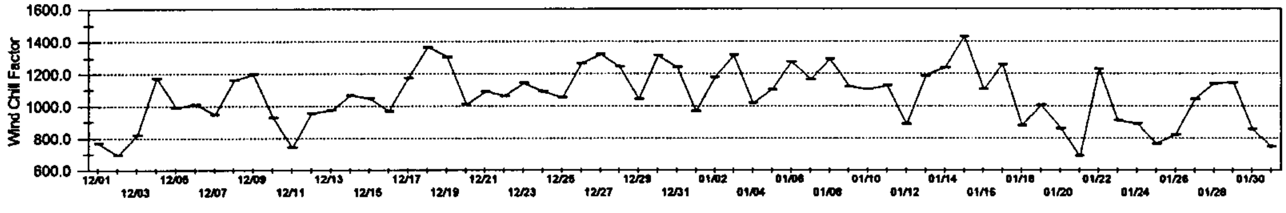
Reports from the local ice observer are missing for this year and, hence, it is not possible to ascertain the progression of the ice cover and link it to water level changes with any certainty. Strip chart records of water levels (Appendix G) and meteorological data are, however, available for that year, and these make it possible to provide some insight into the ice processes at Badger (Figure 4-3).

The water level records in the period when the ice front was near Badger show periods when the levels rose by ~0.3 m in one hour and then fell by similar amounts in the next hour or following

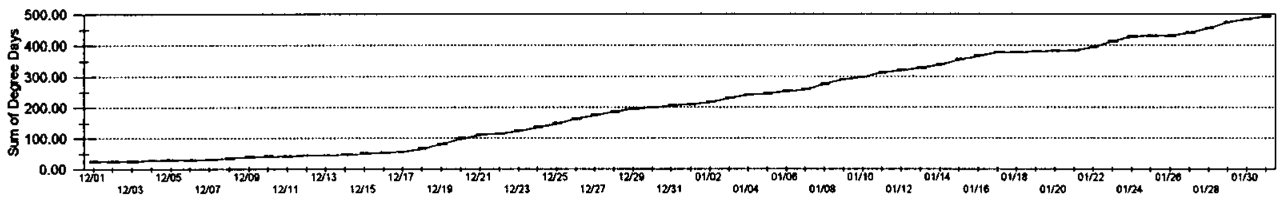
Exploits Ice Progression Modelling
1987/88 Air Temperature



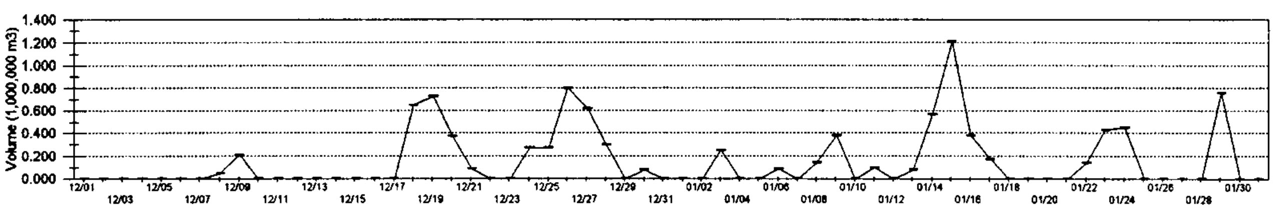
Exploits Ice Progression Modelling
1987/88 Wind Chill Factor



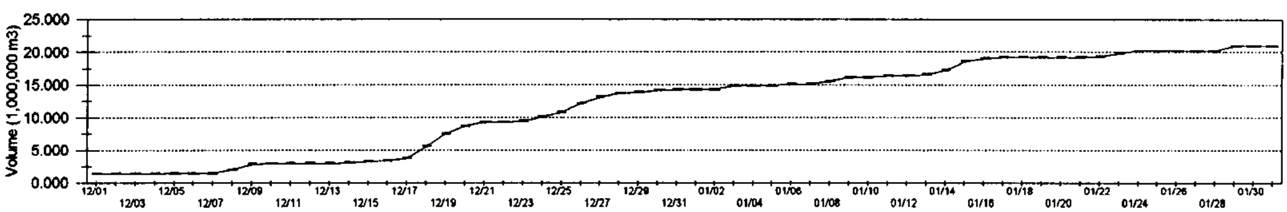
Exploits Ice Progression Modelling
1987/88 Sum of Degree Days



Exploits Ice Progression Modelling
1987/88 Slush Gen. This Day Seg 1-21



Exploits Ice Progression Modelling
1987/88 Total Slush Generated To Date



Exploits Ice Progression Modelling
1987/88 Water Levels

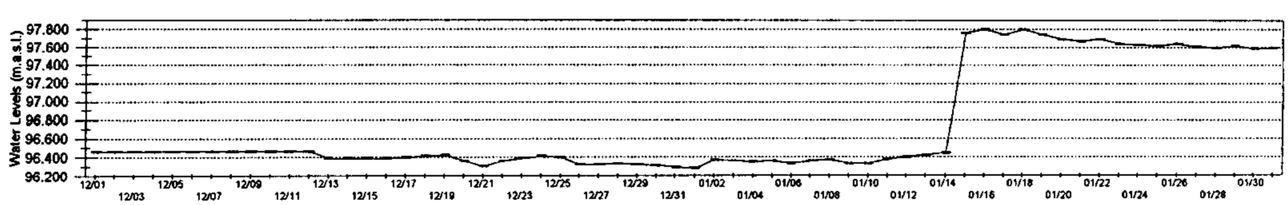
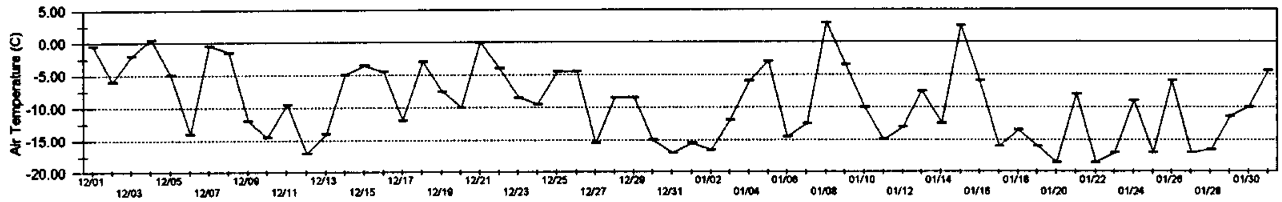
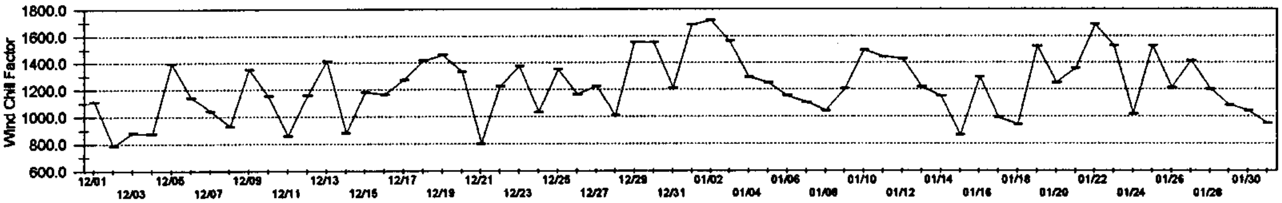


Figure 4-2

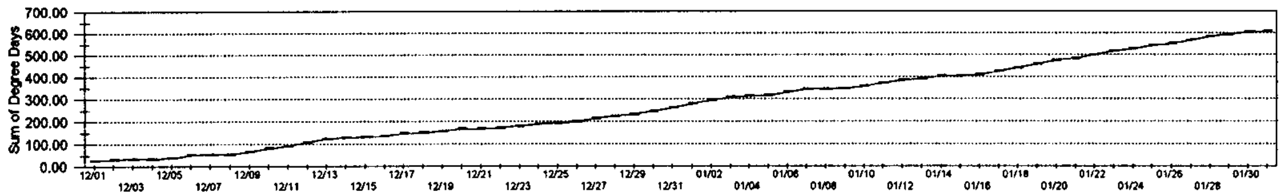
Exploits Ice Progression Modelling
1988/89 Air Temperature



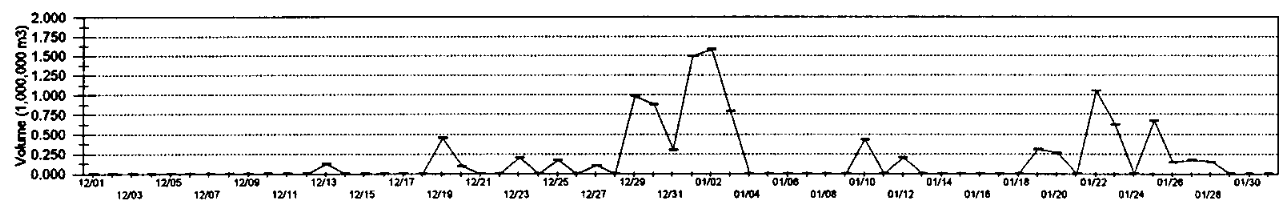
Exploits Ice Progression Modelling
1988/89 Wind Chill Factor



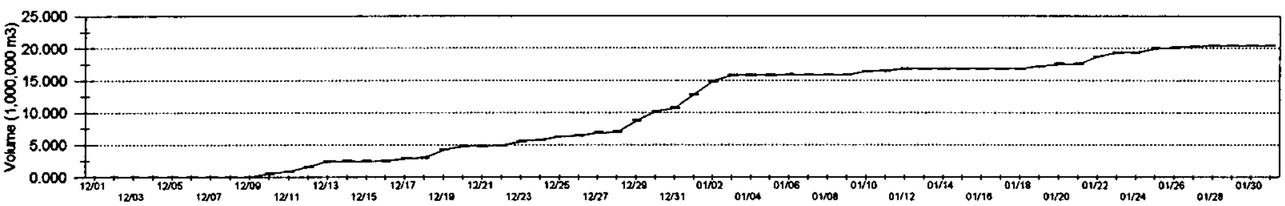
Exploits Ice Progression Modelling
1988/89 Sum of Degree Days



Exploits Ice Progression Modelling
1988/89 Slush Gen. This Day Seg 1-21



Exploits Ice Progression Modelling
1988/89 Total Slush Generated To Date



Exploits Ice Progression Modelling
1988/89 Water Levels

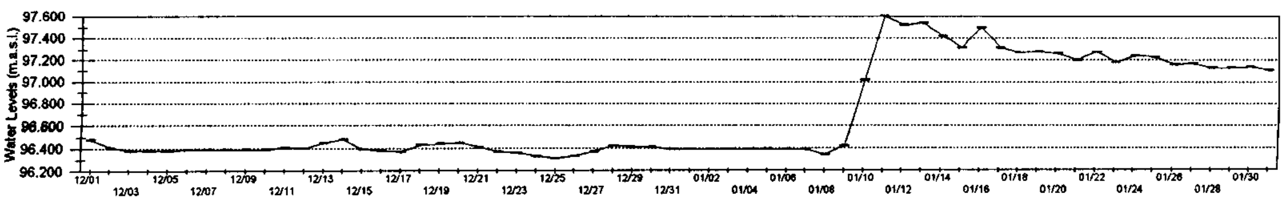


Figure 4-3

hours (Table 2.6). These small "sawtooth" changes are reflections of minor compressions/shoves in the frazil ice jam which are typical of years when there is no flooding.

1989-90

Meteorological conditions, frazil ice production and water levels in the winter of 1989-90 are summarized in Table 2.7, Appendix G, and Figure 4-4. The figure illustrates gradually declining air temperatures and increasing wind chill factors from mid-December to early January and the regular production of frazil ice after 22 December. Following a brief stagnation period on December 26th, 3.67 x 10^6 m^3 of frazil ice was produced before the ice front reached Badger on 2-3 January.

The average rate of frazil ice production at this time was ~0.52 x 10^6 m^3/day which is relatively low and did not cause flooding. Oscillations in the water level during ice progression were only in the order of 0.25 to 0.3 m - which is in keeping with years which have no flooding.

1990-91

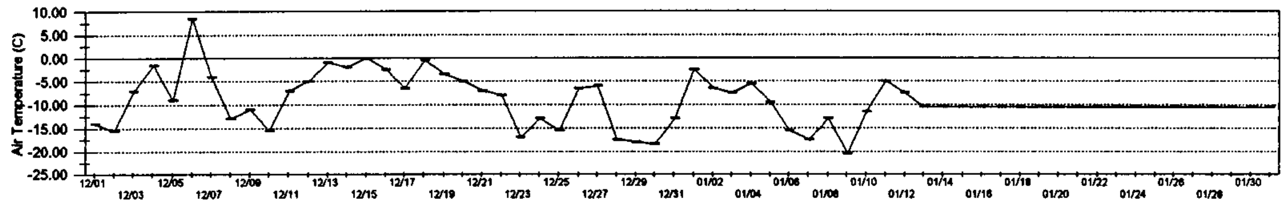
The 1990-91 ice and water level observations are provided in Table 2.8 (and Appendix G) and summarized with simulated ice conditions in Figure 4-5.

Temperatures were periodically mild in late 1990 and it was not until late December that frazil ice began to accumulated to any degree (during a brief cold period with winds). Sustained cold weather in January continued to generate frazil ice and culminated on January 11th with the largest, single-day production of frazil ice in the most recent nine years (~3.4 x 10^6 m^3). This volume essentially filled the river from Badger Chute to Badger in a single day. The following four days provided modest frazil amounts to complete the ice coverage at Badger.

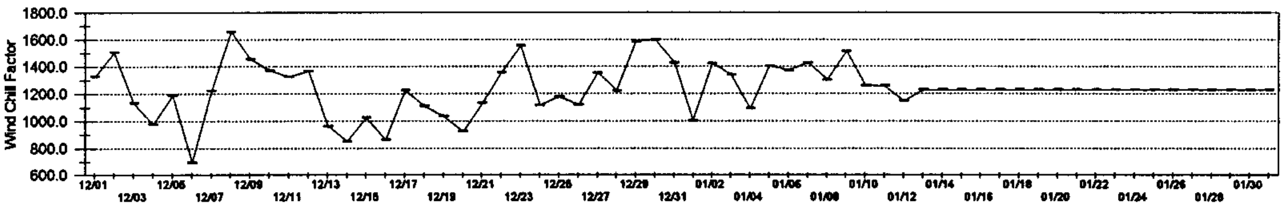
Although the plotted (daily average) water levels do not show the dramatic ~2 m drop and subsequent 3 m rise on January 16 (discussed in Section 2.1.2), it is noteworthy that the average rate of ice progression for an extended duration such as this (~10 x 10^6 m^3 in 10 days/~1 x 10^6 m^3/day) does not - on its own - "forecast" that water levels would rise so high.

As a result of this unusually rapid ice progression, it is recommended that ice volume generation rates for flood forecasting consider only the period when the ice front is between Badger Chute and Badger. This consideration is a refinement of the 1985 analysis and would have enabled projection of flood levels in the range of 99.4 to 99.7 m (compared to 99.5 m actual).

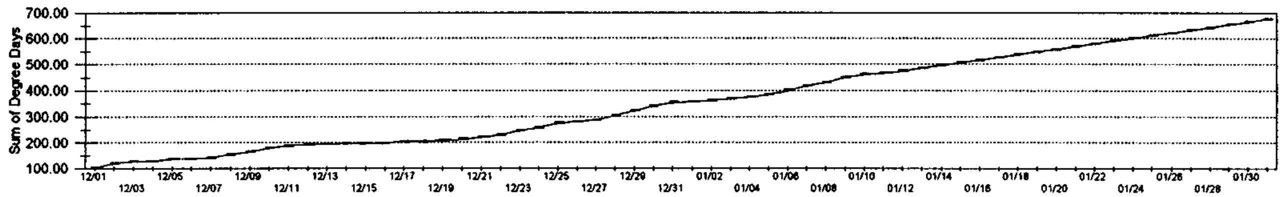
Exploits Ice Progression Modelling
1989/90 Air Temperature



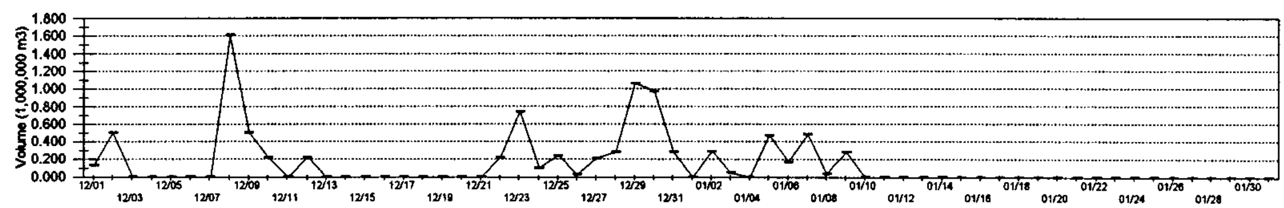
Exploits Ice Progression Modelling
1989/90 Wind Chill Factor



Exploits Ice Progression Modelling
1989/90 Sum of Degree Days

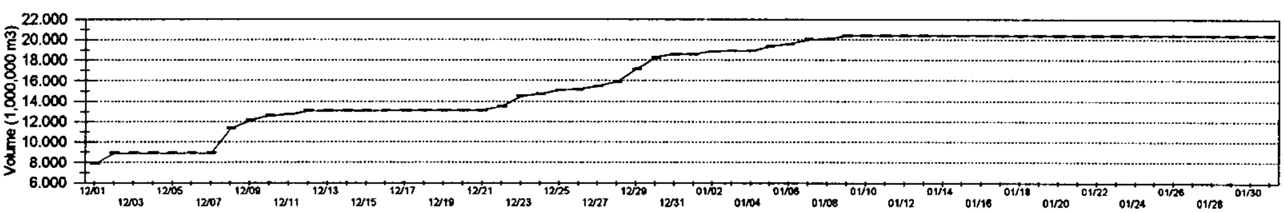


Exploits Ice Progression Modelling
1989/90 Slush Gen. This Day Seg 1-21



meteorological data not reliable after 01/13/90

Exploits Ice Progression Modelling
1989/90 Total Slush Generated To Date



Exploits Ice Progression Modelling
1989/90 Water Levels

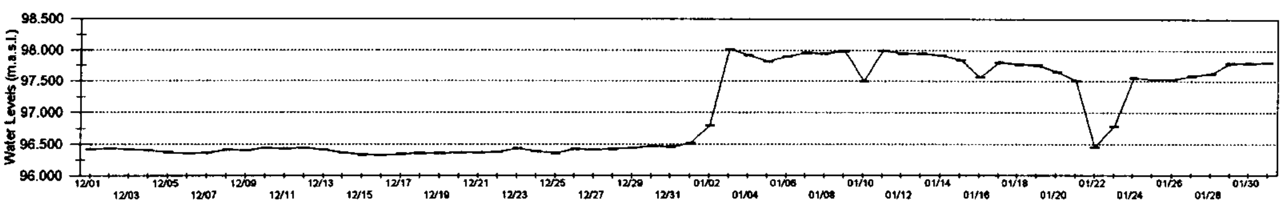
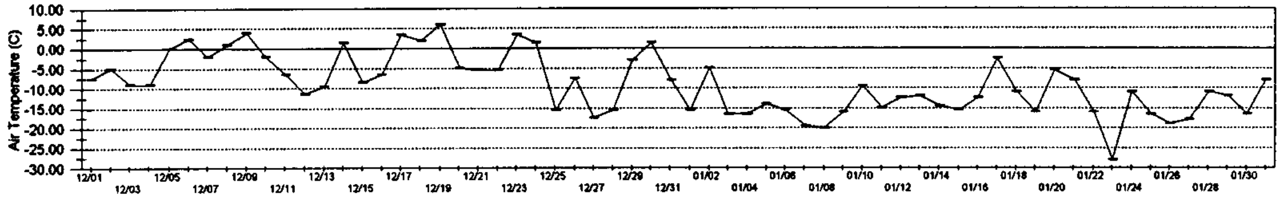
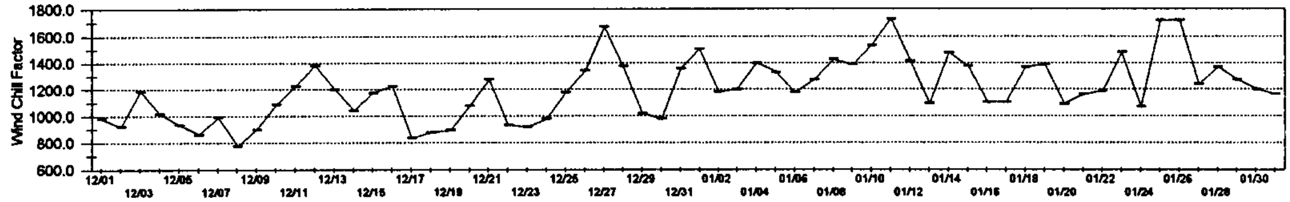


Figure 4-4

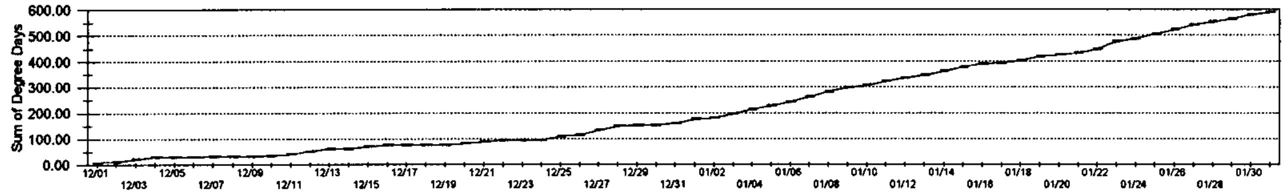
Exploits Ice Progression Modelling
1990/91 Air Temperature



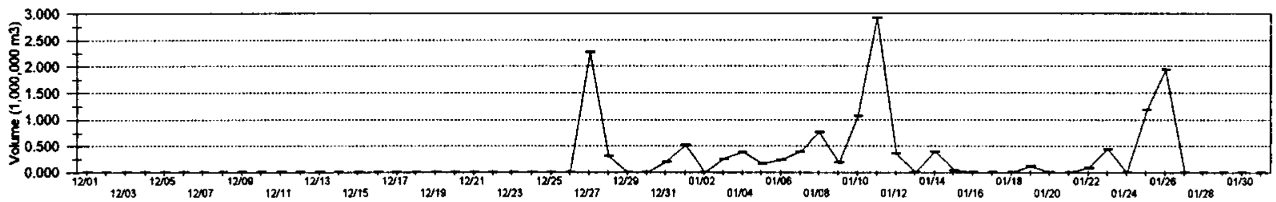
Exploits Ice Progression Modelling
1990/91 Wind Chill Factor



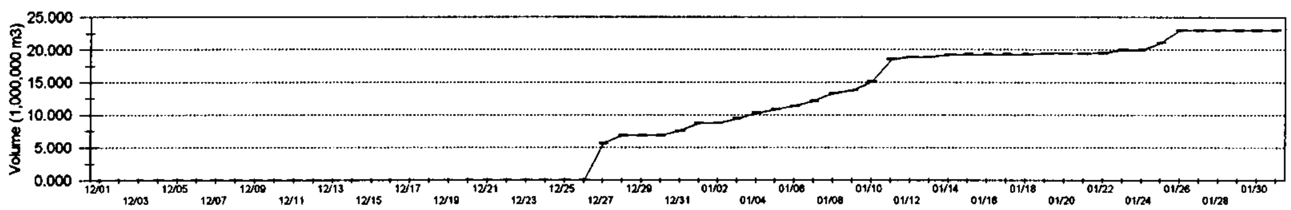
Exploits Ice Progression Modelling
1990/91 Sum of Degree Days



Exploits Ice Progression Modelling
1990/91 Slush Gen. This Day Seg 1-21



Exploits Ice Progression Modelling
1990/91 Total Slush Generated To Date



Exploits Ice Progression Modelling
1990/91 Water Levels

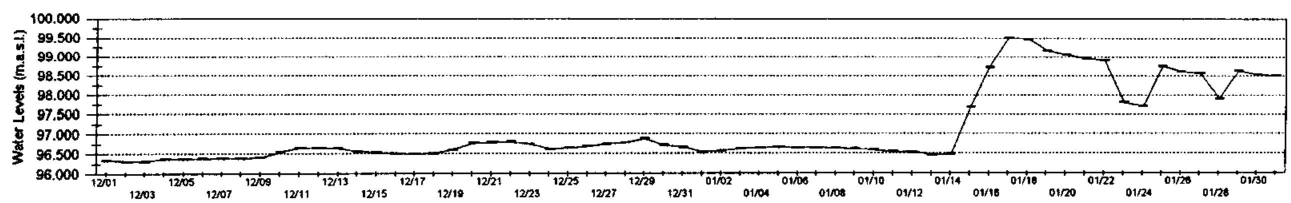


Figure 4-5

1991-92

Ice and water level observations for this year are given in Table 2.9 and Figure 4-6.

The ice cover progressed to Badger Chute by late December 1991 and then remained in that vicinity through a mild period which ended on January 15. From then until January 22, there was daily frazil ice generation which totalled ~4.6 x 10^6 m^3 in the five-day period before the ice cover reached Badger (average rate of ~0.9 x 10^6 m^3/day). This rate would not have been sufficient to have raised any alarm and, indeed, flood levels were not reached.

In keeping with non-flood years, hourly water level fluctuations (which cannot be shown in Figure 4-6) were small and in the range of ~0.3 m/hr.

1992-93

Water level observations from the observer and digital records are presented in Table 2.10 and shown as daily averages in Figure 4-7. Aside from some questionable (unconfirmed by the local observer) oscillations over a two-hour period on January 6, when the ice cover was below Badger Chute, there were no significant rises or falls in water levels until the ice front reached Badger.

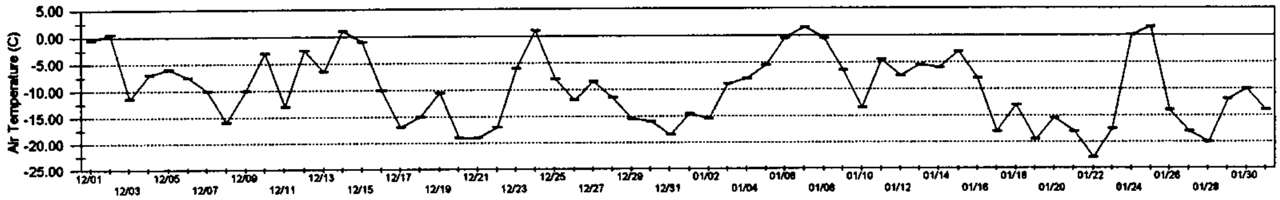
Meteorological conditions in the period from January 2-8 provided mild temperatures with low wind speeds. A cold period with higher winds produced ~3.2 x 10^6 m^3 of frazil ice in the next five days. This was sufficient to carry the frazil ice front upstream of Badger, but the average rate of ice production (~0.6 x 10^6 m^3/day) was not sufficient to cause flood-producing shoves/ compressions in the frazil ice cover.

1993-94

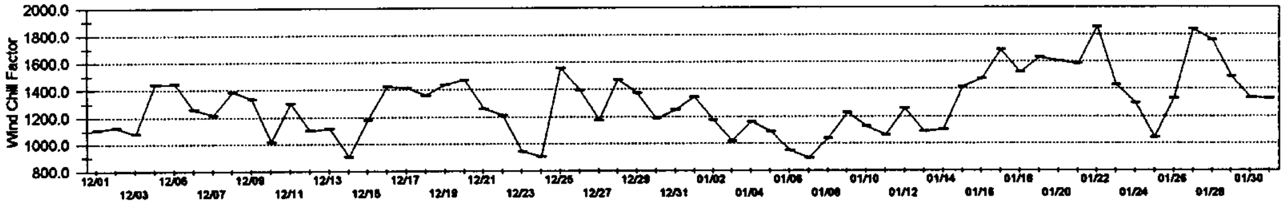
Ice conditions in 1993-94 were affected by warm weather and high flows which flushed much of the ice from the river in December. As shown in Figure 4-8, however, cold windy weather in late December and early January produced sufficient volumes of frazil slush to bring the ice front into the area of the Big Bend. It remained there until colder weather from the 16th to the 20th generated sufficient ice to carry the frazil cover to Badger on the 19th or 20th.

Water levels (detailed in Table 2.11) fluctuated in the night of January 17-18 in response to ice production on the 17th. Levels rose slightly before receding as a result of warmer weather (without frazil production) on January 18, 1994.

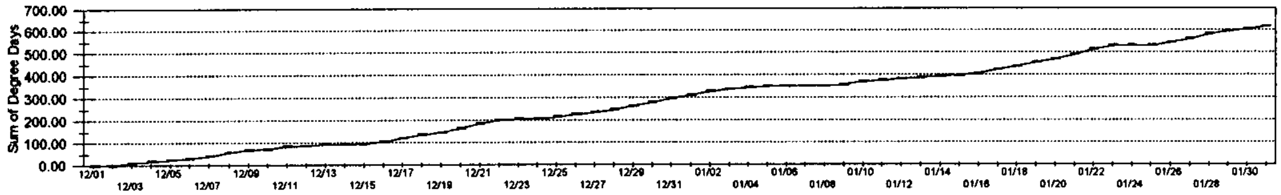
Exploits Ice Progression Modelling
1991/92 Air Temperature



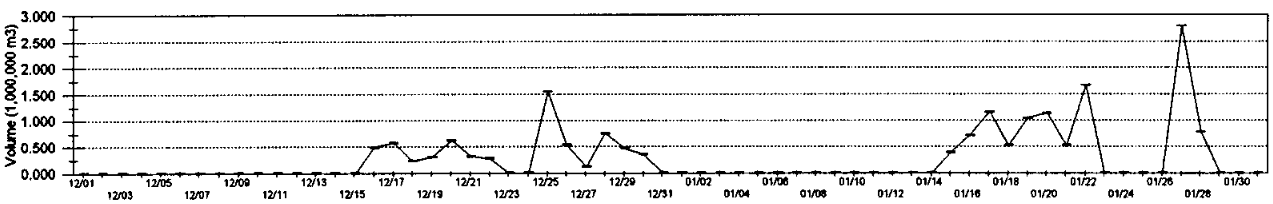
Exploits Ice Progression Modelling
1991/92 Wind Chill Factor



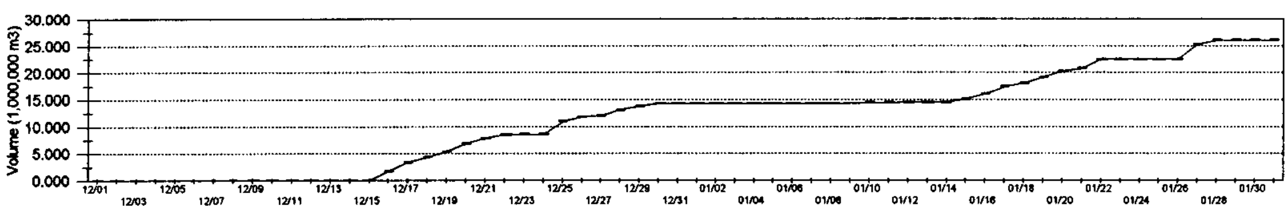
Exploits Ice Progression Modelling
1991/92 Sum of Degree Days



Exploits Ice Progression Modelling
1991/92 Slush Gen. This Day Seg 1-21



Exploits Ice Progression Modelling
1991/92 Total Slush Generated To Date



Exploits Ice Progression Modelling
1991/92 Water Levels

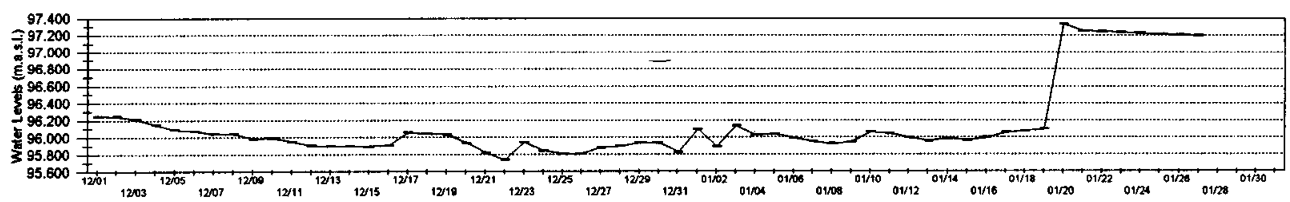
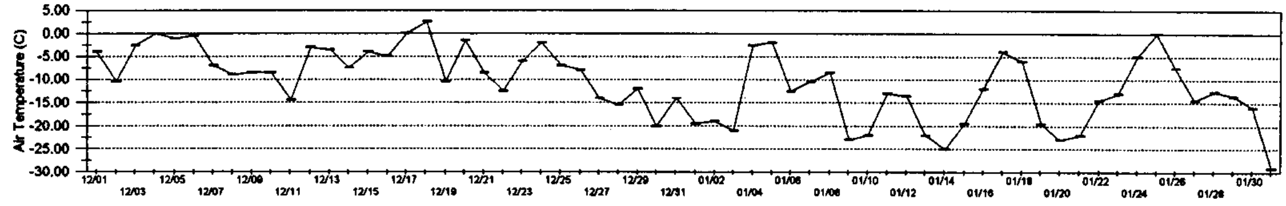
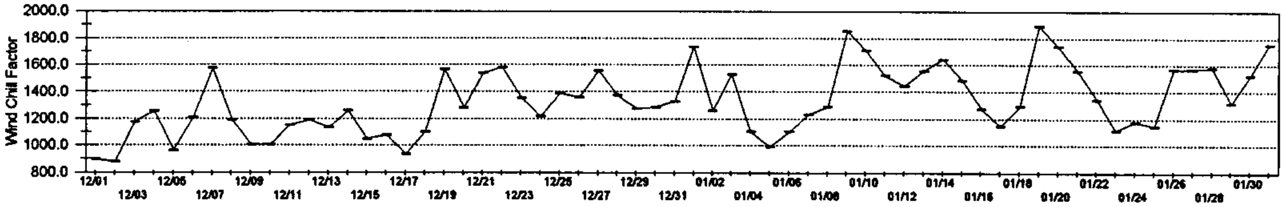


Figure 4-6

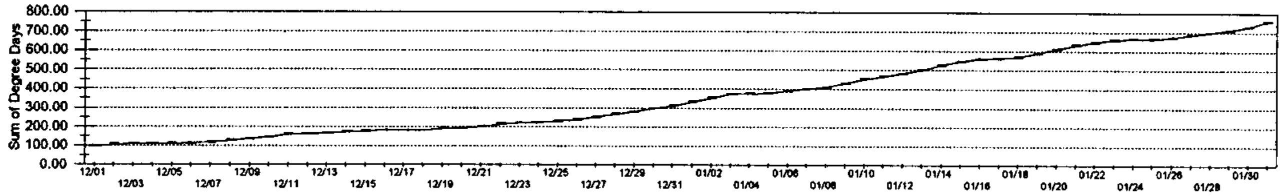
Exploits Ice Progression Modelling
1992/93 Air Temperature



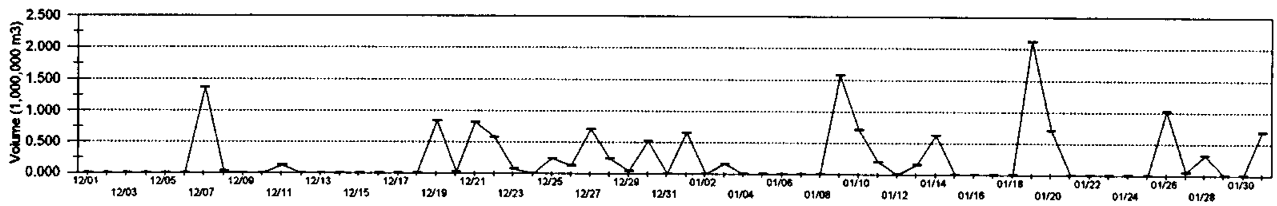
Exploits Ice Progression Modelling
1992/93 Wind Chill Factor



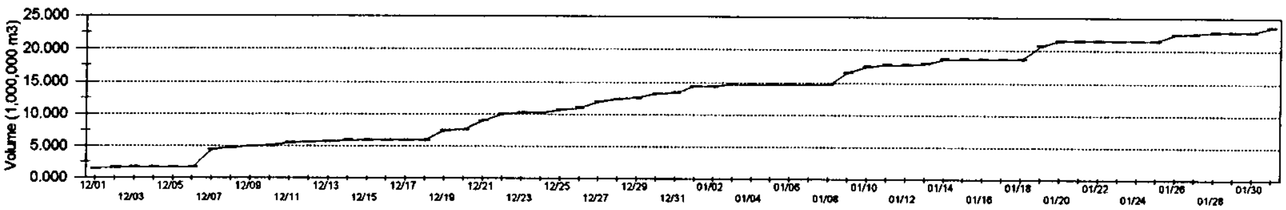
Exploits Ice Progression Modelling
1992/93 Sum of Degree Days



Exploits Ice Progression Modelling
1992/93 Slush Gen. This Day Seg 1-21



Exploits Ice Progression Modelling
1992/93 Total Slush Generated To Date



Exploits Ice Progression Modelling
1992/93 Water Levels

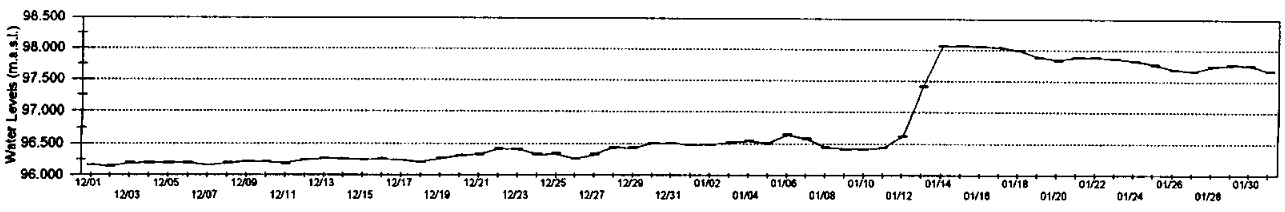
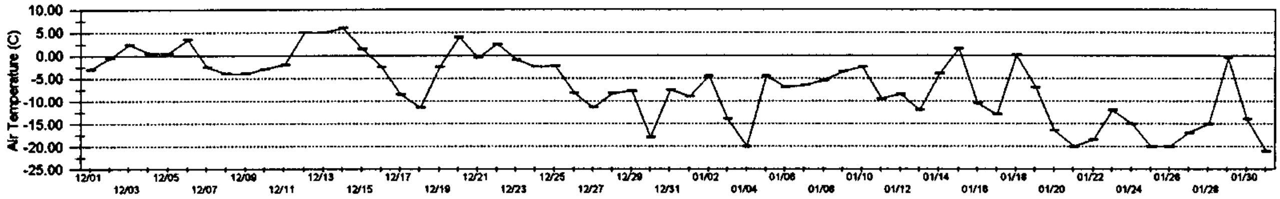
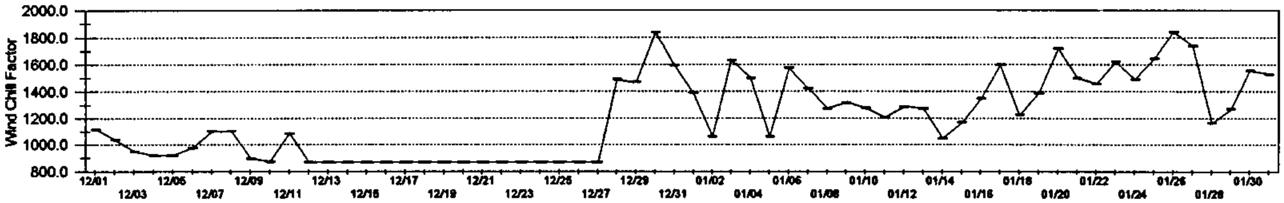


Figure 4-7

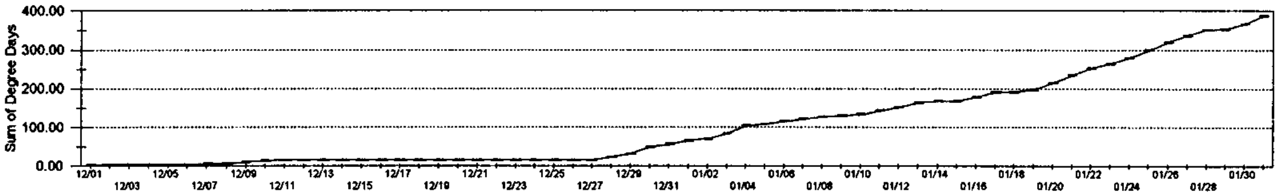
Exploits Ice Progression Modelling
1993/94 Air Temperature



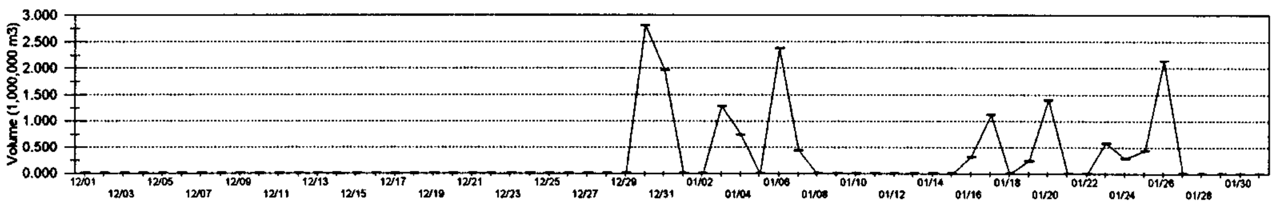
Exploits Ice Progression Modelling
1993/94 Wind Chill Factor



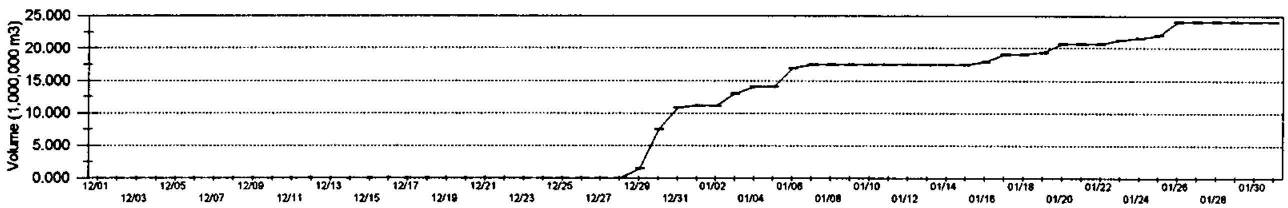
Exploits Ice Progression Modelling
1993/94 Sum of Degree Days



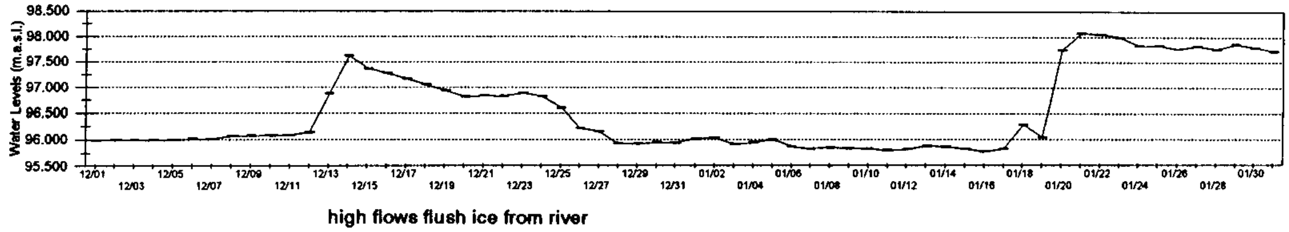
Exploits Ice Progression Modelling
1993/94 Slush Gen. This Day Seg 1-21



Exploits Ice Progression Modelling
1993/94 Total Slush Generated To Date



Exploits Ice Progression Modelling
1993/94 Water Levels



high flows flush ice from river

Figure 4-8

A second volume of frazil ice was generated by colder weather on January 19th and 20th (~1.6 x 10^6 m^3) following stagnation of the ice accumulation on the 18th. This two-day period of frazil ice production had an average rate of ~0.8 x 10^6 m^3/day, which is not sufficient to cause flood-producing frazil ice jams. As illustrated, water levels rose slightly above 98 m before gradually declining.

Figure 4-8 shows the daily variations in water levels during this winter and Table 2.11 describes these variations in more detail. In general, hourly rises and falls were in the 0.2 to 0.5 m range which typifies conditions during problem-free years.

1994-95

Ice cover progression on the Exploits River was delayed by warm weather in December and January 1995. As shown in Figure 4-9, the ice cover reached the area of Badger chute in mid-January and then did not advance upstream until early February. By then, cooler air temperatures and moderate winds had chilled the river to a point where frazil ice production resumed on February 3 1995. A total ice volume of ~4.1 x 10^6 m^3 was generated in the next five days (average rate ~0.83 x 10^6 m^3/day) to carry the ice front to Badger. Water levels reached their peak on February 9 before declining gradually.

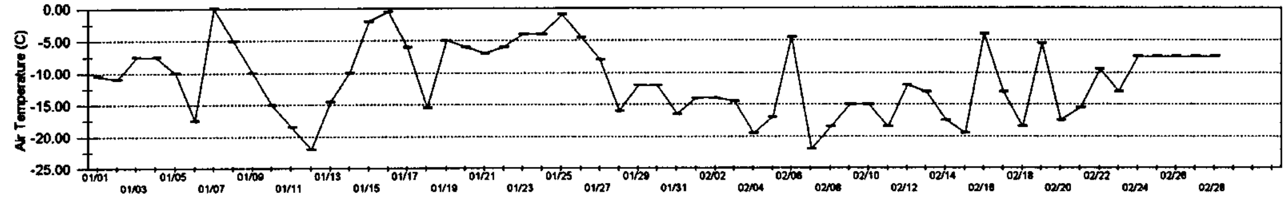
Table 2.12 and earlier discussions in Section 2.1.2 provide additional information about water levels and their variation during February 1995. Overall, water level oscillations were modest (range of 0.13 to 0.2 m decreases in various hours) and the rate of ice accumulation was not sufficient to create a flood condition.

However, as in 1990-91, water levels rose somewhat higher than anticipated. This was likely triggered by the unusually high volume of frazil ice which was generated on February 5 (2.8 x 10^6 m^3) and which may have formed a thick, obstructive ice jam which did not shove/compress.

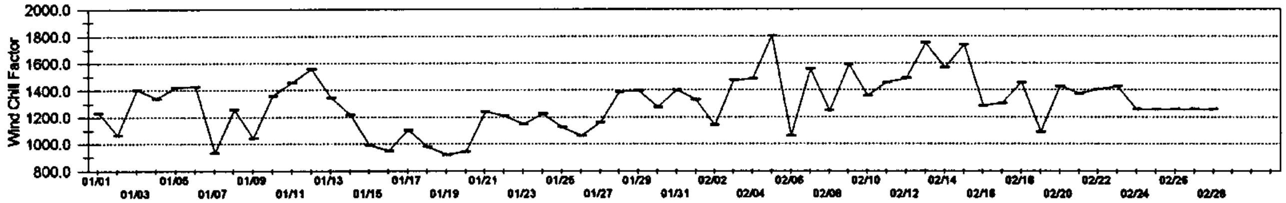
It is premature to make a strong recommendation relating to single day accumulations. However, review of historical data presented in the Technical Appendix of the 1985 report points to single-day ice generation rates of ~2.9 x 10^6 m^3 or higher as contributing to past flooding (e.g., 1976-77, 1956-57).

Overall, the 1994-95 results (as in 90-91) contained single-day ice generation rates which were higher than normal for the period when the ice cover is progressing upstream from Badger Chute.

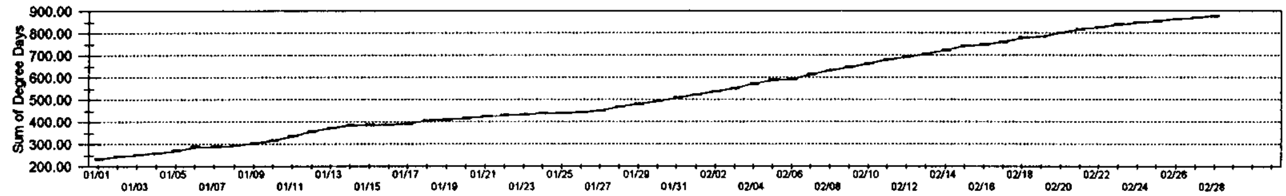
Exploits Ice Progression Modelling
1994/95 Air Temperature



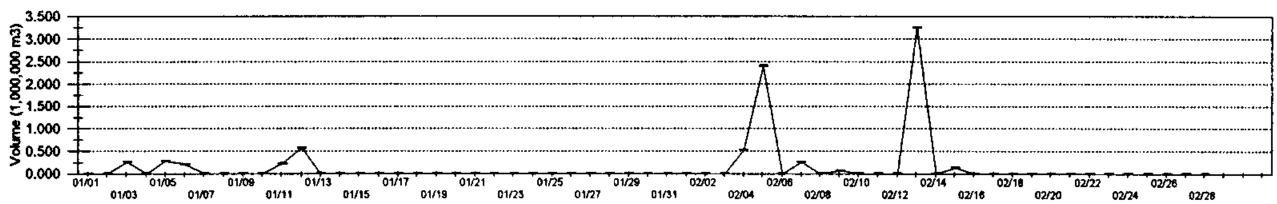
Exploits Ice Progression Modelling
1994/95 Wind Chill Factor



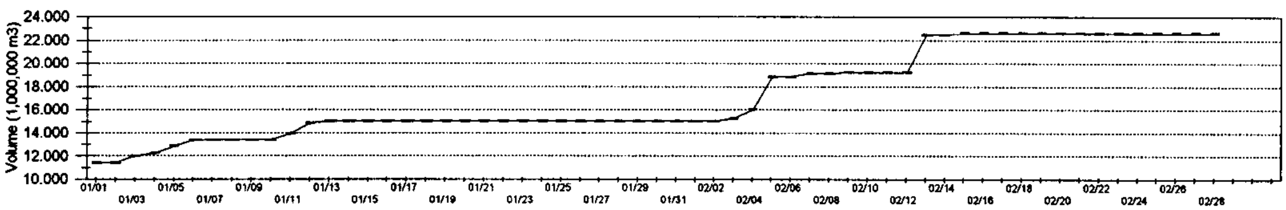
Exploits Ice Progression Modelling
1994/95 Sum of Degree Days



Exploits Ice Progression Modelling
1994/95 Slush Gen. This Day Seg 1-21



Exploits Ice Progression Modelling
1994/95 Total Slush Generated To Date



Exploits Ice Progression Modelling
1994/95 Water Levels

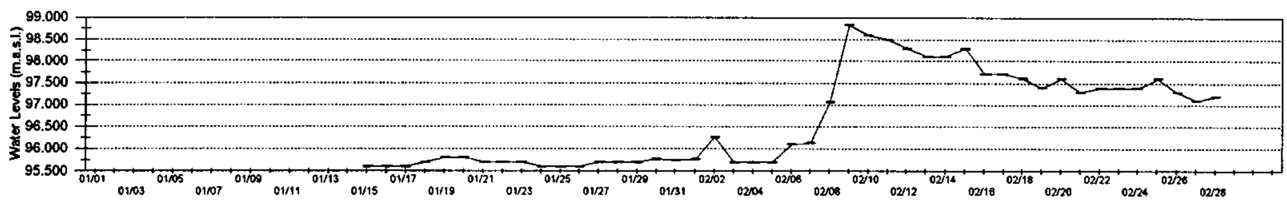


Figure 4-9

The single-day rates did not contribute to frazil accumulations leading to flooding, but they did result in higher-than-expected water levels.

4.1 Current Ice Regime and Modelling - Analysis

Following the re-simulations described above, the ice progression volume/rates and water level results were then compared to the analysis of ice progression through Badger described in Section 7.4.2 (page 7-22) of the original report (1985).

The original (1985) analysis concluded that the single, clear difference between flood years and non-flood years at Badger was the rate at which the ice cover approached Badger following a period of stagnation at a location downstream of Badger. The floods of 1936-37 or 1982-83, for example, were unusual because of the massive volume of frazil ice which formed the ice cover as it moved upstream through the Badger area.

All years in which meteorological conditions and flood levels were available (or assumed because there was no flooding) were simulated in 1985 to provide data for analyzing/forecasting flood levels. The results for the years from 1986-87 to 1994-95 were added to the assessment as part of this study. Table 4.1 presents the updated summary of ice volumes, duration, rate of ice production and resulting water levels as the cover passes upstream at Badger. (The results from 1994-95 are also presented but are tentative, pending future assessment of the ice observer's notes.)

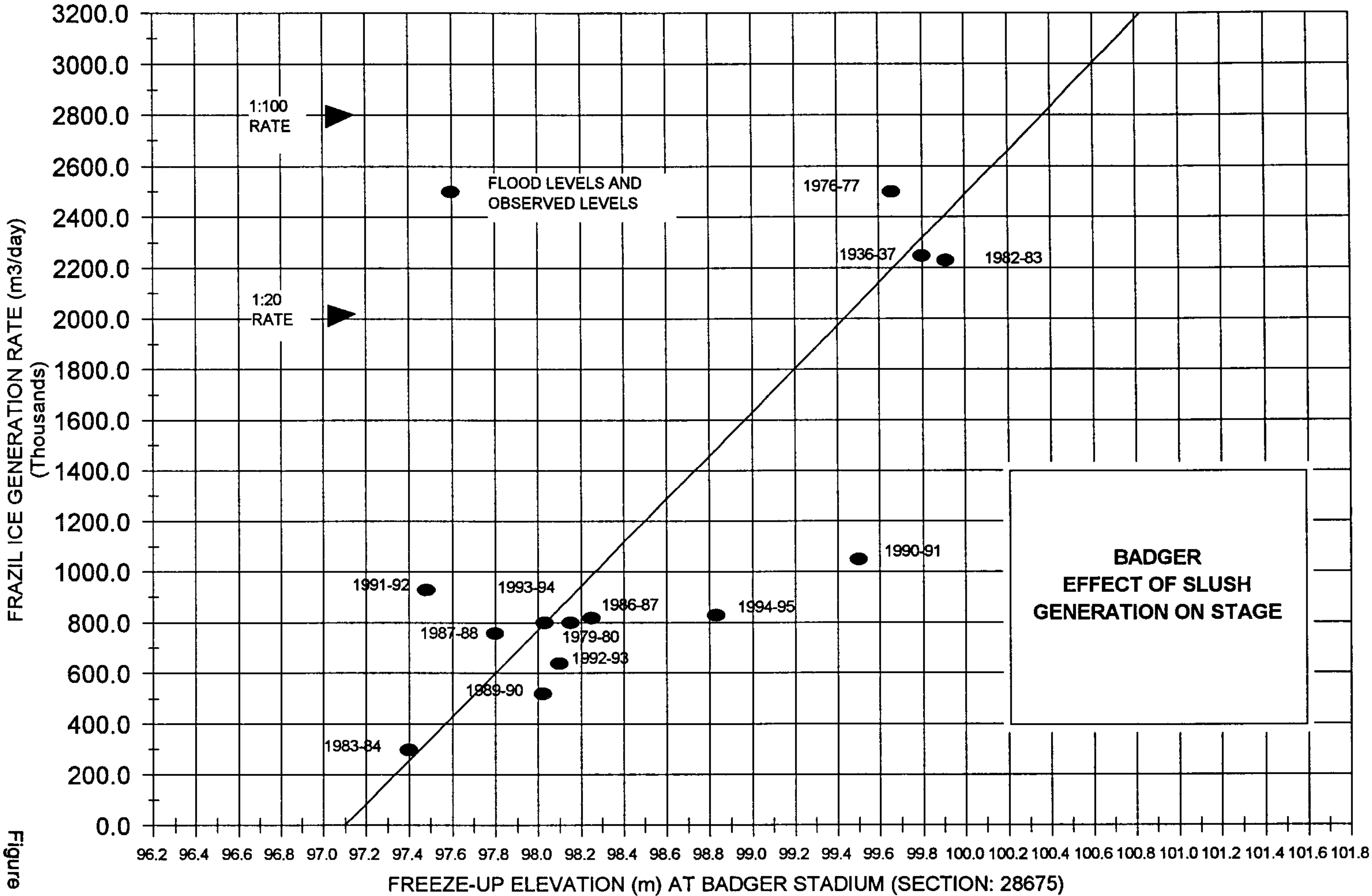
The recent data on ice production and Badger water levels are provided in Figure 4-10 which reproduces the original (1985) figure with the addition of recent data points.. It illustrates that the recent average daily water levels and corresponding daily frazil slush generation rates provide information which complements the 1985 study. It is also noteworthy that the instantaneous peak elevations in 1990-91 lie outside of the general envelope of daily levels vs. daily ice volumes curve. Now that there is the capability to obtain records of instantaneous flood levels, a new curve (perhaps including hourly frazil generation) may be developed to parallel the existing, daily forecast curve.

Overall, it is concluded that the existing ice progression model has been used by the Province in a way that is consistent with that developed by its authors in 1985. As mentioned above, some of the calibration parameters (originally unpublished but now provided in Appendix A)

TABLE 4.1
Exploits River
Simulated Historical Ice Generation Rates Through the Badger Area

Water Year	Ice Volume Passing Badger [1] (m^3x10^6)	Duration of Ice Passage [2] (days)	Ice Volume/Day [3] (m^3x10^6)	Comment and Water Level Estimate [4]
1936-37	2.7	1.2	2.25	- ***flood (elev. 99.8 m est.)
1942-43	missing key meteorological data		--	- ***flood (elev. 99.9 m est.)
1944-45	1.2	2.0	0.6	- ice did not reach Badger
1945-50	missing key meteorological data		--	- ***one flood (elev. 99.05 m est.)
1950-51	1.3	1.0	1.30	-
1953-54	7.2	4.6	1.56	-
1954-55	0.9	1.0	0.90	-
1955-56	8.0	14.0	0.57	- ice did not reach Badger[5]
1956-57	5.0	3.0	1.67	- *high/no flood (98.3 m est.)
1957-58	1.0	2.0	0.50	- ice did not reach Badger
1958-59	5.2	5.0	1.04	-
1959-60	1.0	1.0	1.00	-
1960-61	5.2	5.8	0.90	-
1961-62	1.3	1.75	0.74	-
1962-63	6.4	5.2	1.23	-
1963-64	0.3	1.0	0.30	-
1964-65	0.6	1.2	0.50	-
1965-66	1.8	1.6	1.13	-
1966-67	0.9	0.9	1.00	-
1967-68	0.9	2.0	0.45	- ice did not reach Badger
1968-69	0.3	1.0	0.30	- ice did not reach Badger
1969-70	2.0	4.0	0.50	- ice did not reach Badger
1970-71	0.9	1.6	0.56	-
1971-72	0.85	1.0	0.85	-
1972-73	2.20	2.3	0.96	-
1973-74	2.0	4.0	0.5	-
1974-75	14.8	12.5	1.18	-
1975-76	0.65	1.0	0.65	-
1976-77	5.0	2.0	2.50	- *** flood (elev. 99.66 est).
1977-78	0.6	1.0	0.60	- ice did not reach Badger
1978-79	3.0	4.0	0.75	-
1979-80	0.8	1.0	0.80	- *no flood (98.15 m est.)
1980-81	1.2	1.0	1.20	- ice did not reach Badger
1981-82	1.15	3.0	0.38	-
1982-83	2.90	1.3	2.23	- *** flood (99.91 m est.)
1983-84	1.2	4.0	0.30	- *formation elevation 97.4 m
1986-87	1.63	2.0	0.82	- *ice elev. 98.25 m est.
1987-88	2.28	3.0	0.76	- *recorded elev. 97.8 m
1989-90	3.67	7.0	0.52	- *recorded elev. 98.02 m
1990-91	10.15	10.0	1.02	- *recorded elev. 99.5 m (slight flood)
1991-92	4.64	5.0	0.93	- *recorded elev. 97.48 m
1992-93	3.22	5.0	0.64	- *recorded elev. 98.1 m
1993-94	1.60	2.0	0.80	- *recorded elev. 98.12 m
1994-95	4-4.4	3-5	0.83-1.3	- *recorded elev. 98.83 m

1 total volume of frazil slush in accumulation reaching or passing Badger following a period of ice front stagnation for several days at a site below Badger.
2 total number of days between end of stagnation period below Badger and date on which ice front reaches Badger
3 ratio of ice volume passing Badger[1] to duration of ice passage[2]
4 *asterisks mark years when levels are known or can be estimated
5 values for years in which ice did not reach Badger are taken from the period in which the ice came closest to reaching Badger



BADGER
EFFECT OF SLUSH
GENERATION ON STAGE
FRAZIL ICE GENERATION RATE (m3/day)
(Thousands)
FREEZE-UP ELEVATION (m) AT BADGER STADIUM (SECTION: 28675)
1:100
RATE
1:20
RATE
FLOOD LEVELS AND
OBSERVED LEVELS
1976-77
1936-37
1982-83
1990-91
1991-92
1993-94
1986-87
1994-95
1987-88
1979-80
1992-93
1989-90
1983-84

Figure 4-10

have been exceeded in some years, but realistic flood forecasts were provided. In view of the 1990-91 outlier and the number of data points which lie on one side of the correlation curve, it is evident that some adjustments are now required to the best fit curve to the data.

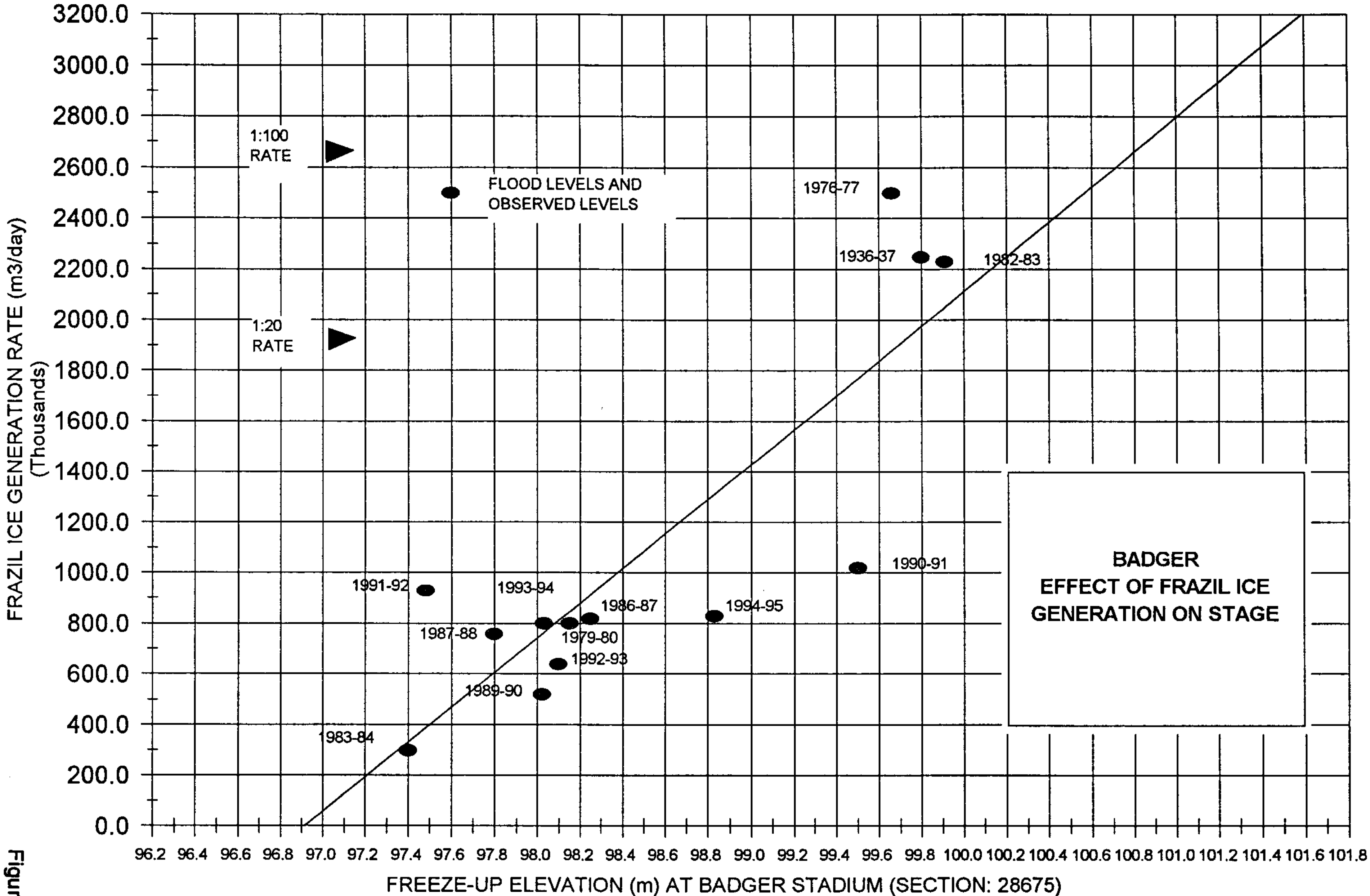
First, the data were replotted and matched with linear and curvalinear curves of best fit (Figures 4-11 and 4-12). The exponential curvalinear relationship provided the best fit to the data and was selected (from a choice of logarithmic, exponential, power and polynominal curve fitting techniques) as it also accounts for overbank spilling at higher levels and reflects that a modest level of frazil generation is required (e.g., as in 1983-84) to initiate a water level rise.

Following this, frazil ice generation rates were re-assessed to determine the 100-year and 20-year return period frequencies of ice generation. The Consolidate Frequency Analysis program, CFA-88 (Environment Canada), was employed and the results (appended) indicate that the Three-Parameter Lognormal distribution provides a good fit to the data. The 100-year and 20-year ice production rates based on inclusion of the recent data are 2,660 x 10^3 m^3/day and 1,920 x 10^3 m^3/day, respectively. The addition of data from recent years has slightly reduced the frazil generation rate projected by the earlier data:

Frazil Ice Generation Rates, m^3/day		
Updated Analysis		**Original Analysis (1985)**
100-year	2660	2800
20-year	1920	2020

The last step involved evaluation of the 100-year and 20-year freeze-up flood levels from the corresponding ice generation rates. Figure 4-12 identifies the revised ice generation rates (arrow heads) and the 100-year and 20-year flood levels as 100.33 m and 97.79 m, respectively.

Comparison between these values and those generated in 1985 is given below.



BADGER
EFFECT OF FRAZIL ICE
GENERATION ON STAGE
FRAZIL ICE GENERATION RATE (m3/day)
(Thousands)
FREEZE-UP ELEVATION (m) AT BADGER STADIUM (SECTION: 28675)
1:100
RATE
1:20
RATE
FLOOD LEVELS AND
OBSERVED LEVELS
1976-77
1936-37
1982-83
1990-91
1991-92
1993-94
1986-87
1994-95
1987-88
1979-80
1992-93
1989-90
1983-84

Figure 4-11

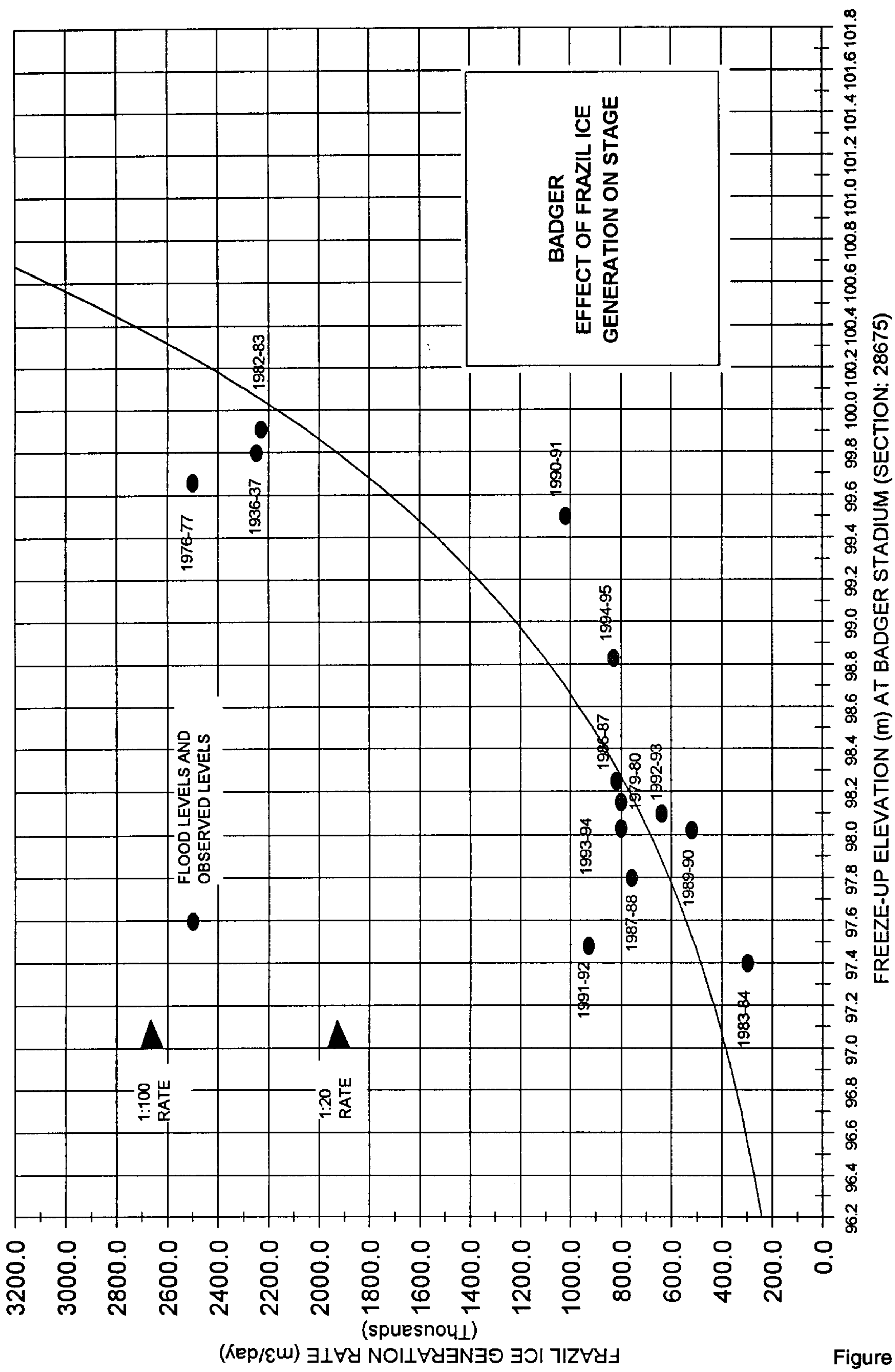

BADGER
EFFECT OF FRAZIL ICE
GENERATION ON STAGE
FLOOD LEVELS AND
OBSERVED LEVELS
1:100
RATE
1:20
RATE
1976-77
1936-37
1982-83
1990-91
1994-95
1986-87
1979-80
1992-93
1993-94
1989-90
1987-88
1991-92
1983-84
FRAZIL ICE GENERATION RATE (m3/day)
(Thousands)
3200.0
3000.0
2800.0
2600.0
2400.0
2200.0
2000.0
1800.0
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
FREEZE-UP ELEVATION (m) AT BADGER STADIUM (SECTION: 28675)
96.2
96.4
96.6
96.8
97.0
97.2
97.4
97.6
97.8
98.0
98.2
98.4
98.6
98.8
99.0
99.2
99.4
99.6
99.8
100.0
100.2
100.4
100.6
100.8
101.0
101.2
101.4
101.6
101.8

Figure 4-12

Badger: Ice-Related Flood Levels at Town Centre (Section 28675)		
Updated Analysis		**Original Analysis (1985)**
100-year	100.33 m	100.36 m
20-year	99.79 m	99.48 m

The updated projection of the 100-year flood level is practically identical to the 100-year level determined by two independent approaches in 1985. The results of those methods and this update would also provide almost identical flood change estimates and, as a result, the current 100-year flood level (100.36 m) is recommended for continued use at Badger.

The 20-year flood level provided by the updated analysis (Figure 4-12) is slightly higher than the original 1985 analysis (using the same ice production modelling approach). The 20-year flood level (99.58 m) presented in 1985 through use of "perception stage" approach also projected a higher level, as does the linear regression in Figure 4-11 (supporting a 20-year level in the order of ~99.7 m).

Overall, recent data suggest that the 1994 flood levels (established in 1985) for the 20-year return period ice condition underestimate that value. However, given that there is spread in the data, it is recommended that the current 20-year flood level (99.48 m) be retained for regulatory purposes.

5.0 SUMMARY OF FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

5.1 Data Collection and Monitoring

1) The ongoing ice observer program has provided a significant quantity of baseline data for assessing past and future ice conditions at Badger. In that much of the baseline data has been collected for certain elements (i.e., ice thickness), it is recommended that the program be modified to focus on providing:

   - detailed mapping of the upstream progression of the frazil ice accumulation until such time as complete ice cover is upstream of Three Mile Island. Figure 2-1 provides an example of the qualitative information which will benefit future work.

   - increased frequency of ice progression observations in the period when the ice cover is upstream of the Big Bend (upstream of Badger Chute). This could include observations every second or third day during this period and should include rapid (i.e., faximile) transmission of the data to the Province.

   - increased frequency of staff gauge readings when the readings (remotely obtained) indicate rapidly falling or rising levels. This set of readings is simply to confirm the readings given by the automatic recorder.

2) The ongoing ice observer monitoring program can now be simplified to:

   - eliminate ice condition observations on Junction Brook and Little Red Indian Brook;

   - eliminate ice thickness measurements at all locations except the Exploits River near the stadium. These measurements need only be taken until two weeks after the ice cover has reached Three Mile Island;

   - eliminate the staff gauge readings at Junction Brook.

3) The current compilation of historical streamflow, water levels and meteorological data (most of which has been compiled for ice progression modelling) should be continued into the foreseeable future. It provides the basis for future analysis and, in that these analysis may be based on hourly variations, it is recommended that hourly data files be kept.

4) The Provincial engineer responsible for the program at Badger has correctly observed that snowfall has an influence on frazil ice production. Similarly, it is recognized that wind direction (particularly if along the axis of the river channel) increases surface water cooling and the potential for frazil ice production. Both of these meteorological factors have potential application for refined flood forecasting and should now be included in the meteorological data base. As time permits, the hourly records of these parameters from previous years should be added to the above mentioned hydrometric (flow) data base.

5) Water level recording data from the Badger Stadium location provides a new set of extremely valuable data for flood forecasting at Badger. The importance of this information cannot be overstated and it is strongly recommended that the Stadium gauge be maintained and viewed as the primary source of information for flood forecasting.

6) Water temperature is included as a sampling parameter in ongoing provincial water quality monitoring programs. It is also an important element in the forecasting of ice production in the Exploits River upstream of Badger. As a result, it is recommended that water temperatures from existing programs be reported to the ice modeller and that water temperatures be taken twice monthly (December 1st to February 28th) at the outlet of Exploits Dam. This could be undertaken by the ice observer or through an agreement with Abitibi Price.

7) It is further recommended that water temperatures be measured at Badger on the same dates that they are measured at Exploits Dam for a period of about two years.

5.2 Modelling and Analysis

1) Analysis of water level recording data from the 1987 to 1995 period (and particularly the 1990-91 period) provides a strong indication that:

- decreases in water levels in the range of 2 m are indicative of unusually significant frazil ice blockages downstream of Badger. In 1990-91, these decreases were followed by similar and larger increases in flood water levels in about 24 hours.

- remote monitoring of water levels, which are likely to reflect decreases during the frazil producing night hours, should be closely monitored for water level decreases during the period when the ice front is in the Big Bend/Badger Rough Waters area.

- similarly, rapid increases in levels should continue to be closely monitored - in conjunction with reports from the ice observer, tracking of meteorological conditions and projected frazil ice volumes.

2) Analysis of water level data showed a number of oscillations in water levels which may be related to changes in streamflow or ice conditions. In that early knowledge about ice-induced changes in water levels is imperative, it is also recommended that an open water stage-discharge relationship be prepared for the Badger Stadium gauge site. This relationship, when coupled with ice observer reports, will provide a valuable indication of the downstream location where frazil ice blockages begin to contribute to elevated water levels at Badger. This relationship should also provide data on the volume of water which is being transformed into ice and assist in future refinements to the ice observation and modelling work.

3) Review of river ice models was completed as part of this study to determine if any recent (1983-1995) models would be applicable to improve water level forecasting from frazil ice accumulations. The non-proprietary models (the Ice Cover Evolution Module of RIVICE and RIVJAM) are recommended for testing to determine if they can enhance the information provided by the existing ice progression model. These models are not, however, recommended for immediate application to replace any portion of the existing flood forecasting model.

4) RIVJAM and the ice cover evolution module of RIVICE are suggested for review because they may provide additional insight into the processes of ice cover thickening, transport,

stability and erosion in the area downstream of Badger. The existing model should, however, be retained to account for other conditions such as heat balance, open water ice generation, ice cover initiation, etc. Certain refinements can be made (and have been as part of this study) to the existing model, but there is no compelling reason to recommend a broad change in the modelling approach.

5) The existing ice modelling approach employed by the Province was also reviewed as part of this study and was found consistent with that developed by the authors of the model in 1985. Realistic flood forecasts were provided in this period, but it is recommended that the range of the adjustment parameters (provided in Appendix A) be employed as a guide for future flood forecasting modelling.

6) The existing ice model uses river water temperature as input to the assessment of ice production data. It was found that the current model should be modified to use water temperatures which are measured during the winter, and this modification was completed in the model to enhance the forecasting capability in future applications.

7) Ice modelling results for the most recent nine years were analyzed to determine if recent information would alter the current approach to forecasting flood levels. The recent observations and simulations confirmed that:

   - there is a direct relationship between the frazil ice generation rate and freeze-up flood elevation;

   - this relationship can be used to forecast potential flood situations.

8) Analysis of the recent modelling results (in concert with historical information) confirms that the 100-year flood level at Badger is 100.36 m (Badger Stadium). There are strong indications that the 20-year flood level (99.48 m) should be slightly higher, but this change cannot be advanced until completion of additional years of monitoring.

9) Analysis of the recent modelling (and re-analysis of the 1985 simulations) indicated that exceptionally high volumes of frazil ice generation on a single day may contribute to water levels which are higher than would normally be forecast at Badger. It is

recommended that forecasted elevations be increased by ~0.7 m when single-day frazil ice generation rates exceed 2.9 million m^3 during the period when the ice cover is between Badger Chute and Badger.

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Dec 17 - Dec 31, 1987
Jan 1 - June 10, 1988
Oct 21 - Dec 31, 1988
Jan 1 - May 24, 1989
Nov 1 - Dec 31, 1989
Oct 5 - Dec 31, 1990
Jan 1 - July 19, 1990
Jan 1 - Aug 15, 1991

Water Level Data, 1991-95. Water Level Records from Oct 16, 1991 at Badger Stadium Gauge.

appendix a

Existing Exploits River Model

APPENDIX A
EXISTING EXPLOITS RIVER MODEL

1.0 USER INFORMATION

A listing of the model and the output for several portions of an example ice year are given in the technical appendices of the *Hydrotechnical Study of the Badger and Rushy Pond Areas* (Fenco Newfoundland, 1985).

The input data, other than the meteorology and streamflow files are summarized in the first page of the output.

1.1 Model Input Data

Line 1 defines the starting and ending years and months which will be simulated. Four integer values are entered on this line in free format: START YEAR, START MO., END YR., and END MONTH.

Line 2 provides a second set of values which define the winter season (months) for each run. The integer values are entered on this line in free format with the first being the START SEASON and the second being the END SEASON. These values are typically the same monthly values provided in line 1.

Line 3 provides five values which may be employed by the modeller to adjust the rate of cover progression along the river. These are real numbers entered in free format in the following order: QFLUSH, PORADJ, TEXADJ, BDRADJ, FRDADJ and VOLADJ.

QFLUSH is the flow rate in m^3/s which is known to flush ice from the river.

PORADJ is a non-dimensional multiplier used to adjust the ice content of the ice cover. The ice content is set within the model to 0.5, hence a value of 1.4 for PORADJ will set the content at 0.7. A range from 0.8 to 1.4 is recommended.

TEXADJ is a value in °C used to change the temperature of discharge entering the river from Exploits Dam. This is set at 3.0° C within the model, hence a value of 1.0 for TEXADJ will set this discharge temperature to 4.0° C. A range from 0 to -2.0 is recommended.

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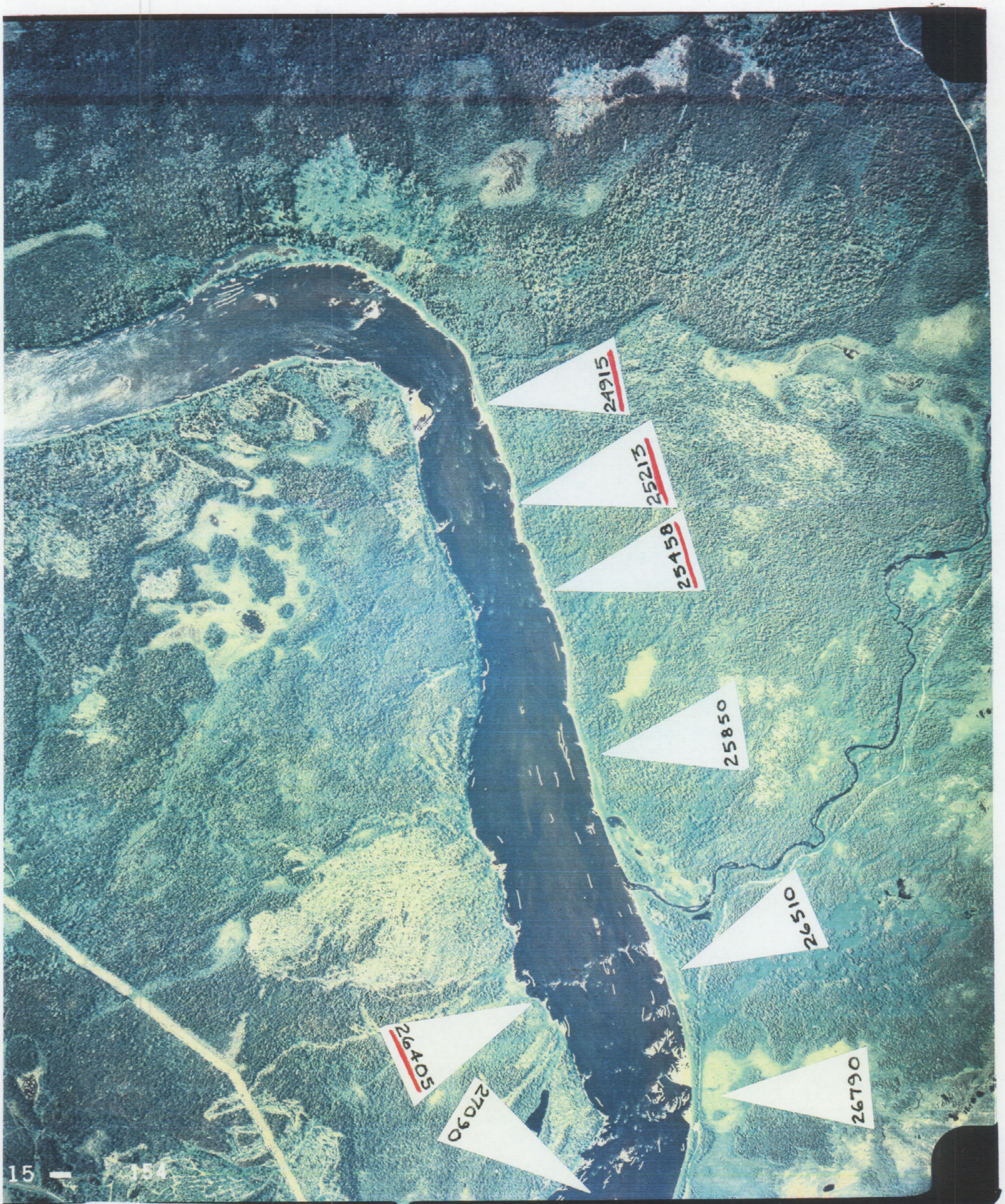

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A revised version of the model has been prepared to allow for daily revision of inflow water temperatures. It is discussed in Section 1.4 of this Appendix.

BDRADJ is a non-dimensional multiplier used to increase or decrease the rate of border ice growth (and thus closure) according to the field observations in a given year. If there are no observations, the value is set at 1.0. A value greater than 1.0 will speed the growth, and less than 1.0 will slow the rate of border ice growth. A range from 0.5 to 2.0 was found to be effective in the 1985 study.

FRDADJ is a non-dimensional multiplier used to change the data of ice closure at the Rushy Pond ice boom. The data of closure is set in the model on a day in which there is frazil slush passing the boom and Froude Number at the boom is 0.08. A positive value of FRDADJ above 1.0 will slow closure by increasing the value of the critical Froude Number. A value less than 1.0 speeds the closure. A range from 0.75 to 1.25 is recommended.

VOLADJ is a non-dimensional multiplier used to ensure that closure at the ice boom takes place on a date when there is sufficient slush to form the start of a stable ice field at the boom. A value of 500,000 m^3 is assumed in the model (1 m thick by two river widths in length), but it may be increased or decreased by corresponding changes in VOLADJ. A value of 1.0 is recommended.

** Only lines 1-3 may be modified by the user to precisely calibrate model outputs to ice conditions during a given year. The remaining input data (lines 4-36) are constants and would not change unless the river was changed by diversion, channelization, addition of new dams, etc.

Line 4 gives the number of segments the river has been divided into (32 segments, each being 2.5 km in length). Line 4 also provides initial values for the river temperature and ice cover on the starting day of simulation. The latter are assumed to be 4.0 and 0.0 in all runs.

Lines 5-36 list the physical parameters relating to each river segment. The river segments are numbered from segment 1 (the first below Exploits Dam) to segment 32 (the first above Goodyear's Dam). The input data is segment number, water depth (m), surface area (m^2), ice storage volume (m^3), river "mileage" (km) from Goodyear's Dam, and the drainage area (km^2) from Exploits Dam to Grand Falls. Table A-1 gives these parameters for each river segment.

The meteorological data which follows is printed as a model output. Dewpoint temperature is not often forecasted; hence, for modelling purposes, it is recommended that dew point be taken as 2C° colder than the air temperature (Appendix H).

TABLE A-1
Physical Data - Cross Sections

Segment Number	Average Depth (m)	Surface Area (m^2)	Segment Volume (m^3)	Distance From Goodyear's Dam (km)	Drainage Area (km^2)
1	1.5	490000	735000	81.0	60
2	1.5	310000	465000	77.5	354
3	1	350000	350000	75.0	363
4	1.5	350000	525000	72.5	373
5	2.5	325000	812500	70.0	383
6	2.5	325000	812500	67.4	393
7	2.5	335000	837500	65.0	446
8	2.5	335000	837500	62.5	483
9	2	515000	1030000	60.0	493
10	1.5	515000	772500	57.5	502
11	1.5	490000	735000	55.0	1315
12	1.5	490000	735000	52.5	1369
13	1	620000	620000	50.0	1375
14	1.5	620000	620000	47.5	1383
15	1.5	500000	500000	45.0	1390
16	1	500000	500000	42.5	1396
17	1.5	515500	515500	40.0	1404
18	1.5	580000	1160000	37.5	1410
19	1	696000	1045000	35.0	1418
20	1.5	644000	1610000	32.5	1425
21	1	644000	773000	30.0	2339
22	1	637000	1456000	27.5	2403
23	1.8	683000	2400000	25.0	2438
24	2	618000	2236000	22.5	2448
25	1.5	786000	1965000	20.0	2569
26	1.5	760000	2020000	17.5	2620
27	1.5	1082000	1623000	15.0	2677
28	1	1418000	1918000	12.5	2766
29	1	773000	1773000	10.0	2778
30	2	871000	1871000	7.5	3302
31	4	1750000	1050000	5.0	3317
32	5	722000	515000	2.5	3368

1.2 Model Output

Lines 37-38 list the year, month and day being simulated. The air temperature (°C), equilibrium temperature (°F and °C) are then provided. The wind chill factor (w/m^2) is then given, followed by three values of the coefficient of surface heat exchange (BTU/ft^2 day °F, m/s, w/m^2 °C). The freezing degree day value is then given followed by the total freezing degree days to that date. The last two entries are the flow rates at Exploits Dam and Grand Falls (m^3/s).

Lines 39-41 give the simulated river temperatures in each segment progressing downstream from Exploits Dam to Goodyear's Dam.

Lines 42-44 provide values of frazil slush generated on the given day in the full river and above Badger Rough Waters. Line 44 gives the total slush accumulated above Goodyear's Dam.

Lines 45-47 provide a one to ten day summary of the total slush produced above Badger Rough Waters.

Line 48 identifies the river segment containing the front of the ice cover.

Program end provides a graphical summary of the ice field progression through time.

1.3 Model Sensitivity

The sensitivity of the ice progression model was tested for various parameters using the winter of 1936-37 as the test year. This year was an ice jam year and thus appropriate for testing the relative sensitivity of input parameters.

Cover Initiation

This is regulated by parameter BDRADJ or FRDADJ. The former (BDRADJ) regulates the rate of closure at Goodyear's Dam by border ice growth, and three values were tested.

BDRADJ	0.3	0.6	1.0	
Date of Closure	10 Dec.	6 Dec.	2 Dec.	(4-8 days difference)
Date at Badger	17.2 Feb.	17 Feb.	16.5 Feb.	(.2 to .8 days difference)
Progression Rate*	2.25	2.37	2.36	(0.01 to 0.12 difference)
Ice Elev. at Badger	99.75	99.88	99.85	(0.1 m to 0.13 m difference)

Although the initial date of closure is highly sensitive to this parameters, projected flood levels and the date at which the ice cover reaches Badger are insensitive to the date of closure. This is generally the case in other years as well.

Ice Porosity

This is regulated by parameter PORADJ, which for all simulations was kept at 1.6 (ice content in slush is 0.8 or porosity is 0.2). This parameter regulates the speed of cover progression. Hence, if progression is too fast or too slow, the ice will be simulated to arrive at Badger too early or too late (and during a completely different set of weather conditions which influence slush production). Two values were tested other than the recommended value of 1.6.

PORADJ	1.6	1.4	1.2	
(ice content)	0.8	0.7	0.6	
(porosity)	0.2	0.3	0.4	
Date of Closure	10 Dec.	10 Dec.	10 Dec.	(no difference)
Date at Badger	17.2 Feb.	16.5 Feb.	12.5 Feb.	(.7 to 4.7 days early)
Progression Rate*	2.25	2.48	0.62	
Ice Elev. at Badger*	99.75	100.00	97.88	(.25 m high to 1.87 m low)

The simulation results are insensitive to ice cover ice content values which are 10% of the recommended value (1.6). Beyond this range, progression will be too rapid or too slow, and ice elevation projections for Badger will be inaccurate because they will be based on slush generation for a different weather sequence.

River Temperature

This is set within the mode at 3.0° C and modified for each simulation by parameter TEXADJ. In years when lake levels are low, this parameters may range from -0.5 to +0.5, and when lake levels are high, it may be set at 1.0. Three values were tested with the following results:

TEXADJ	0.5	0.3	1.0	
Closure Date	10 Dec.	10 Dec.	10 Dec.	(no difference)
Ice at Badger	17.2 Feb.	16.4 Feb.	Badger not reached	(.8 day early to very late)
Progression Rate	2.25	2.37	Badger	(.13 higher)
Ice Elev.	99.75	99.87	not reached	

The simulation results are relative insensitive to a 40% change in TEXADJ. Beyond this range, however, the date at which ice is projected to reach Badger (and whether or not it reaches Badger at all) and the ice elevation become quite sensitive to this parameter.

Meteorological Conditions

Air temperature (air and dew point) and wind speed are the principal meteorological inputs. Model sensitivity to these elements were tested by adjusting the historical record to reflect possible errors which might be introduced in a five-day forecast. In the test year (1936-37), observed values were maintained until 13 February. On that date through to 17 February, values were then adjusted for sensitivity analysis.

Wind Speed

Sensitivity of the model to wind speed was tested by assuming forecasted speeds to be 5 km/hr faster or slower than historical values.

Speed	historical	+5 km/hr	-5 km/hr	
Closure Date	10 Dec.	10 Dec.	10 Dec.	(no difference)
Ice at Badger	17.2 Feb.	16.6 Feb.	2 Mar.	(0.6 day early to +10 day late)
Progression Rate	2.25	3.35	1.84	
Ice Elev.	99.75	101.0	99.27	(1.25 higher to 0.5 lower)

Wind speed greatly affects river cooling and the volume of frazil ice generated in the river above Badger. The selected range for analysis (5 km/hr difference from historical) represents an error in the five-day estimate of 25% of more which, although seemingly large, is quite realistic for such forecasts. The model is sensitive to this parameter and particular care should be paid while obtaining values for wind speed - particularly when very cold temperatures are forecasted.

Air Temperatures

Model sensitivity to air temperature estimates was tested by assuming the five-day forecast for 13-17 February 1937 was 2° C warmer or colder than historical values. This range is about 10% of recorded values.

Temperatures	historical	+2° C	-2° C	
Closure	10 Dec.	10 Dec.	10 Dec.	
Ice at Badger	17.2 Feb.	19 Feb.	16.7 Feb.	(1.8 day late to 0.5 early)
Progress Rate	2.25	0.92	3.14	
Ice Elev.	99.75	98.23	100.75	(1.52 lower, 1.00 higher)

The model is very sensitive to the accuracy in air temperature estimates and, again, particularly so when cold weather is coupled with high wind speeds. Warmer air temperatures delay the date and place the time of arrival of the ice cover during a sequence of low progression rates (and hence lower water levels). Colder temperatures do the opposite.

Overall, problems at Badger occur when the ice cover is just downstream of the town and a period of very cold temperatures with high winds has been experienced in the following day. As noted in the main report, both active and inactive frazil will be presented in the Badger Rough Water area during these conditions. Should this weather situation develop in future years, considerable effort should be made to ensure that accurate meteorological forecasts are obtained and regularly updated.

1.4 Revised Version of Ice Progression Model

The revised model (ICE4I2.EXE, Feb.27/95) allows the user to change the values of the parameters PORADJ and TEXADJ on any day in the input file. The initial values (as coded in line 3, fields 2 and 3 of the input file) are used until new values are entered.

For each day of data in the input file, the user can either do nothing, change the PORADJ value, change the TEXADJ value, or change both values. This is done by entering one of the following changes in the right-most column:

- enter a 0 for no change
- enter a 1 followed by the revised PORADJ value
- enter a 2 followed by the revised TEXADJ value
- enter a 3 followed by the revised PORADJ value and the revised TEXADJ value.

Whenever no change is requested, the previous value is used.

When the user uses START SEASON and END SEASON to run only a portion of the input data, the last change coded previous to START SEASON in the input file is used as the starting condition. An example of the revised input file is presented on the next page.

1993	12	1994	4		
12	4				
420.0	0.8	0.0	4.0	5.0	1.0
32.0	6.0	0.0			
1.0	1.5	490000.0	0.1	81.0	60.0
2.0	1.5	310000.0	0.1	77.5	354.0
3.0	1.0	350000.0	0.1	75.0	363.0
4.0	1.5	350000.0	0.1	72.5	373.0
5.0	2.5	325000.0	0.1	70.0	383.0
6.0	2.5	325000.0	0.1	67.4	393.0
7.0	2.5	335000.0	0.1	65.0	446.0
8.0	2.5	335000.0	0.1	62.5	483.0
9.0	2.0	515000.0	0.1	60.0	493.0
10.0	1.5	515000.0	0.1	57.5	502.0
11.0	1.5	490000.0	0.1	55.0	1315.0
12.0	1.5	490000.0	0.1	52.5	1369.0
13.0	1.0	620000.0	620000.0	50.0	1375.0
14.0	1.5	620000.0	620000.0	47.5	1383.0
15.0	1.5	500000.0	500000.0	45.0	1390.0
16.0	1.0	500000.0	500000.0	42.5	1396.0
17.0	1.5	515500.0	515500.0	40.0	1404.0
18.0	1.5	580000.0	1160000.0	37.5	1410.0
19.0	1.0	696000.0	1045000.0	35.0	1418.0
20.0	1.5	644000.0	1610000.0	32.5	1425.0
21.0	1.0	644000.0	773000.0	30.0	2339.0
22.0	1.0	637000.0	1456000.0	27.5	2403.0
23.0	1.8	683000.0	2400000.0	25.0	2438.0
24.0	2.0	618000.0	2236000.0	22.5	2448.0
25.0	1.5	786000.0	1965000.0	20.0	2569.0
26.0	1.5	760000.0	2020000.0	17.5	2620.0
27.0	1.5	1082000.0	1623000.0	15.0	2677.0
28.0	1.0	1418000.0	1918000.0	12.5	2766.0
29.0	1.0	773000.0	1773000.0	10.0	2778.0
30.0	2.0	871000.0	1871000.0	7.5	3302.0
31.0	4.0	1750000.0	1050000.0	5.0	3317.0
32.0	5.0	722000.0	515000.0	2.5	3368.0

1993	11	1	1.0	1.0	5.0	2.0	-999.0	150.0	0		
1993	11	2	1.0	1.0	5.0	2.0	-999.0	150.0	0		
1993	11	3	1.0	1.0	5.0	2.0	-999.0	150.0	0		
1993	11	4	1.0	1.0	5.0	2.0	-999.0	150.0	0		
1993	11	5	1.0	1.0	5.0	2.0	-999.0	150.0	0		
1993	11	6	1.0	1.0	5.0	2.0	-999.0	150.0	0		
1993	11	7	1.0	1.0	5.0	2.0	-999.0	150.0	0		
1993	11	8	1.0	1.0	5.0	2.0	-999.0	150.0	0		
1993	11	9	1.0	1.0	5.0	2.0	-999.0	150.0	0		
1993	11	10	1.0	1.0	5.0	2.0	-999.0	150.0	1	0.1	
1993	11	11	1.0	1.0	5.0	2.0	-999.0	150.0	0		
1993	11	12	1.0	1.0	5.0	2.0	-999.0	150.0	0		
1993	11	13	1.0	1.0	5.0	2.0	-999.0	150.0	0		
1993	11	14	1.0	1.0	5.0	2.0	-999.0	150.0	2	1.2	
1993	11	15	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	0		
1993	11	16	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	0		
1993	11	17	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	3	0.3	1.5
1993	11	18	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	0		
1993	11	19	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	0		
1993	11	20	-999.0	-999.0	-999.0	-999.0	-999.0	-999.0	0		
1993	11	21	2.0	-6.0	50.0	0.0	-999.0	-999.0	0		
1993	11	22	0.5	0.0	25.0	3.3	-999.0	-999.0	0		
1993	11	23	-6.5	-15.0	25.0	3.3	-999.0	-999.0	0		
1993	11	24	-8.0	-4.0	20.0	0.0	-999.0	-999.0	0		

appendix b

RIVICE

APPENDIX B
RIVICE

1.0 TECHNICAL DESCRIPTION - ICE COVER EVOLUTION

The theoretical formulations used in the ice cover evolution model, as well as the calculation procedure, are summarized below:

1.1 Leading Edge Progression

Accumulation of incoming ice at the leading edge(s) of the ice cover(s) can be represented in RIVICE by one of two optional methods :

(i) Juxtaposition of the ice according to the following relationship (Pariset, 1966; Michel, 1971)

$$\frac{V}{\sqrt{gH}} = \sqrt{2\frac{(\rho-\rho_i)}{\rho}(1-e)\frac{t}{H}}\left(1-\frac{t}{H}\right)$$

Where :

V	=	Mean velocity of flow in open water upstream of leading edge (m/s)
H	=	Mean hydraulic depth in open water upstream of leading edge (m)
ρ	=	Density of water (kg/m^3)
ρ_i	=	Density of ice (kg/m^3)
e	=	Porosity of ice pans/floes at the leading edge (i.e. ratio of volume of voids filled with water to the total volume of the ice pan -user specified)
t	=	Thickness of ice accumulation (m) which will form with the combination of V and H; this relationship only holds for **t/H** ratios less than ⅓, which is the limiting condition for juxtaposition.

(ii) It has been observed that in conditions where ice approaches the leading edge in a steady stream of pans or as a continuous blanket of slush ice, that the classic leading edge stability equation as defined by (i) does not apply. The tendency of drawdown of individual ice fragments is significantly reduced by the protection provided by the continuous stream of surface ice. The user can represent this case, which results in a leading edge thickness of 0.15 m. Further thickening downstream of this edge would occur if shoving is shown to be necessary, as described in subsequent parts of this section. No submergence of the approaching ice under the leading edge is permitted under this option, and all ice accumulates as an advancing thickness of 0.15 m. The user would apply this approach if, in his/her judgement, the conditions of the ice approaching the leading edge would cause this to occur.

Note : A third option which involves the equation of stability of individual ice blocks developed by Ashton (1986), should be considered to be added in future versions of RIVICE. It has not been included at this point because of uncertainty of representing leading edge thickness in the case where the blocks underturn.

1.2 Thickening of Cover Due to Hydraulic Forces

An ice cover on flowing water is subjected to hydraulic forces which can cause deformation and thickening. The classic means of analyzing this has been with the "bell-curve" developed by Pariset, Hausser and Gagnon (1966), However, two disadvantages arise from direct use of the bell-curve:

- It can only represent the ice cover thickness and stability at a distance of several river widths from the leading edge.
- It represents the stability of a constant width channel, with constant velocity, etc., which rarely occurs.

A refinement to this concept which avoids the difficulties cited above has been used in RIVICE and is suited to computation by a computer program. It involves the incremental summation of computed forces on the ice cover in a step-mode beginning from the leading edge and advancing from cross-section to cross-section in the downstream direction. It computes:

(i) Forces exerted by the flowing water on the ice cover :

- Hydrodynamic thrust on the leading edge (Michel, 1971)

$$F_t = \left(1-\frac{d}{H}\right)^2 V_u^2 BH\frac{\gamma}{2g}$$

Where :

F_t	=	Hydrodynamic thrust of the flow (N)
H	=	Depth of water upstream of leading edge (m)
d	=	Depth of flow under the leading edge (m)
V_u	=	Velocity under the leading edge (this is a mean value across the width of the channel, in m/s)
B	=	Width of ice cover (m)
γ	=	Specific weight of water (9800 N/m^3)
g	=	Acceleration due to gravity (m/s^2)

- Hydraulic drag of the flow on the ice under-surface (Michel, 1971) :

$$F_d = \left(\frac{\gamma\, d_t s n_i^{1.5}}{2 n_c^{1.5}} \right) A_{iw}$$

Where :

F_d	=	Hydraulic frictional drag force (N)
γ	=	Specific weight of water (9800 N/m^3)
S	=	Slope of hydraulic grade line
n_i	=	Manning's roughness coefficient of the ice under-surface
n_c	=	Manning's roughness coefficient of the composite cross section
d_t	=	Depth of flow under the ice cover (m)
A_{iw}	=	Under-surface area of ice exposed to flow (m^2)

- The component of weight of the ice cover and the water contained in its voids, acting along the hydraulic gradient :

$$F_w = \gamma_i V_o S$$

Where :

F_w	=	Gravitational force acting along the channel (N)
γ_i	=	Specific weight of ice (9020 N/m^3)
V_o	=	Volume of ice cover (including voids infilled with water and voids above the phreatic line) (m^3)
S	=	Slope of hydraulic grade line

(ii) Force shed to the river banks includes cohesion of the ice cover to the banks and friction of the ice cover against the river banks.

The cohesion expression (Pariset, 1966) is given as

$$F_c = 2ctL$$

Where :

F_c	=	Force of cohesion of ice to two river banks (N)
c	=	Cohesion per unit area of ice/bank interface (Pa)
t	=	Average thickness of ice cover between cross sections (m)
L	=	Distance between cross sections (m)

The hydraulic forces exerted on the ice cover in the stream-wise direction create stresses in the ice which are spread laterally towards the riverbanks. The lateral stress results in a reaction of static friction at the bank, which acts as a stabilizing influence on the cover.

From Pariset (1966) :

$$F_f = 2ftLK_1 \tan\phi$$

Where :

F_f	=	Friction force on the ice along the river bank (N)
f	=	Accumulative stress in the ice cover in the direction of flow (Pa)
K_1	=	A coefficient equal to the ratio of lateral stress to longitudinal stress in the ice cover (a ratio less than or equal to 1.0)
tan ϕ	=	Tangent of angle of friction of ice/bank interface
L	=	Distance between cross-sections (m)
t	=	Average ice thickness between sections (m)

As the calculation proceeds downstream, the stress in the ice cover is determined from

$$S_i = \frac{(F_t + F_d + F_w - F_c - F_f)}{tW}$$

Where :

S_i	=	Stress in the ice cover (Pa)
F_t,etc	=	As defined above
t	=	Ice thickness (m)
W	=	Ice width (m)

The accumulation of stress in the ice cover is computed in increments of 10% of length between the mesh points. Load is shed to the banks in each increment according to the average streamwise stress in the increment. The tenth increment (i.e. the downstream mesh point) thereby properly reflects the accumulation of hydraulic loading which is reduced by the bank resistance.

If the stress exceeds the maximum resistance of the ice cover, shoving or telescoping of the ice must occur to attain the minimum required thickness. The resistance is determined from Pariset (1966):

$$F_{ir} = \gamma_i \left(1 - \frac{\gamma_i}{\gamma}\right) \frac{t^2 W}{2} K_2$$

Where :

F_{ir}	=	Internal resistance of ice cover (N)
K_2	=	A coefficient greater than or equal to 1.0, a Rankine passive coefficient in soil mechanics
t	=	Ice thickness (m)
W	=	Ice width (m)
γ_i	=	Specific weight of ice (9020 N/m^3)
γ	=	Specific weight of water (9800 N/m^3)

The values of K_1, tan ϕ, and K_2 are key components of this procedure. The value of each is not known precisely, but it has been shown that the combination :

$$\mu = K_1 K_2 \tan\theta$$

is normally between 1.0 and 1.60 (Acres, 1986; Pariset, 1966; Beltaos, 1983; Beltaos, 1988). The value of the individual factors K_1, K_2, tan ϕ is left to the discretion of the user, with default values of .18, 8.7 and .9, respectively.

It should be noted that some investigations show "μ" as including a term (1-e) where "e" is the ice cover porosity. However, the original derivation (Pariset, 1961 and 1966) did not include this term, and it is not proposed for RIVICE.

The simulation of a shove is done by :

- Thickening of the ice cover at an unstable location (i.e. stress in ice cover exceeds its internal resistance) to achieve a stable thickness; this may be restricted in any given time step by the maximum rate of movement of the ice as described below.

- Reduction in ice volume at the leading edge to be equivalent to the volume required to thicken at the unstable location (a downstream "recession" of the leading edge results).

The volume of ice which is supplied to thicken the cover at an unstable location is limited by the maximum rate of movement of the ice cover, estimated to have a maximum speed equal to the average flow velocity:

$$V_M = V_s t_s W_s \Delta t$$

Where :

V_M	=	maximum volume which can shove to an unstable location during a given time step, (m^3)
V_s	=	mean flow velocity at the unstable cross section (m/s)
t_s	=	ice thickness at unstable cross section before shoving occurs (m)
W_s	=	width of ice cover at unstable location (m)
Δt	=	time step (seconds)

This has been introduced because there must be an upper limit to the volume of ice which can move in a shove during a time step. It is believed that the local flow velocity is an indicator of this. The sensitivity of the simulation of shoves should be evaluated in future testing of RIVICE.

1.3 Cover Thickness Changes Due to Deposition/Erosion

If the user-selected algorithm for leading edge stability (see (1) above) indicates that ice will be drawn under with the flow, then ice transport under the cover is considered by the program. The ice-in-transport can deposit at locations where the velocities are low and cause a hanging dam. The characteristics of the deposition process are not well defined, and three options are available to the user to represent this phenomenon :

(i) A maximum velocity of deposition, whereby the incoming ice would deposit until the maximum velocity is exceeded, and then pass downstream to the next point of low velocity.

(ii) A treatment of the problem by a sediment transport approach, using the Meyer-Peter equation, which when adapted to the ice covered condition (Acres, 1980) is

$$3281\frac{v^2}{c^2} = 12.3d_i + 0.84q_u^{\frac{2}{3}}$$

Where :

V	=	mean velocity under ice cover (m/s)
C	=	Chezy roughness coefficient for water passage ($m^{1/2}/s$)
d_i	=	characteristic dimension of ice fragments (m)
q_u	=	ice discharge per unit width under the cover weighed under water with apparent density 0.08

The main difficulty of this method is the determination of the appropriate dimension "d_i" for the problem being analyzed. The transport rate computed by the Meyer-Peter method will be no more accurate for ice transport than it is for sediment transport. However, it does acknowledge the concept that ice will have more tendency to deposit at higher velocities if the incoming ice volumes are high.

(iii) A densimetric Froude number (Tesaker, 1975)

$$F_r = \frac{V}{\sqrt{gH\frac{(\rho-\rho_i)}{\rho}}}$$

Where :

F_r	=	maximum Froude number at which deposition of ice will occur (user selected)
V	=	mean velocity of flow (m/s)
g	=	gravitational acceleration (m/s^2)
H	=	hydraulic mean depth below the ice under-surface (m)
ρ_i, ρ	=	density of ice and water respectively (kg/m^3)

d_i = dimension of ice particle (m)

Transport of ice under the ice cover is tracked by RIVICE from time period to time period. Movement is estimated to occur at the following velocity :

$$V_{ice} = V_{water} \times VFACTR$$

Where :

V_{ice} = velocity of ice-in-transport at a specific location (m/s)
V_{water} = mean velocity of flow at that cross-section (m/s)
VFACTR = a user specified factor which gives the ratio of ice movement speed to the mean velocity of flow

Under some conditions such as increasing flows or large increases in ice thickness due to shoves, high velocities can occur under the ice cover. These high velocities would tend to erode the ice under-surface and pass the entrained ice downstream. Two means of representing this are included in the logic of RIVICE :

(i) A simple specification of the mean velocity above which erosion will occur.

(ii) Calculation of tractive force at the ice/water interface, using the formula

$$F_d = \gamma RS$$

Where :

F_d = tractive force (Pa)
γ = specific weight of water (N/m^3)
R = hydraulic radius of flow under ice (m)
S = friction slope

The user would specify the maximum allowable value, and erosion would be simulated by the model if it is exceeded at any cross section.

The erosion of the ice cover in both cases would be uniform over the bottom of the ice cover. This is a simplified representation of the real phenomenon whereby erosion occurs preferentially in parts of the cross section where the velocity is highest, and can result in grounding of ice in shallow areas.

Erosion is not allowed to completely eliminate the surface ice at any location during any time step. The ice cover thinning due to erosion is not allowed to cause thicknesses less than 0.15 m.

2.0 PROGRAMMING INSTRUCTIONS

The programming manual for RIVICE concludes by presenting programming instructions for the ice cover evolution module for use in coding, model testing and for subsequent additions/modifications.

2.1 Ice Cover Evolution

This module is lengthy and complex because of the difficulty in representing in mathematical terms the complicated process of ice cover formation. The equations and methodology are described in Section 9 of Volume II, and have been programmed as four separate subroutines:

(i) "ICECE" - this is a central subroutine which calls three other subroutines in which the detailed calculations are performed. "ICECE" contains no calculations. The logic is simple and does not require a flowchart. The code is in Volume IV.

(ii) "ICECEA" - this subroutine contains the logic which addresses the conditions at the leading edge of the ice cover. This portion of The Evolution Module has been called "Block A", and its overall configuration is shown in the global flowchart of Figure 5.8.1. The detailed flowcharts for each part of Block A (ie. "ICECEA") are given at the end of this section. Due to the complexity of this and the other parts of the Ice Evolution Module, it has been accompanied by a series of notes which are intended to clarify the logic presented in the flowcharts. The code for "ICECEA", and for the other subroutines is in Volume IV.

(iii) "ICECEB" - this subroutine addresses the movement of ice submerged at the leading edge, and the movement of ice-in-transit under the ice cover during the time step. This subroutine contains both Blocks B and C, whose general framework is described in global flowcharts of Figures 5.8.2 and 5.8.3. The detailed flowcharts and explanatory notes are at the end of this section.

(iv) "ICECED" - this subroutine considers the forces exerted on the ice cover and the shoves or telescoping of the ice cover which may result from this. This is termed "BLOCK D" of the Ice Evolution Module, and its overall logic is summarized in Figure 5.8.4. As for the other blocks, detailed flowcharts and explanatory notes are at the end of Section 5.8.

Notes - Sub-Block A-1

A-1-1 - Initialize required variable

- N1 is the first cross-section downstream of the leading edge with a full ice cover.

- Initialize water levels and ice-in-transit for all cross-sections.

A-1-2 - Check whether N1 is the upstream-most cross-section in the reach.

- Check of this reach is the furthest upstream in the system.

A-1-4 - Set the submersed volume at the leading edge to zero, and pass through to Sub-Block A-6.

A-1-5 - The next upstream reach has been located. Set N2 equal to the first cross-section in that reach.

A-1-9 - N2 is set to the next cross-section number within the same reach as N1.

A-1-10 - Set parameters for calculations of leading edge progression (XFROZE = existing leading edge length within cross-section N2; TLE - existing leading edge thickness at start of time period).

Notes - Sub-Block A-2

A-2-1 - This series of statements computes the friction slope, "S1", and the energy level, "TMPH1" of cross-section "N1".

A-2-2 - This series of statements sets a hypothetical ice cover with a thickness of one third the hydraulic mean depth on cross section "N2", and computes the resulting energy and water level in a standard step trial calculation.

A-2-3 - Check wether the correct energy level at cross-section N2 has been attained.

A-2-4 and A-2-5 - Counter to monitor whether standards step iteration is converging (non-convergence indicated critical flow, with obvious impossibility of leading edge progression).

A-2-6 - Re-estimate trial water level at cross-section N2.

A-2-7 - Begin trial-and-error calculation of what minimum water level would be required with an ice thickness of 1/3 hydraulic mean depth.

A-2-8 - Compute hydraulic mean depth (HMD2) at cross-section N2 for water level EL2LES.

A-2-8A - If LEOPT = 3 (i.e. case in which a continuous train of ice pans or floes is coming into the leading edge), then skip the following.

A-2-8B - If LEOPT = 1 or 2, compute the minimum flow area required for ice cover progression with an ice thickness of 1/3 the hydraulic mean depth, using function "LEAD".

A-2-9 - Check whether satisfactory convergence has been attained.

A-2-10 - Convergence has not been attained; revise water level estimate to calculate water depth at leading edge.

A-2-11 - Check whether the water level is high enough for minimum condition of leading edge stability. If it is, pass to Sub-Block A-3 to calculate the leading edge thickness.

A-2-12 - Approach velocity is too high for advancement; set volume submersed equal to incoming ice volume plus any previously existing ice volume in section "N1"; then pass to Sub-Block A-6.

Notes - Sub-Block A-3

A-3-1A	-	If LEOPT $\neq$ 2, pass to A-3-1C.
A-3-1B	-	Set leading edge thickness "TPROG2" to 0.15 m.
A-3-1C	-	Initialize variables for an iterative solution of the water level at cross-section N2 which satisfies the Bernoulli equation between N1 and N2, and the leading edge stability equation (applied through function "LEAD"). Sketch A-3-1 shows graphically the solution technique.
A-3-1D	-	Set EL2 to current water level.
A-3-1E	-	This series of calculations computes the energy level at N2 for a given ice thickness.
A-3-1F	-	Check whether a convergence on the energy level has been attained.
A-3-1G	-	Not acceptable convergence, estimate a correction to the water level at cross-section N2.
A-3-2	-	This series of calculations computes the energy level at N2 for a given ratio of t/H where "t" is the assumed ice thickness and H is the hydraulic mean depth. It is part of an iterative solution of the Bernoulli equation between N1 and N2.
A-3-3	-	Check whether a convergence on the energy level has been attained.
A-3-4	-	Not acceptable convergence, estimate a correction to the water level at cross-section N2.
A-3-5	-	Initialize variable for solution to the leading edge condition.
A-3-6	-	This series computes the minimum water level required for the assumed t/H ratio (t is ice thickness, H is depth of flow).

A-3-7 - Check whether convergence has been attained in solution of leading edge stability for the given t/H ratio.

A-3-8 - No convergence, re-estimate water level at N2 and cycle back through iteration.

A-3-9 - Convergence attained; now check if Bernoulli solution equals leading edge solution.

A-3-10 - It does not, so make a re-estimate of the t/H ratio and cycle back through the calculations. Sketch A-3-1 demonstrates the solution technique graphically.

A-3-11 to A-3-15 - Convergence attained between Bernoulli solution and leading edge solution. Now determine the stable thickness of ice and the volume if it were to extend completely through the length of cross-section N2. Compute the volume of ice, VP2, which corresponds to this hypothetical extension. Then pass to Sub-Block A-4.

Notes - Sub-Block A-4/A-5

A-4-1 - Compute the total ice ("VACT") at the leading edge including the incoming volume plus the partial coverage of N2 which existed at the start of the time period. See Sketch A-4-1 for a schematic explanation.

A-5-1 - Check whether there is enough ice to allow the ice cover to pass completely through the length of cross-section N2. If there is not enough, pass to Sub-Block A-9.

A-5-2 - If there is enough, set the "tentative" location of the leading edge ("XFRZ1T"), and the "tentative" leading edge thickness ("TLE1T"), and pass to Sub-Block A-6.

Notes - Sub-Block A-6

A-6-2 - Set the end-of-period parameters for leading edge, and then pass to Block B.

Notes - Sub-Blocks A-9 to A-12

A-9	-	Set variable in preparation for passing to next upstream cross-section. Deduct the total potential ice volume "VP2" from the known inflow volume; the remainder passes to the next upstream cross-section to assess its accumulation there.
A-10-1	-	Check if the new N1 (old N2) is the most upstream cross-section in this reach.
A-10-2	-	Check if this reach is the furthest upstream in the system being simulated. If so, pass into Sub-Block A-6 to set variables.
A-11-1	-	N1 has been found not to be furthest upstream section in this reach. Check if there are any more ice segments upstream. If not, pass into Sub-Block A-11-4 to set indices of next cross-section N2.
A-11-2	-	Check if the next upstream cross-section is the downstream **and A-11-3**end of the next ice segment. If not, pass into Sub-Block A-11-4 to set indices of next cross-section N2. If so, pass into Sub-Block A-11-3 to set leading edge parameters and proceed to one Block "B".
A-12-1	-	Select the next upstream section to N1 as being N1-2.
A-12-2 and A-12-3	-	Check if the next upstream cross-section is the downstream end of the next ice segment.
A-12-4	-	Set leading edge parameters and pass into Sub-Block A-6-2.
A-12-5	-	Determine the length of reach characterized by cross-section N2.

Notes - Function "LEAD"

This function is formulated to compute the required flow area at the leading edge of the ice cover, given the following:

Q	-	discharge at the leading edge (m^3/s)
HMD	-	hydraulic mean depth (m)
POROS	-	porosity of ice pans at the leading edge
TOVERH	-	ratio of ice thickness to hydraulic mean depth.

The basis of the calculation is described in Volume II.

Notes - Sub-Block B-1

The objective of Block B is to permit the settling out, or deposition, from the ice-in-transit bank during the time period "dt", without yet considering the movement of the ice-in-transit (reserved for Block C).

B-1-1 to B-1-3	-	Sub-Block B-1 is a single loop which covers all cross-sections in the system but ignores cross-sections which are not within the ice segment being addressed at this time (ice segment number "NISEG"). This Sub-Block requires a prior identification of the ice segment number to which each cross-section "belongs", through the vector NICEST(L), L = 1, NSNTOT.
B-1-4	-	Is cross-section "N1" located in the last reach?
B-1-5	-	Is there more than one reach being simulated and is "N1" the last cross-section in a reach? If yes, return to loop B-1-1.

Notes - Sub-Blocks B-2 to B-7

B-2-1 and B-2-2	-	Loop through all reaches and check if "N1" is the last cross-section in each? If yes, return to loop B-1-1.
B-2-3	-	Set length of reach characterized by cross-section "N1".
B-2-4	-	The program branches at this point to the algorithm associated with the user-specified option of ice deposition. This can be one of: 1. maximum velocity criterion

2. a Meyer-Peter relationship based on a sediment transport analogy
3. a maximum Froude number.

Details of these algorithms are given in Volume II.

B-3-1 - In this case, Option 1 has been chosen by the user and the velocity at that cross-section is compared to the maximum velocity for deposition. If it exceeds the user-specified threshold value ("VDEP") then the program passes to Sub-Block B-8 to assess the potential for ice cover erosion. If it is below the threshold value, ice can be deposited, and it passes into Sub-Block B-4.

B-3-2 - Check to determine first whether there is any ice-in-transit ("VTRNT(N1)") at this cross-section, N1. If there is not, the routine can skip directly back to B-1 to check the next cross-section.

B-4-1 - This series of statements computes the maximum volume of ice which could be accommodated if deposition occurred up to the maximum velocity "VDEP".

B-4-2 - This is a check to determine whether the maximum deposition volume is greater than the ice-in-transit volume at that cross-section.

B-4-3 - If the potential deposition exceeds the volume available from the in-transit bank, the deposition amount is pro-rated to correspond exactly with the volume-in-transit ("VTRNT").

B-4-4 - If the potential deposition ("VOLDEP") is less than the available volume, the ice-in-transit bank is debited by the maximum potential volume.

B-4-5 - The end-of-period ice thickness is modified to correspond to B-4-4, and the routine returns to Sub-Block B-1 to cycle to the next cross-section.

B-4-6 - The ice-in-transit volume ("VTRNT") for this section is set to zero.

B-5-1 - This sub-block is invoked by the user's specification of the Meyer-Peter analogy in estimating ice transport under a stationary cover (i.e. the variable "DEPOPT" has been specified as "2").

- The initial group of statements computes various factors required by the Meyer-Peter relationship which determines the velocity below which ice will be deposited at the ice cover/water interface. These are:

QICEW	-	discharge of ice per unit width ($m^3/s/m$)
HR1	-	hydraulic radius (m)
ENCO1	-	Manning's n-value of composite riverbed/ice cover
VMEYER	-	velocity below which ice will deposit at this location (m/s). The computation of this requires the input of the average ice particle diameter in metres ("DIAICE").

B-5-2 - A check is made here whether the actual velocity of flow is greater than the threshold velocity computed by the Meyer-Peter analogy. If it is, then ice deposition is impossible and the logic must branch to Sub-Block B-8.

B-5-3 - The velocity is less than the Meyer-Peter threshold value so deposition will occur. "VOLDEP" is computed as the maximum volume which can be deposited and which will drive the velocity under the deposit, up to exactly the threshold velocity computed above.

B-5-4 - Compare the maximum potential deposit volume with the volume in transit at this location.

B-5-5 - The deposit potential exceeds the available supply, and all the ice-in-transit can be deposited at this location. Ice thickness is adjusted accordingly, and the end of period volume in transit is set to zero. The logic then returns to Sub-Block B-1.

B-5-6 - The deposit potential is less than the available supply of ice, so only part of the ice in transit can be deposited. The trial end of period ice in transit volume and ice thickness are adjusted. The program then returns to Sub-Block B-1.

B-6-1 - A densimetric Froude criterion has been selected by the user (see algorithm presented in Volume II. First, the densimetric Froude number is computed for that cross-section for the estimated end-of-period water level and beginning-of-period ice thickness.

B-6-2 - This is the comparison between the computed densimetric Froude Number ("FROUDE") and the user-specified maximum ("FRMAX"). If FROUDE>FRMAX, no deposition can occur, and the subroutine cycles to Sub-Block B-8 to check for ice cover erosion due to high velocity.

B-7-1 - Deposition is possible, and an interactive procedure is required to determine the new ice thickness which satisfies the limiting densimetric Froude criterion. The estimate of hydraulic mean depth is initialized at the actual value previously computed in B-6-2.

B-7-2 - The hydraulic mean depth is re-calculated based on the velocity computed for the limiting Froude condition. The Froude number is re-computed ("FRDEST").

B-7-3 - This is a check on the comparison between the target Froude number ("FRMAX") and the re-computed actual value ("FRDEST").

B-7-4 - If there is not an acceptable match at B-7-3 (i.e. not within 1%), the hydraulic mean depth is re-estimated and the computation in B-7-2 is re-invoked.

B-7-5	-	There is an acceptable match, and the maximum potential volume of ice deposition to satisfy "FRMAX" is computed. The calculation now cycles through steps B-4-2 to B-4-5, as described above for the limiting velocity condition.
ZSTRT (NSNTOT)	=	Water level when a border ice cover begins to form at a cross-section at time "t+dt", m.
ZT (NSNTOT)	=	Water surface elevation at time "t", m.
ZTT (NSNTOT)	=	Water surface elevation, at time "t + dt".
ZZK1TAN	=	Coefficient relating transfer of stress to river bank.
ZZK2	=	Coefficient of ice strength analogous to passive conditions in soil mechanics.
ZZM	=	Coefficient to relate degree days of freezing to border ice growth.

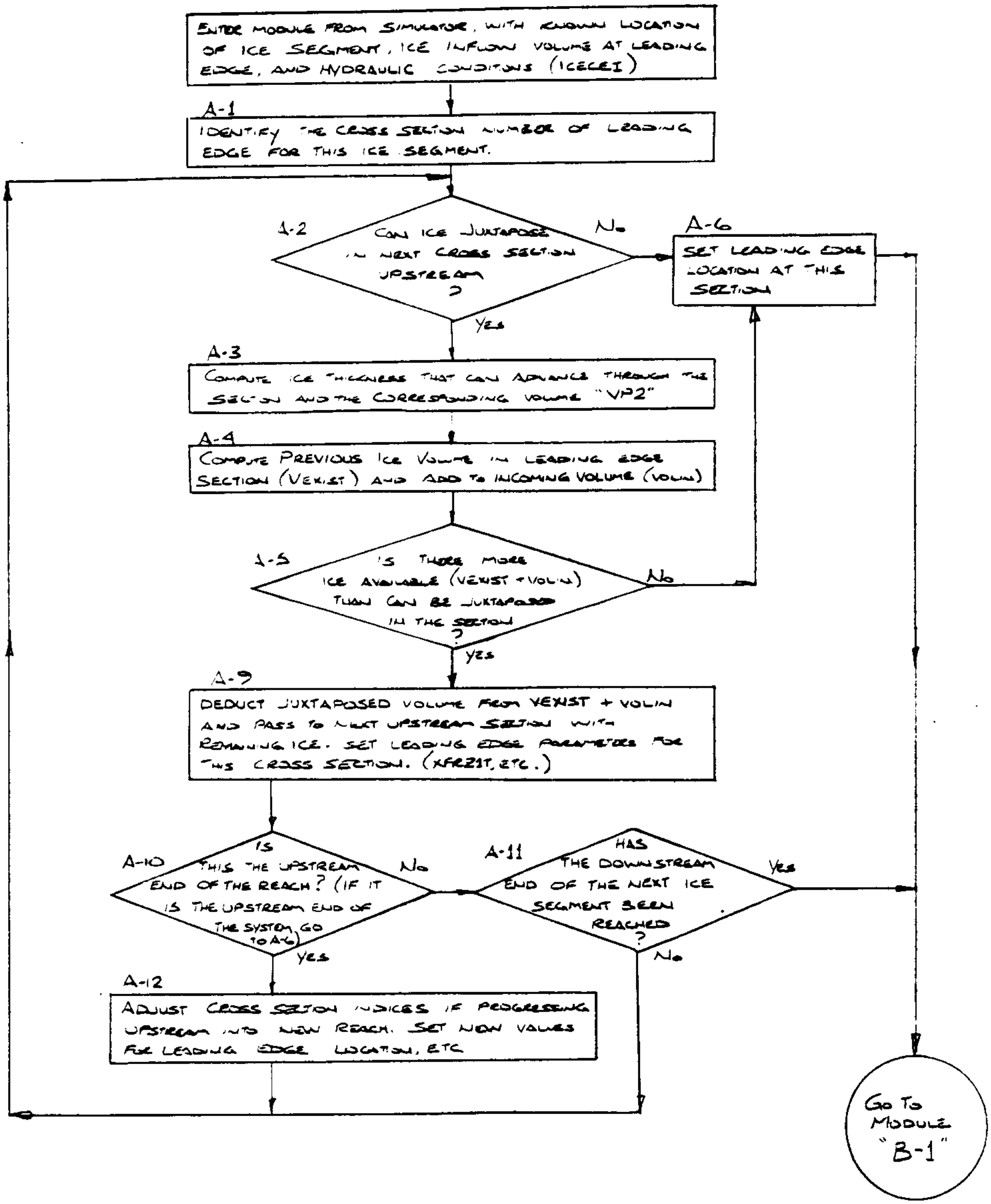


FIGURE 5.8.1

"RIVICE" MARCH 1992
ICE EVOLUTION MODULE
BLOCK A - LEADING EDGE ANALYSIS
GLOBAL FLOWCHART

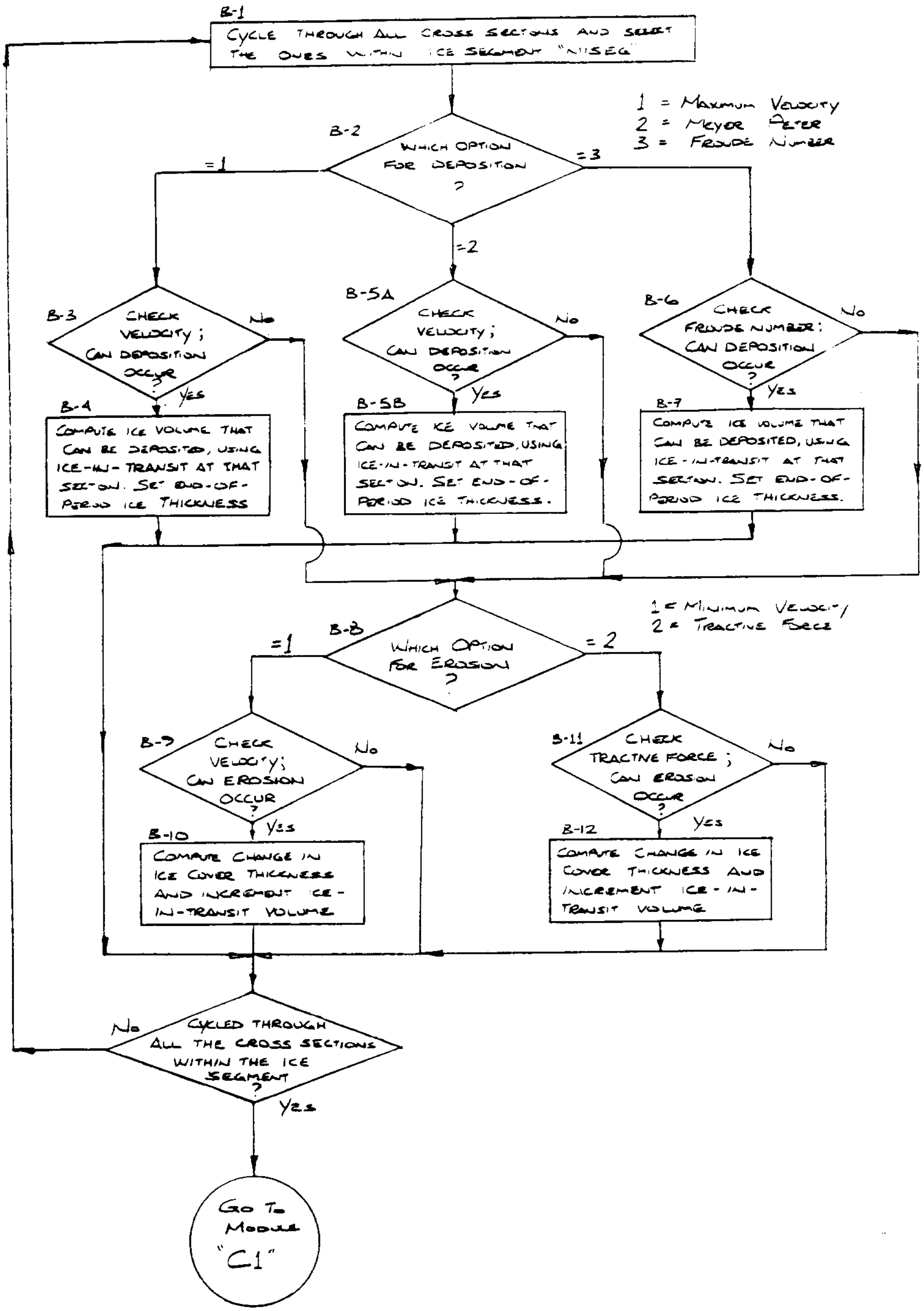


FIGURE 5.8.2

"RIVICE" MARCH 1992
ICE EVOLUTION MODULE
BLOCK B - DEPOSITION AND EROSION
GLOBAL FLOWCHART

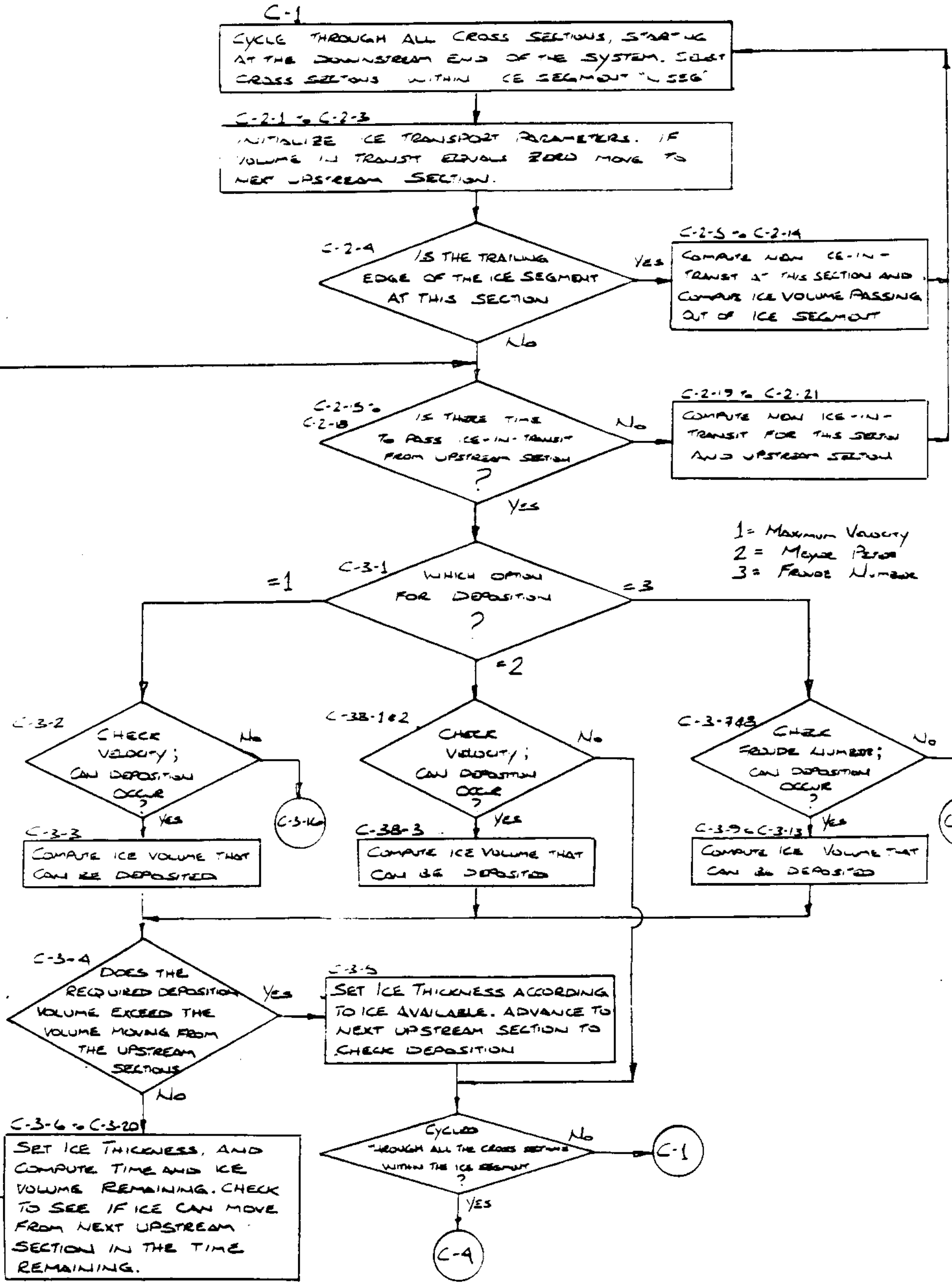


FIGURE 5.8.3

"RIVICE" MARCH 1992
ICE EVOLUTION MODULE
BLOCK C - ICE TRANSPORT
SHT # 1/2
GLOBAL FLOWCHART

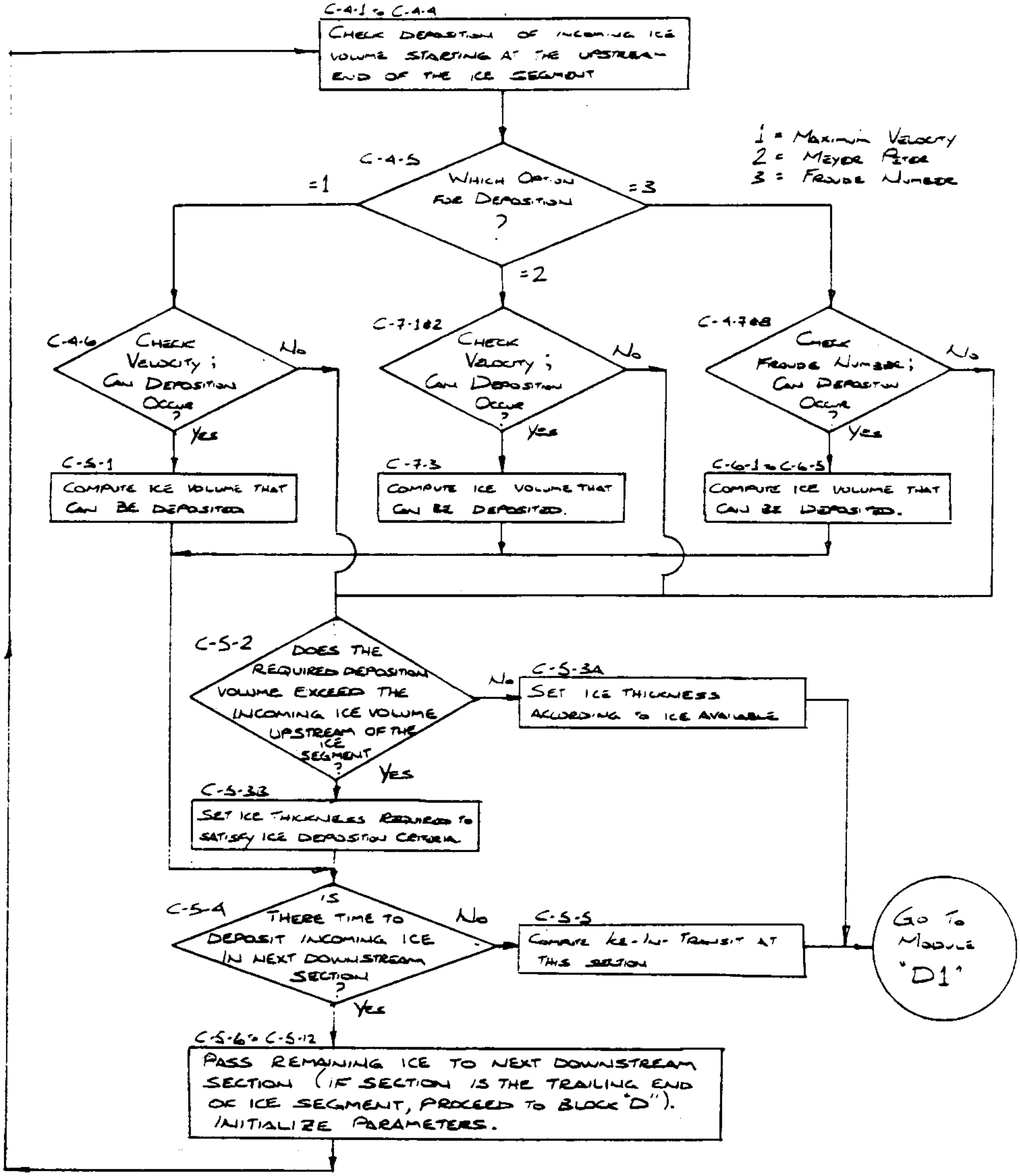


FIGURE 5.8.3

"RIVICE" MARCH 1992
ICE EVOLUTION MODULE
BLOCK C - ICE TRANSPORT
SHT # 2/2
GLOBAL FLOWCHART

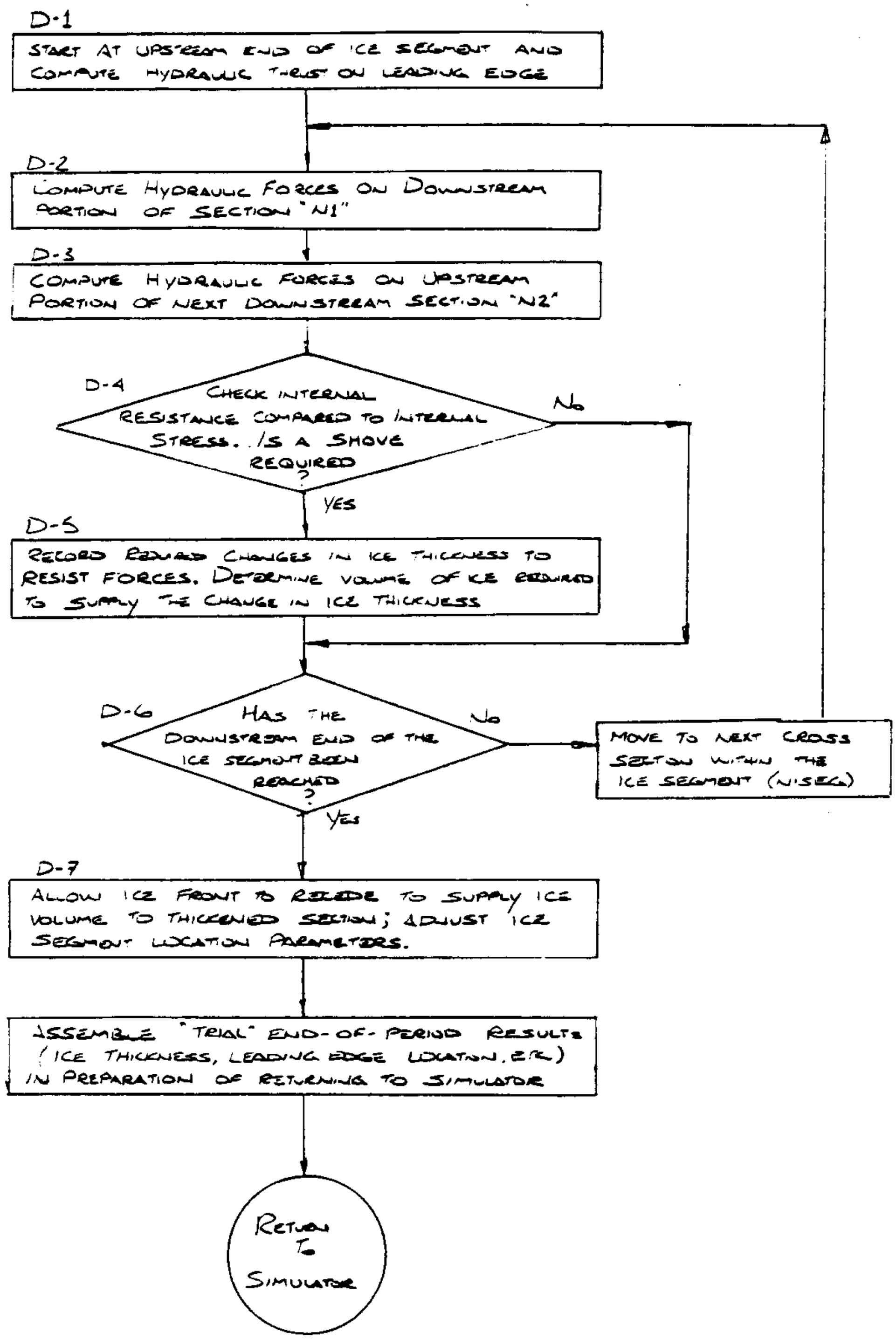
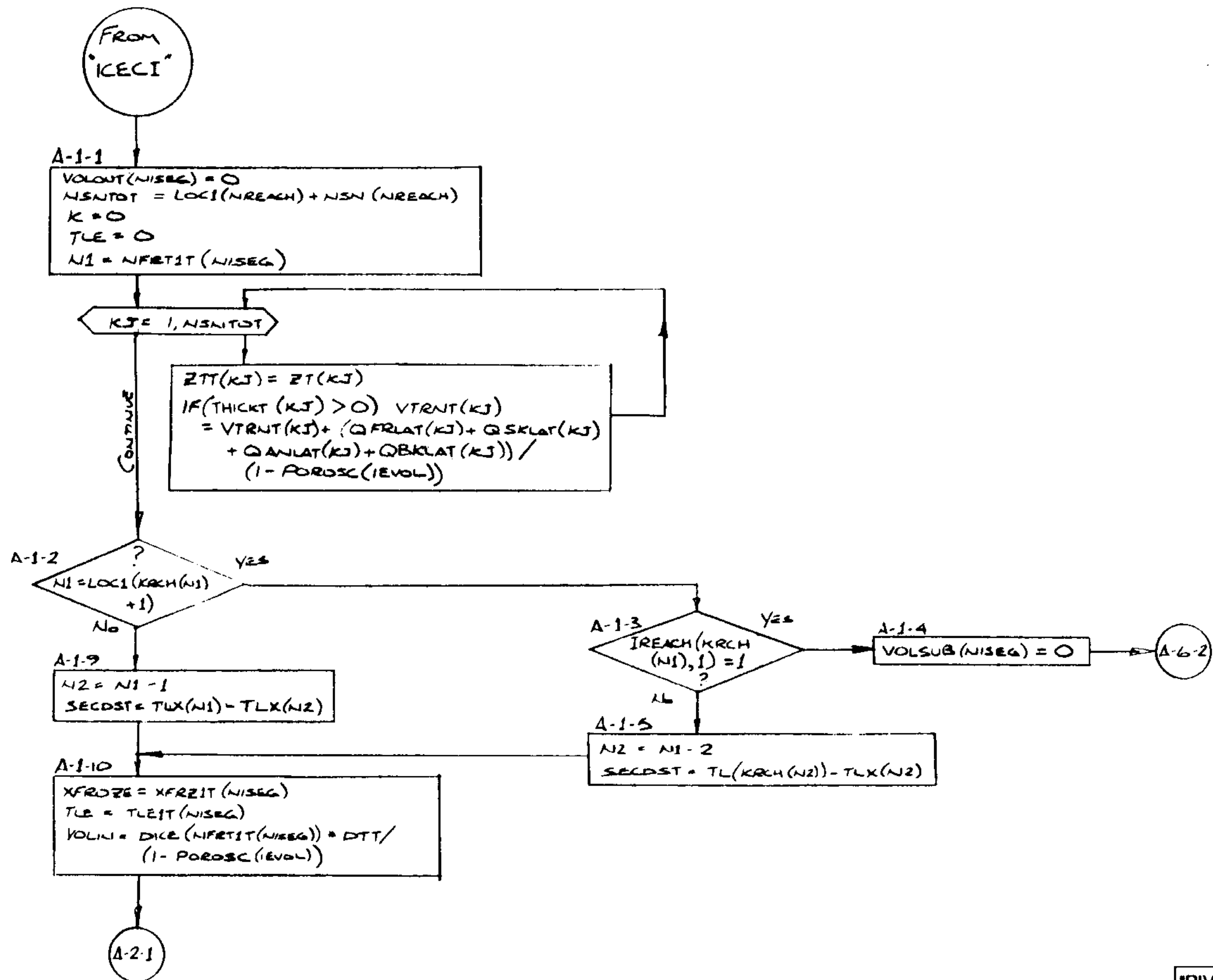


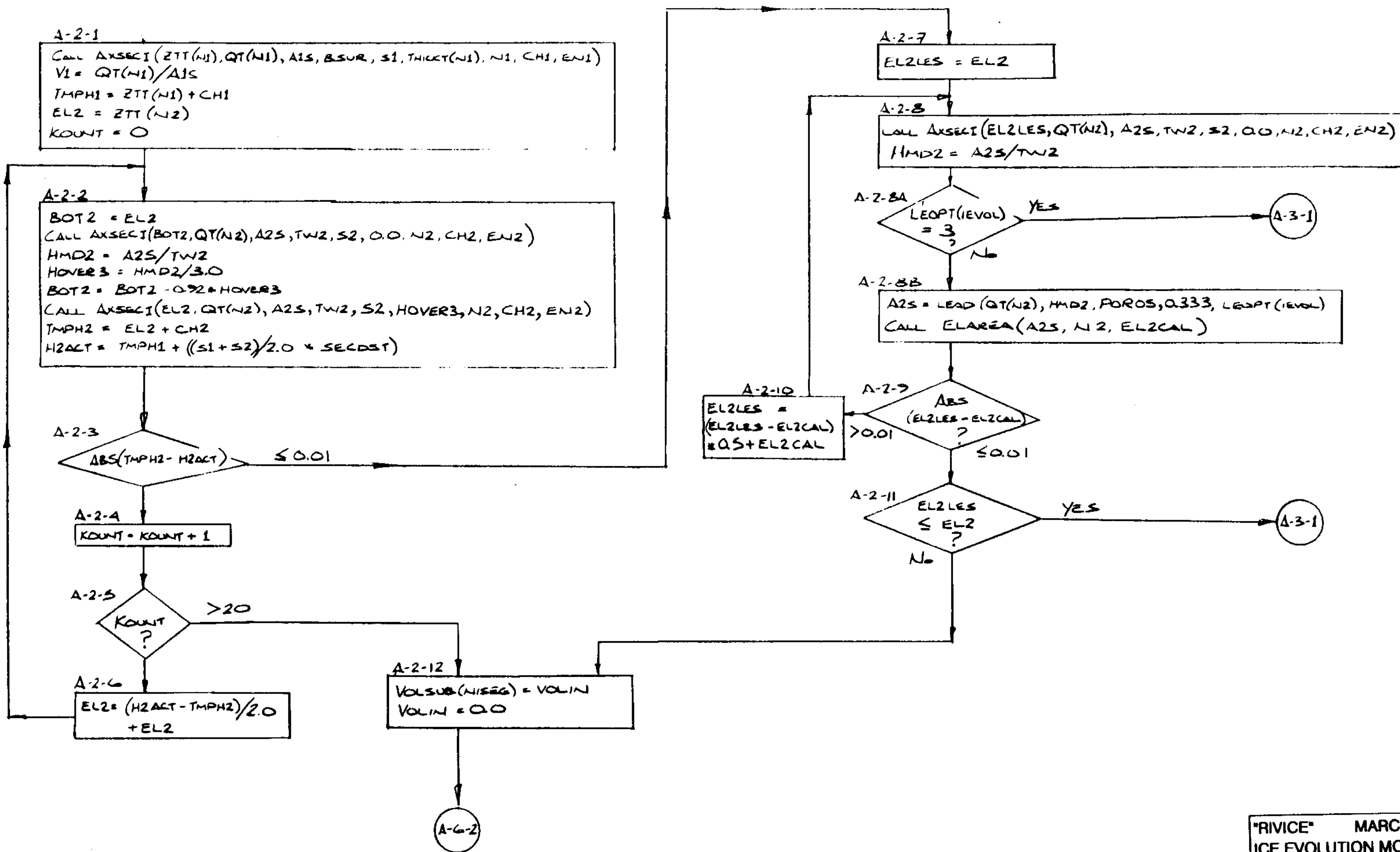
FIGURE 5.8.4

"RIVICE" MARCH 1992
ICE EVOLUTION MODULE
BLOCK D - FORCES / SHOVES
GLOBAL FLOWCHART



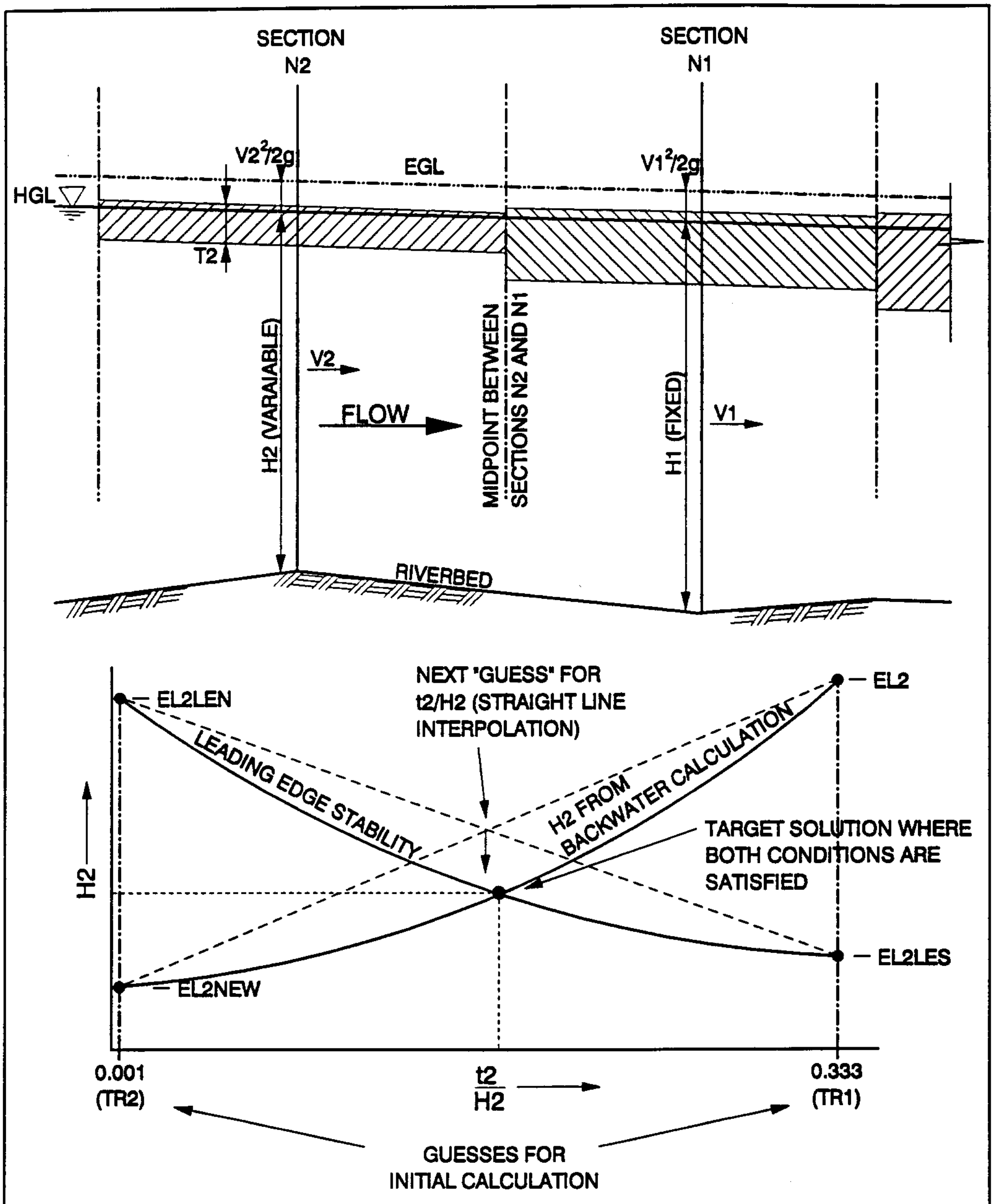
"RIVICE" MARCH 19
ICE EVOLUTION MODUL
"ICECEA.FOR"

SHT # 1/5

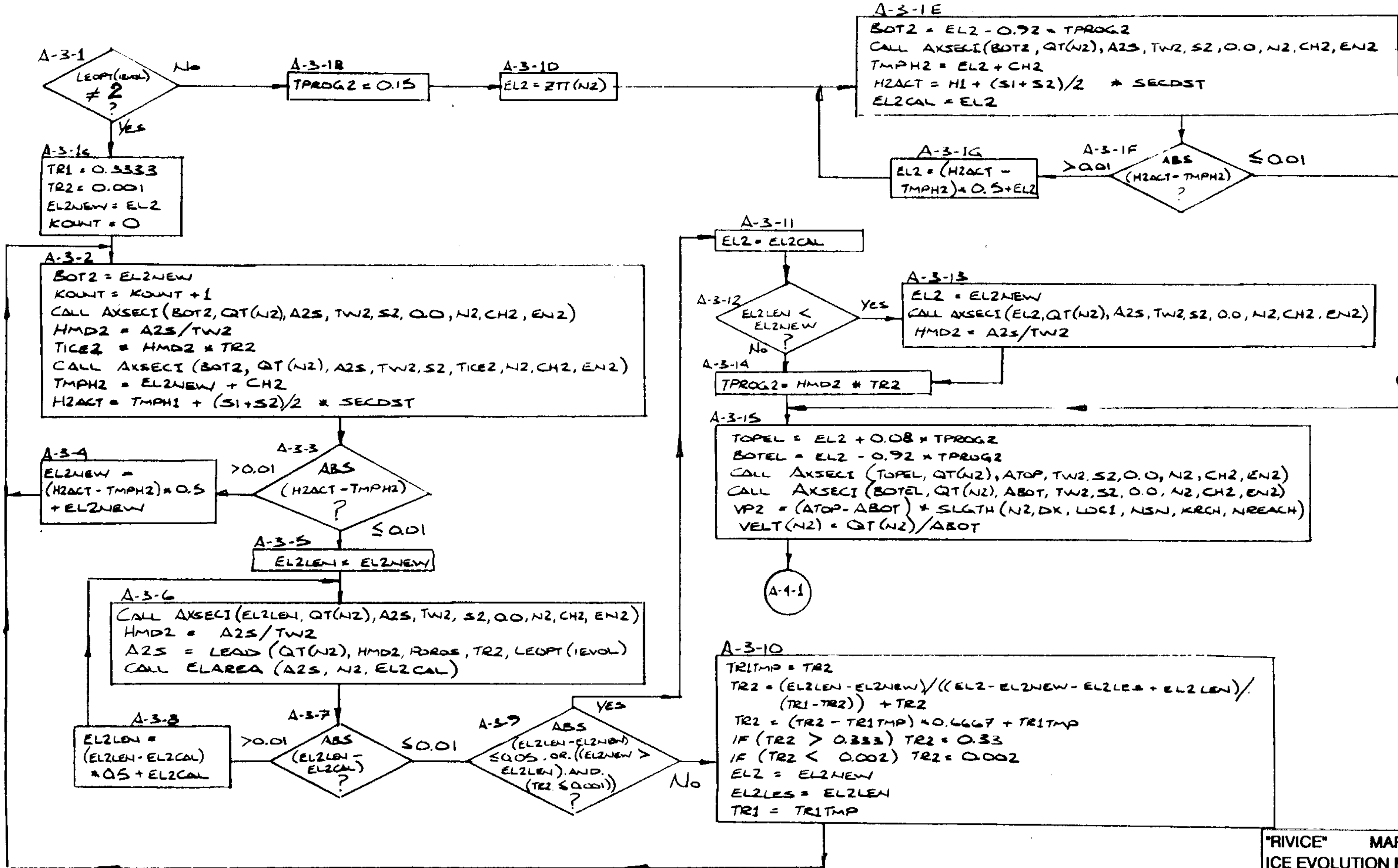


"RIVICE" MARCH 1992
ICE EVOLUTION MODULE
"ICECEA.FOR"

SHT # 2/5

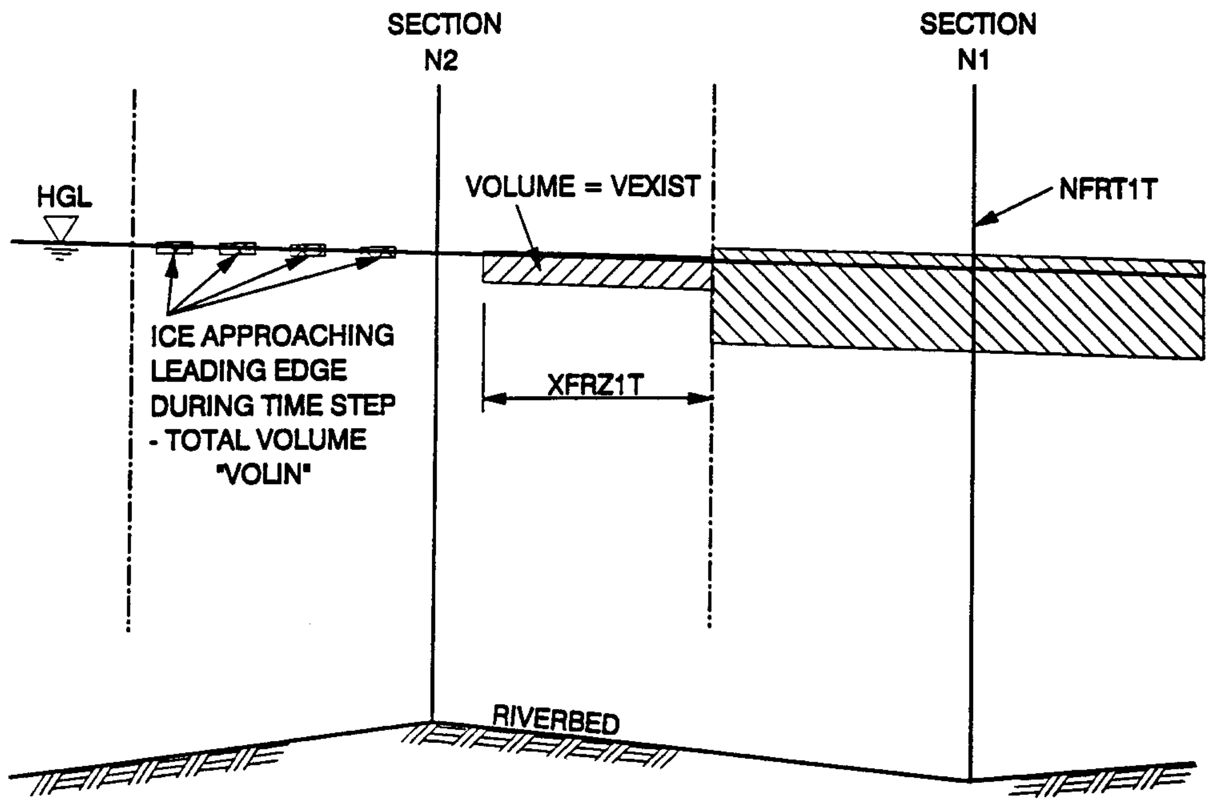


"RIVICE"
ICE EVOLUTION MODULE
BLOCK A - LEADING EDGE ANALYSIS
SKETCH A-3-1



"RIVICE" MARCH 1992
ICE EVOLUTION MODULE
"ICECEA.FOR"

SHT # 3/5



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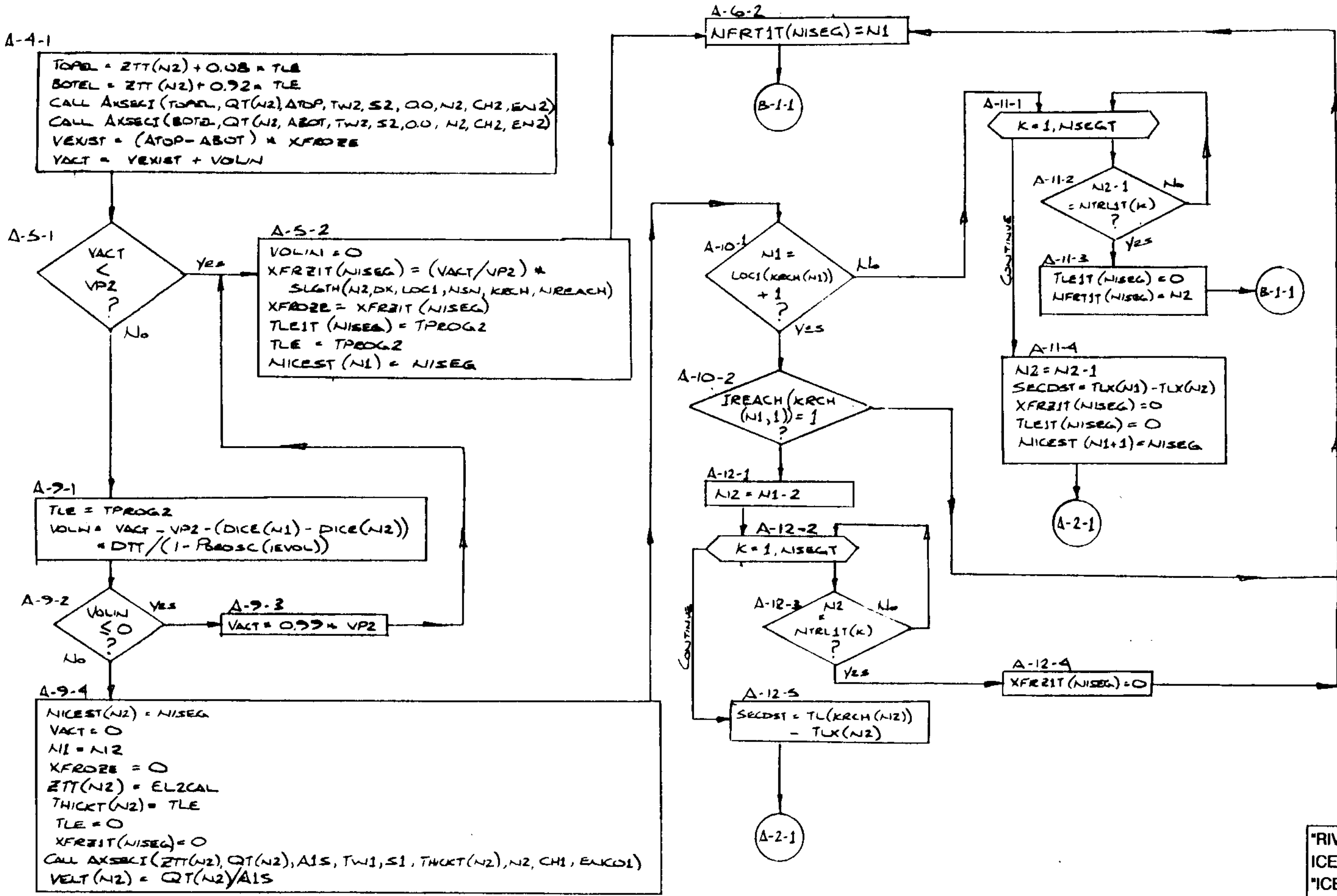

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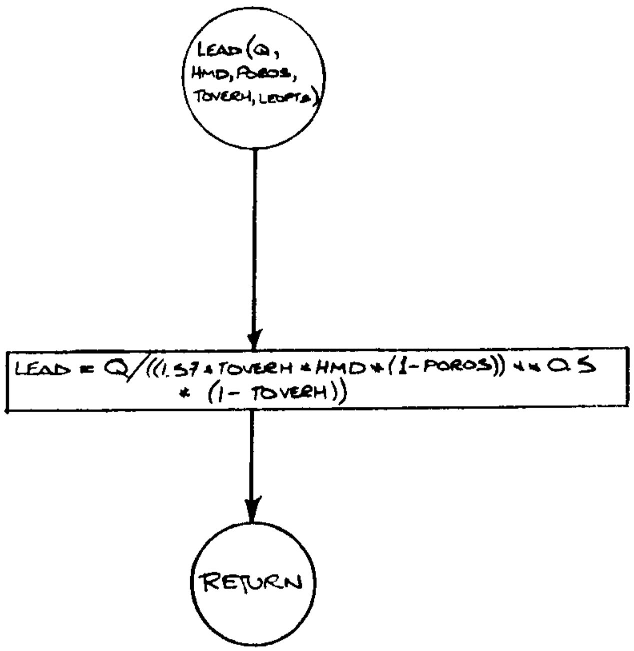

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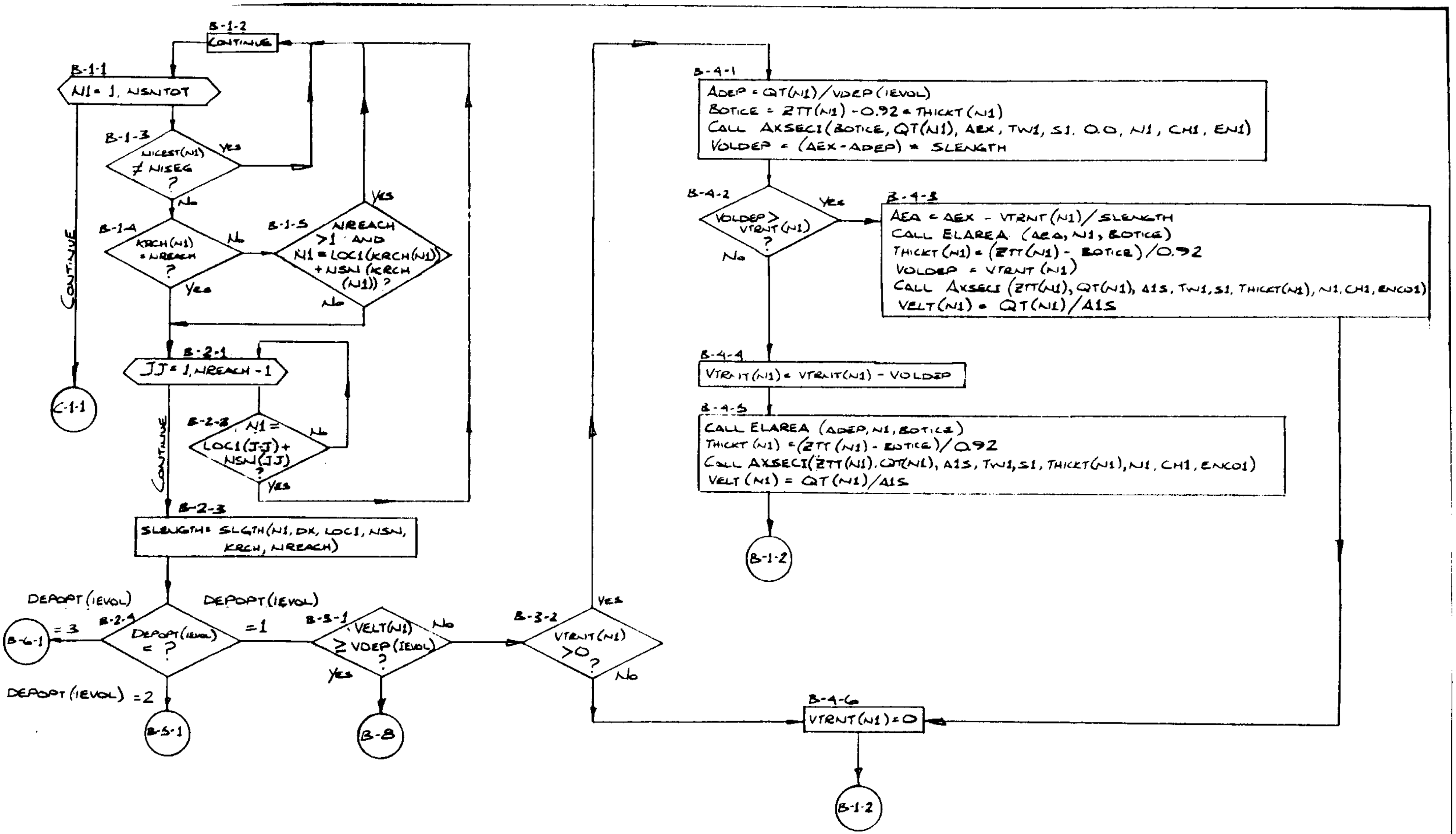

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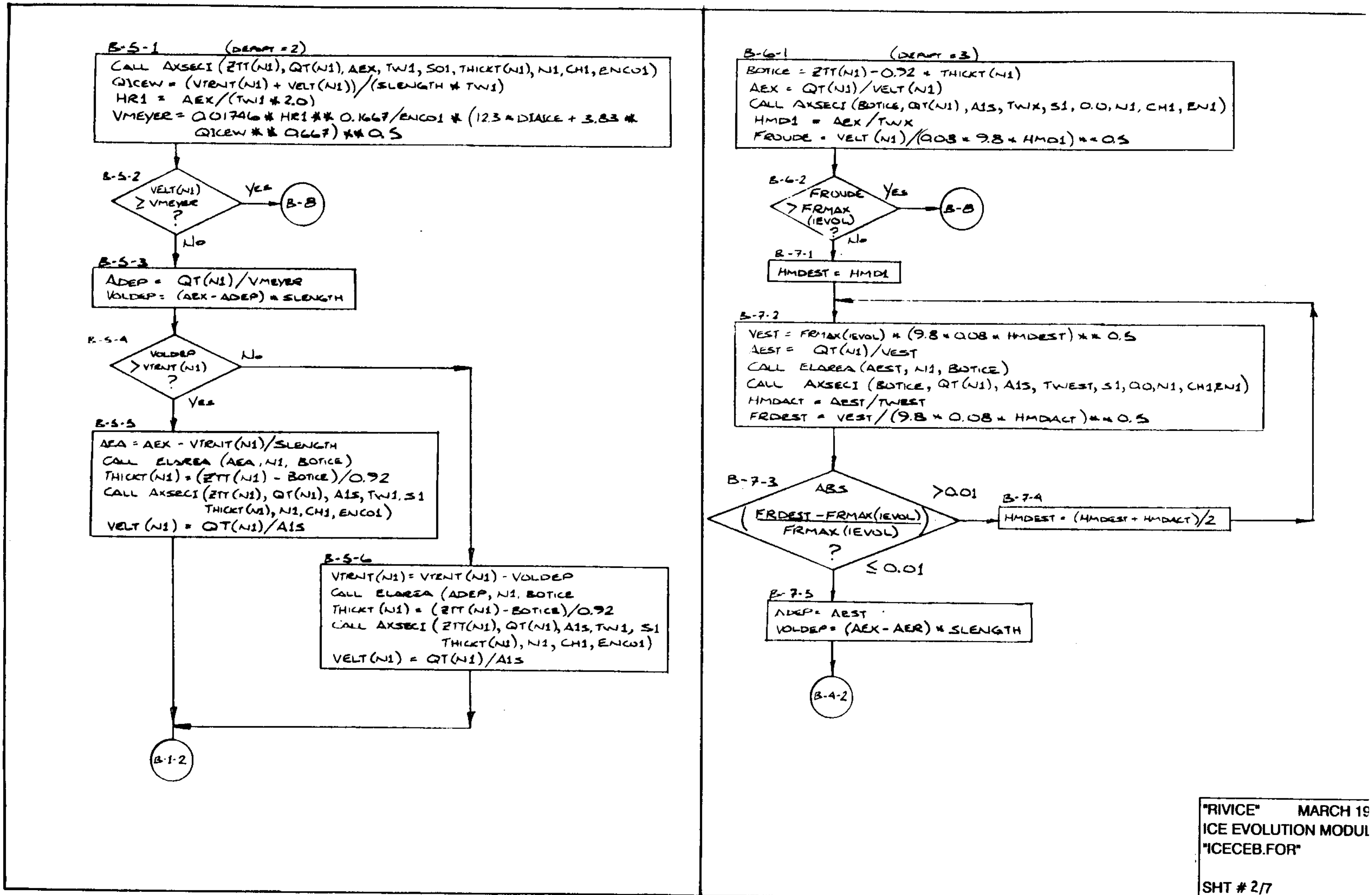

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SHT # 2/7

appendix c

Numerical Computation of River Ice Jams

Numerical computation of river ice jams

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A numerical model called RIVJAM has been developed to compute the configuration of and water levels caused by ice jams of the "wide" kind, under natural stream conditions and regardless of whether the jam has attained its full potential, known as equilibrium. Account of seepage flow through the voids of the jam enables predictions of grounding conditions to be made, in accord with observations. The model is applied to three case studies of ice jam events and found to perform satisfactorily. The various model coefficients fall within the expected ranges, with the exception of a parameter characterizing the intensity of seepage flow. More field data are needed to elucidate this matter.

Key words: grounding, ice, jam, model, numerical, river, seepage, thickness, toe, wide.

Un modèle numérique appelé RIVJAM a été développé afin de calculer la configuration des embâcles de glace d'envergure, ainsi que les niveaux d'eau qui en résultent lorsque les conditions de cours d'eau sont naturelles, sans se préoccuper de savoir si l'embâcle a atteint la condition d'équilibre ou non. Le fait que des exfiltrations aient été constatées à travers les vides de l'embâcle permet d'établir des prévisions des conditions du sol en conformité avec les observations effectuées. Le modèle a été utilisé dans trois études de cas d'embâcle de glace et il a permis d'obtenir des résultats satisfaisants. Les divers coefficients s'inscrivent à l'intérieur des plages prévues, à l'exception du paramètre caractérisant l'intensité des exfiltrations. Des données in situ supplémentaires sont nécessaies afin de résoudre cette question.

Mots clés : sol, glace, embâcle, modèle, numérique, rivière, exfiltration, épaisseur, pied aval, large.

[Traduit par la rédaction]

Can. J. Civ. Eng. **20**, 88-99 (1993)

Introduction

Despite the progress made in the past three decades, our understanding of ice jams and associated phenomena remains limited. One of the major unknowns is the configuration of jams near their toe (downstream end), which is related to the question of how ice jams are held in place. In turn, this pertains to jam formation and release, two important events that are not possible to predict at present.

Ice jams can be evolving or steady state (see also IAHR Working Group on River Ice Hydraulics (1986)). This paper will be limited to the latter type, which can be further subdivided into "equilibrium" and "non-equilibrium" jams. An equilibrium jam contains a reach in which the flow depth and the jam thickness are approximately uniform. Ice jams are also classified as "narrow" and "wide," depending on how they are formed. A narrow jam has a thickness determined by the hydraulic conditions at its leading edge (or "head"). The wide jam, on the other hand, is as thick as is necessary to withstand the applied forces of gravity and flow shear; it usually forms after the collapse of a narrow jam that has become too long relative to its strength. For cohesionless jams, which occur frequently at freeze up and almost invariably at breakup, the collapse length is equal to about a river width in all but very small streams.

Limiting our discussion further to cohesionless jams, we expect their configuration to be as sketched in Fig. 1. A convenient first approximation is to ignore the short narrow-type portion at the head and assume the jam to be wide throughout. Much of the previous work on ice jams has concentrated on predicting equilibrium thickness and depth which enables assessment of a jam's full potential for flooding (maximum depth). Non-equilibrium analysis was first carried out by Uzuner and Kennedy (1976) who calculated the shape of the jam in the upstream transition (Fig. 1). Flato and Gerard (1986) developed a numerical solution for the entire length of the jam, while Beltaos and Wong (1986*a*) concentrated on the downstream transition and took into account seepage flow through the jam voids. This makes it possible to predict severe thickening and grounding near the toe (downstream end), in agreement with observations. In the downstream transition, where thickness increases with distance and the water depth decreases, neglect of seepage will produce rapidly increasing flow velocities, exceeding the values known to be capable of "eroding" an ice jam. This limitation can lead to difficulties in predicting the configuration of the jam near the toe (e.g., see Flato (1988)).

At the same time, the Beltaos and Wong algorithm (1986*a*) had several practical limitations, since it was intended for gaining insight into very simple, idealized channels. Herein a more robust model, called RIVJAM, is described and tested against field measurements. Several questions that arise as a result of this new capability are discussed.

Because of the many difficulties associated with obtaining field data on ice jams (see also Ashton (1986)), testing of the model is a slow process and, at present, is at an early phase. The results presented herein provide a fair idea as to the values of the model coefficients, but more case studies are needed. The use of the model in a predictive mode should rely on prior calibration, a common situation when it comes to modelling of river ice processes. If there is no information with which to calibrate the model, considerable judg-

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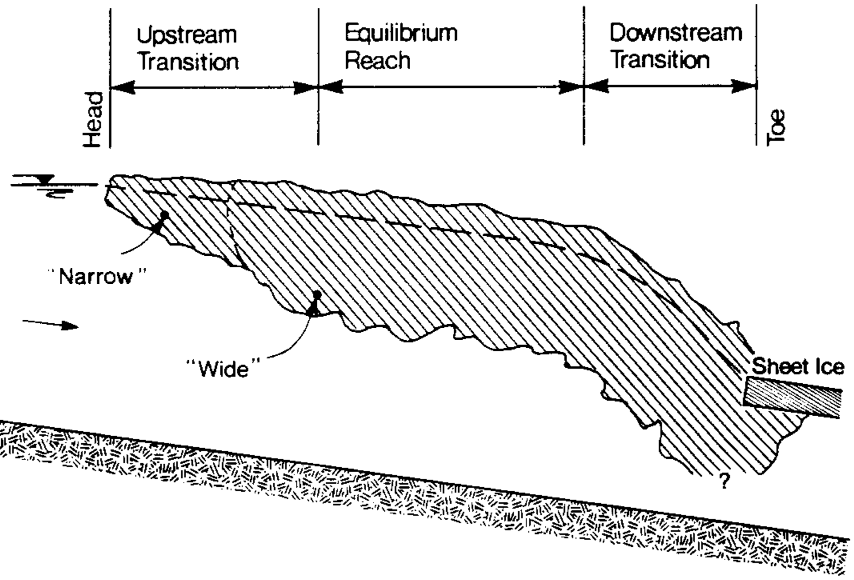

FIG. 1. Schematic illustration of different reaches in an ice jam.

ment should be exercised and appropriate safety margins introduced to compensate for uncertainties caused by lack of calibration. At the same time, the model represents a convenient research tool in assessing quantitative hypotheses concerning the processes that govern the configuration of non-equilibrium portions of breakup jams.

Background information

Beltaos and Wong (1986*a*) assumed, for simplicity, a very wide rectangular prismatic channel and derived a system of three differential equations with three unknowns based on the principles of continuity, momentum, and jam stability, i.e.,

$$[1] \quad \frac{dt_s}{dx} = f_1(t_s, h, S_w)$$

$$[2] \quad \frac{dh}{dx} = f_2(t_s, h, S_w)$$

$$[3] \quad \frac{dS_w}{dx} = f_3(t_s, h, S_w)$$

in which t_s is the submerged portion of jam thickness; h is the depth of flow under the jam; S_w is the slope of the water surface; x is the downstream distance; and f_1, f_2, and f_3 are functions. The solution of these equations proceeds in the downstream direction, starting from the downstream limit of the equilibrium reach; thus the jam is assumed to be of the equilibrium type.

For practical applications, however, the model should accept arbitrary channel bathymetry and lack of prismaticity; it should "march" in the upstream direction as well as the downstream; and it should not be dependent on the existence of an equilibrium reach, that is, it should be able to compute non-equilibrium jam profiles.

The development of RIVJAM began by noting that many difficulties could be eliminated if the flow momentum equation were simplified to the form (used often in gradually varied flow applications):

$$[4] \quad S_w \simeq (\tau_i + \tau_b)\rho g h = 0.25 f_o \rho u^2$$

in which τ_i and τ_b are flow shear stresses applied on the ice jam and riverbed, respectively; ρ is the density of water; g is the acceleration due to gravity; u is the average velocity of the flow under the jam; and f_o is the composite friction factor for the flow under the jam. Equation [4] replaces the full momentum equation, which leads to [3], and relates S_w to t_s and h. Thus, we now have to solve two differential equations with two unknowns, t_s and h. Both these equations (e.g., see [1] and [2]) are of the first order with respect to a vertical dimension such as depth or jam thickness. Note that [3] is of the second order, as it expresses the gradient of the slope; elimination of this equation improves the stability and "robustness" of the numerical solution.

The two-equation solution was first programmed for the case of a very wide prismatic channel, and the output was compared with that of the three-equation solution in a number of different test runs. There was little difference in the results; hence [4] was adopted as a satisfactory approximation.

Model equations

The stability equation for a cohesionless jam in a non-prismatic channel can be written as

$$[5] \quad \frac{dt_s}{dx} = \beta_1 S_w\left(\beta_2 \frac{A_f}{Bt_s} + 1\right) - \beta_3 \frac{t_s}{B}$$

in which A_f is the area of flow under the jam (see also Fig. 2); B is the channel width at the bottom surface of the jam; and the dimensionless coefficients β_1, β_2, and β_3 are defined as

$$[6] \quad \begin{aligned} \beta_1 &= s_i/K_x(1-p)(1-s_i) \\ \beta_2 &= f_i/2f_o \\ \beta_3 &= \mu/K_x(1-p) \end{aligned}$$

in which p is the porosity of the jam; s_i is the specific gravity of ice; K_x is the ratio of the internal longitudinal stress to the vertical stress in the jam (both averaged over the thickness); f_i is the friction factor of the underside of the jam; and μ is the ice jam internal strength characteristic,

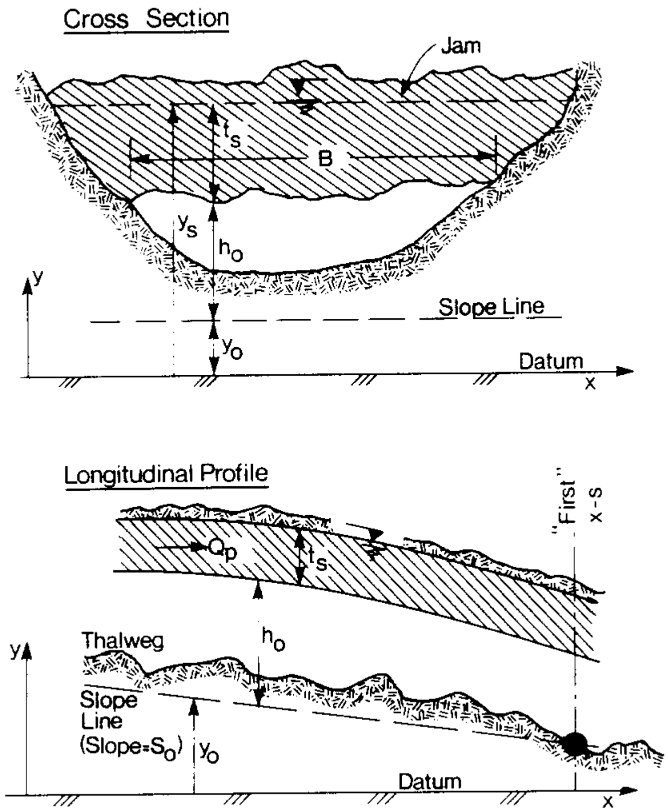

FIG. 2. Definition of variables used in RIVJAM.

as originally defined by Pariset *et al.* (1966) who analyzed the equilibrium condition. Uzuner and Kennedy (1976) presented a non-equilibrium analysis for rectangular prismatic channels. Following these authors, Beltaos (1988*a*) derived [5] by integrating the elementary force balance equation over the thickness of the jam and the width of the channel. The assumptions implicit in [5] are (*i*) that there is symmetry about the channel centreline; and (*ii*) that the ice jam is essentially one-dimensional, i.e., the thickness and the longitudinal internal stress are uniformly distributed across the river. While some evidence exists to support these assumptions in a reach-sense (Beltaos 1988*b*), they are very likely violated in areas where asymmetry prevails, such as bends.

In addition to [5], simple geometry (Fig. 2) requires

$$[7] \quad \frac{dh_o}{dx} = S_o - S_w - \frac{dt_s}{dx}$$

in which h_o is the vertical distance of the underside of the jam from the "datum" line of slope S_o. This slope is normally taken to be equal to the open-water slope in the computation reach (see, also, later discussion).

Assuming steady-state flow conditions, continuity requires that the sum of the flows through and under the jam be constant and equal to the total flow discharge.

While the jam is lengthening in the upstream direction, the flow under it is less than the flow that is incoming at a site far above the head of the jam where the water level is uninfluenced by the jam's backwater. The flow reduction is due to the water volume that goes into storage (e.g., see Uzuner and Kennedy (1976)). When the supply of broken ice is exhausted and the jam ceases to lengthen, the storage effect disappears and the flow under the jam increases to the far upstream value. If this increment is insignificant, the storage effect can be neglected; if it is significant, the theory suggests that the increased forces on the jam would bring about a final collapse and thickening to make the jam stable for the increased flow. In either case, it is reasonable to work with the far upstream discharge.

Analysis and experiments (Beltaos and Wong 1986*b*) have indicated that the seepage component, Q_p, is given by

$$[8] \quad Q_p = \lambda A_j \sqrt{S_w}$$

in which A_j is the "wetted" cross-sectional area of the jam; and λ is a coefficient having dimensions of velocity. The average velocity of the flow through the void spaces in the jam is equal to $\lambda\sqrt{S_w}/p$. More information on seepage flows and the coefficient λ is presented in Appendix A.

The use of [4] and [8] makes it possible to express S_w in terms of A_f, A_j, and B, which shows that [5] and [7] form a system with two unknowns, t_s and h_o. Note that A_f, A_j, and B are specified when t_s and h_o are given.

This first-order system is solved by a Runge–Kutta technique and the computation may proceed either upstream or downstream, starting at a site where t_s and h_o are known. Channel bathymetry is specified by a set of surveyed cross sections. Between successive sections, the bathymetry is synthesized by linear interpolation. This involves the channel widths along planes that are parallel to the "slope line" (see Fig. 2). By analogy with a prismatic channel, this line should have a slope equal to that of open-water flow. However, deviations from this guideline have been found to have little effect; the slope line could also be assumed to be horizontal, for instance.

Coefficients

The composite friction factor, f_o, is calculated as

$$[9] \quad f_o = c t_s^{m_1} h^{-m_2}$$

in which the average flow depth, h, is given by $h = A_f/B$; and c, m_1, and m_2 are user-specified constants. Beltaos and Wong (1986*a*) used $c = 0.51$ and $m_1 = m_2 = 1.17$, which are approximate values deduced from data on equilibrium jams. A positive value for m_1 indicates that the hydraulic resistance of a jam increases with its thickness, a trend that has been established by experience (Nezhikhovskiy 1964; Beltaos 1988*b*).

It should be recognized that no unique set of values for c, m_1, and m_2 is likely to exist; equation [9] is largely empirical and does not explicitly include the hydraulic resistance of the riverbed. The latter is obviously important but very difficult to evaluate in flows under ice jams. It may vary with the hydraulic radius associated with the bed in a site-specific manner (Beltaos 1990). The physical basis of [9] is related to the peculiarities of very rough flow boundaries, as is the case for ice jam conditions. Beltaos (1990) examined the conventional, logarithmic, friction factor versus relative roughness diagram and found that for flow under ice jams the friction factor, f, is roughly proportional to the relative roughness, d/R, where d is the absolute roughness and R is the hydraulic radius. Applying this to both the bed and the jam boundaries gives $f_o \propto d_o/R_o$ and $d_o \propto d_i$ times a function of d_b/d_i; the subscripts o, b, and i denote parameters for the composite flow, the riverbed, and the ice jam, respectively. The absolute roughness of an ice jam, d_i, generally increases with jam thickness or with t_s, being initially proportional to t_s but approaching a constant value for very thick jams (Beltaos 1988*b*). Noting that $R_0 \approx h/2$ and comparing these results with [9] indicates that c has to absorb the effect of d_b/d_i, and m_2 should be close to 1. For relatively thin jams, m_1 should also be close to 1; it should approach 0 for very thick ones. The more familiar Manning- and Chezy-type assumptions can also be represented by [9]. For instance, $m_1 = m_2 = 0$ implies a fixed Chezy coefficient. A constant Manning coefficient is indicated by $m_1 = 0$ and $m_2 = 1/3$.

Near the head and the toe of the jam, [9] might give unreasonably low or high f_0 and the model includes a subroutine to enable the user to specify suitable upper and lower limits.

The coefficient β_2 which depends on the ratio of ice and bed friction factors is often assumed equal to 0.50, implying equality of these factors. On the other hand, Beltaos (1983) found β_2 to vary between 0.3 and 0.8 upon analysis of several field data sets. Moreover, it should be recognized that there is no concrete evidence to support the assumption that β_2 is constant throughout the length of an ice jam. In fact, the opposite is more likely, but this discrepancy does not seem to adversely affect the results of the computation.

The coefficients β_1 and β_3 essentially depend on p, K_x, and μ, since $s_i = 0.92$ for freshwater ice (see [6]). There are no direct measurements for p. A value of 0.40 is often quoted and was recently corroborated by Prowse (1990) based on heat flux considerations. This value is used throughout the paper. We have little knowledge of K_x because previous work has concentrated on the equilibrum condition which is not dependent on this coefficient. A recent field determination indicated that the value of K_x is between 8.3 and 10.4 (Beltaos 1988*b*), as will be discussed in more detail later, in conjunction with the Thames River case study. Several authors have discussed μ (Pariset *et al.* 1966; Beltaos 1983; Calkins 1983; Andres and Doyle 1984). The average value is about 1.2, though the lowest and the highest reported are 0.6 and 3.5 (Beltaos 1983). This author, however, also noted evidence against the reliability of these extremes. A more realistic range, based on all reported values, is from 0.8 to 1.6.

No field values for the seepage parameter λ exist. As explained in Appendix A, extrapolation of laboratory test data suggests that λ should vary in proportion to the square root of the thickness, t_i, of the blocks within the jam, being also sensitive to the porosity, p. For $t_i = 0.5$ m and $p = 0.4$, $\lambda \approx 0.9$ m/s. At the same time, a reanalysis of the data on flow through rockfill revealed a possible scale effect which might cause the actual value of λ to exceed that found by extrapolation of the laboratory results (Appendix A).

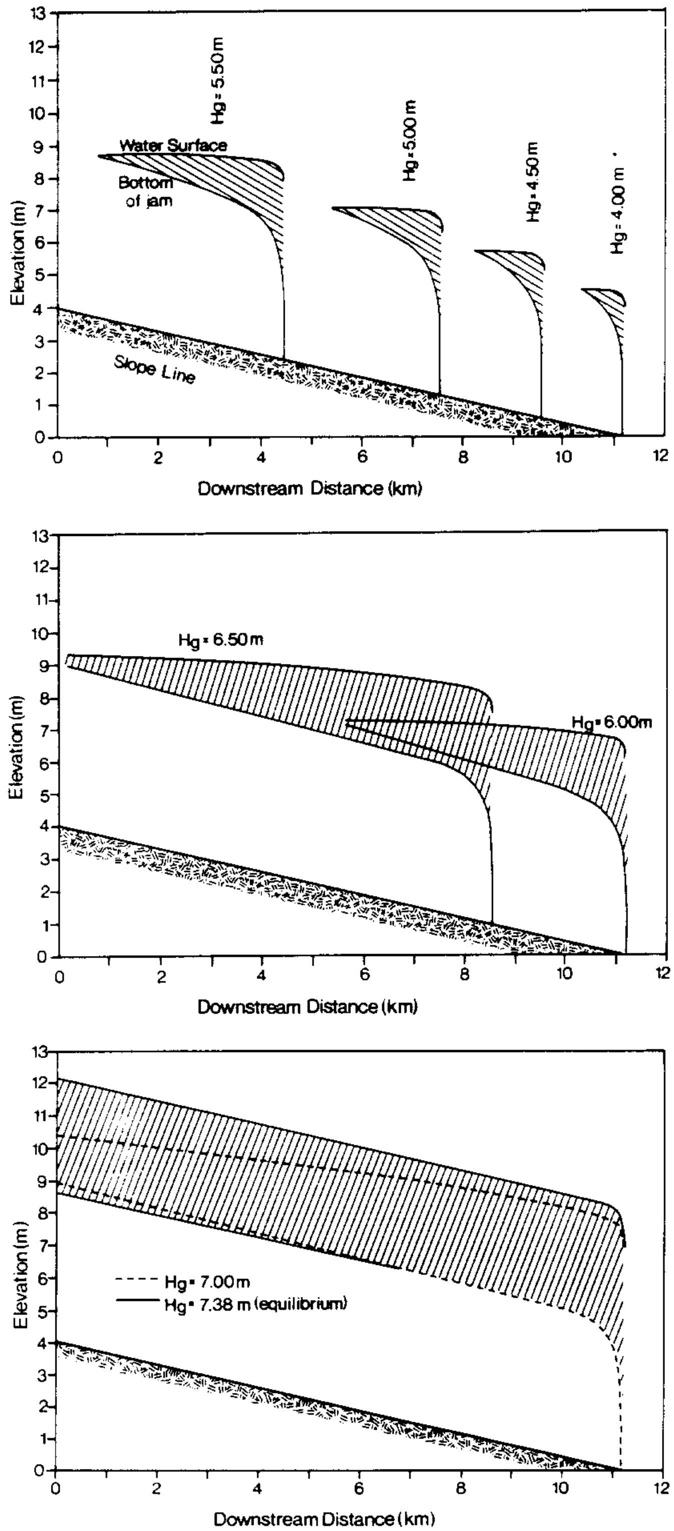

FIG. 3. Calculated ice jam profiles for different grounding depths.

Test runs

Before applying RIVJAM to the actual case studies, a series of runs was carried out to see how the model performs in the case of non-equilibrium jams and to assess their characteristics. A rectangular channel was assumed, having a slope of 0.36 m/km, a width of 560 m, and a discharge per unit width of 2.0 m^2/s. This is an approximation to typical breakup jamming in the Athabasca River near Fort McMurray (Alberta). Other parameters were taken as $p = 0.40$, $\lambda = 0.75$ m/s, $c = 0.51$, $m_1 = m_2 = 1.17$, $\mu = 1.2$, and $K_x = 4.3$. The value $K_x = 4.3$ is considerably less than the measured value, but the latter was not available when these model runs were performed. However, this discrepancy does not alter the qualitative insight gained from these early runs.

Figure 3 shows the results as a series of profiles, each having a different value of the grounding depth, H_g. Note

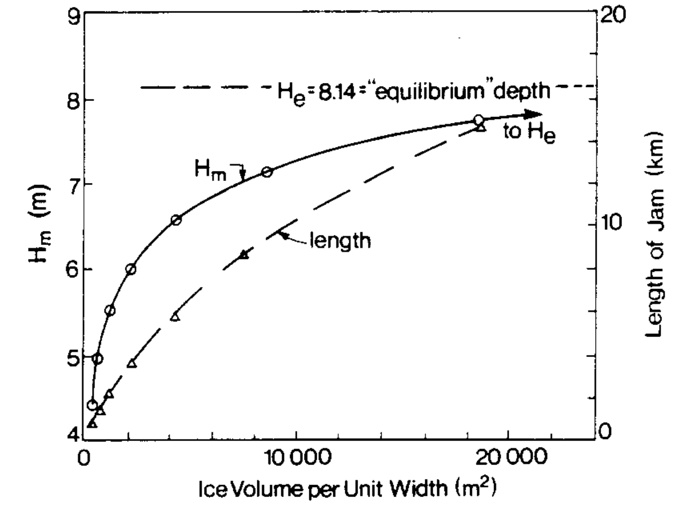

FIG. 4. Effect of ice volume on maximum water depth and length of an ice jam.

that H_g provides a convenient starting condition (i.e., $t = H_g$; $h_o = 0$), but does not represent the actual toe situation, as explained later. As H_g increases, the jam thickens and lengthens until the equilibrium condition is attained (H_g = 7.38 m). In this case the model keeps on computing constant values for t_s and h_o. If H_g is set higher than 7.38 m, the solution "blows up," that is, the calculated thickness first decreases and then grows as we move upstream, a trend that has no physical meaning. The relative sensitivity of the model output was considered by Beltaos and Wong (1986*a*). For instance, H_g decreases when either λ or K_x increases.

Figure 4 shows how the jam length and the maximum water depth, H_m, vary with ice volume in the jam. The latter is seen to have a strong effect on H_m, particularly for short jams. To attain 95% of the maximum possible depth (the equilibrium value of H_m), the jam would have to contain at least 18 500 m^3 of ice per unit width or be 14.5 km long. If the thickness of the sheet ice cover were, say, 0.6 m, then the jam would have to contain all of the ice that broke up in a 31 km reach.

Returning to the question of the actual toe conditions, we can compare H_g with H_d, the water depth well downstream of the jam, which usually represents flow under sheet ice cover. A "naive" way to look at this would be to assume that if $H_g > H_d$, a section of grounded ice rubble forms just upstream of the toe. On the other hand, if $H_g < H_d$, grounding does not occur, but the toe is located at the site where $H_g = t_s + h_o$. In the present case, H_d is only about 3.5 m, hence grounding would be likely. A more detailed discussion of this matter is given in Appendix B.

Case studies

To date, the model has been applied to three ice jams for which some quantitative data are available. The main interest is in finding out how well the model can reproduce the longitudinal water level and thickness variations along an ice jam, particularly near the toe where maximum gradients occur. Related measurements are not easy to perform, which explains why only three cases can be discussed at this time. Reliable water levels can be obtained with photographic and ordinary survey techniques, provided the jam remains steady for a few hours. Thickness measurements are practically impossible for breakup jams. Estimates can be obtained by measuring the height of shear walls after the jam has released.

Ideally, the various coefficients that have to be specified to run RIVJAM would be determined by a rigorous optimization procedure, based on a comparison of the model output with measurements and quantification of model performance in terms of prediction errors. In the present study, this option is not practical because of the limitations and inaccuracies of ice jam measurements. Instead, the following approach has been adopted.

(*i*) Choose the values of as many coefficients as possible, based on an independent analysis of the available data (e.g., Thames River case), or on commonly used or otherwise known values from previous experience (e.g., Rushoon River case). Typically, the latter would result in $p = 0.4$, $c = 0.5$, $m_1 = m_2 = 1$, $\beta_2 = 0.5$, $\mu = 1.2$, and $K_x = 9$.

(*ii*) Determine the flow discharge, or at least a range, based on measurements (rare) or on other hydrometric evidence (e.g., backwater estimates, runoff, gauge data at nearby sites unaffected by the jam).

(*iii*) Allow considerable variation of λ, for which there are no previous field data. Use [A3] as a guide to estimate the order of magnitude.

(*iv*) Select the starting site for the computation and determine the local water level and t_s. This is part of the input and should be known by measurement (e.g., Thames and Restigouche cases). However, t_s is not always possible to measure or even estimate, whereby it may have to be allowed to vary (e.g., Rushoon case).

This approach minimizes the number of free parameters whose various combinations determine the number of model runs that have to be made. If no combination is found with which RIVJAM will adequately reproduce the measurements, then the preselected coefficients (item *i*, above) are allowed to change and new model runs are performed until satisfactory agreement is obtained.

Thames River, Ontario

In mid-January of 1986, a thaw occurred in southwestern Ontario. Much rain fell and several streams, including the lower Thames River, broke up. By January 23, a 10 km long jam had formed just upstream of Chatham. At that time, the weather turned cold and the jam started to freeze in place. It was thus possible to obtain safe ice access and perform detailed measurements of the jam thickness and of the water levels along the jam, using photos taken on January 23. Relevant ice-jam and hydraulic parameters were later deduced by analytical and graphical procedures (see Beltaos 1988*b*). The flow discharge was approximately 290 m^3/s, while the coefficient f_o could be described by $c = 0.62$ and $m_1 = m_2 = 1.0$. The coefficient μ was 1.2 and the ratio $f_i/2f_o$ was between 0.5 and 0.6. Assuming a porosity of 0.4, the latter two values of $f_i/2f_o$ correspond to $K_x = 8.3$ and 10.4.

To apply RIVJAM, p and μ were fixed at 0.4 and 1.2 respectively, while λ was taken as 0.6 m/s (see [A3]; thickness of ice blocks in the jam = 0.2 m). The value of λ in this case has little impact on the solution because the jam was of the floating type throughout and the flow through it was negligible. The computation "marched" upstream, starting at the toe and using the locally measured values of thickness and water surface elevation. Various runs

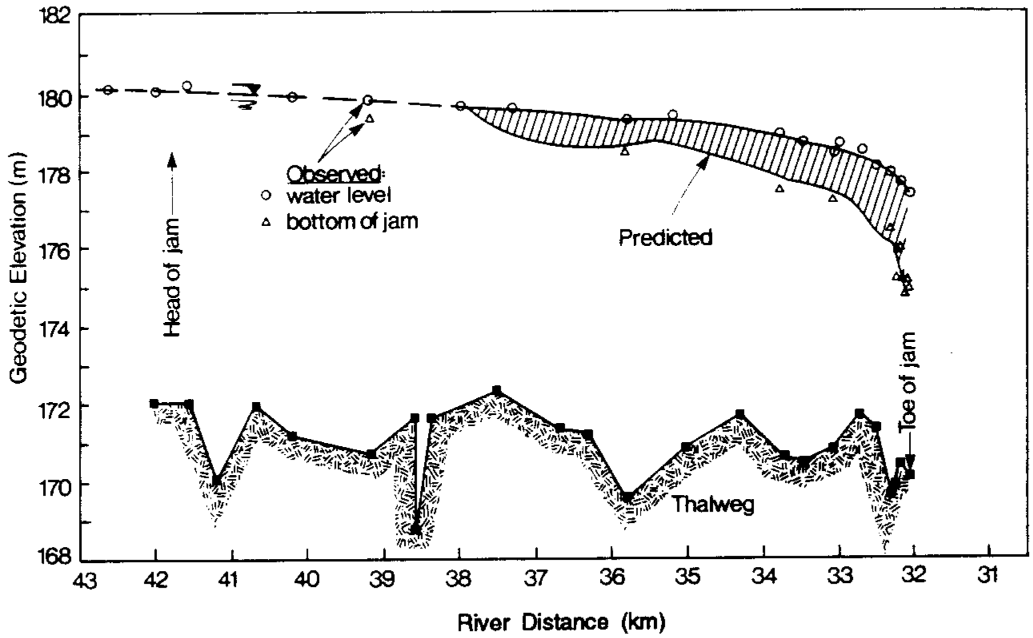

FIG. 5. Comparison between predicted and observed profiles for the 1986 jam in the Thames River near Chatham.

were made with different values of K_x and $f_i/2f_o$, and optimum results were obtained with the pair 9.62 and 0.60 (Fig. 5).

In Fig. 5, the predicted profile is seen to end at about 38 km, even though the head of the jam was observed at about 42 km. This is likely caused by the jam reverting to the "narrow" type or even to a single layer of ice floes upstream of kilometre 37, as deduced by Beltaos (1988*b*).

An interesting feature in Fig. 5 is the odd shape of the jam between 35.5 and 36.5 km. Instead of increasing in the downstream direction, as one would generally expect, the thickness decreases. This can be explained by the relatively large depth prevailing in that reach. If we substitute [4] and [9] in [5] and put $u \approx Q_T/A_f$, we will find that the first term on the right-hand side of [5] decreases when the flow area, A_f, or the flow depth, increases. Normally, this term is greater than the second term, hence $dt_s/dx > 0$. If a deep section is encountered, it is possible that the first term decreases enough to render the thickness gradient negative, thus producing the odd shape shown in Fig. 5. Physically, the effect of increased depth is to reduce the forces applied by the flow on the underside of the jam, which, therefore, need not be as thick. Because very deep sections can have such a pronounced effect on the jam profile, it is important to know their extent. This is not ordinarily furnished by cross-sectional bathymetry obtained at discrete intervals. It is thus advisable to also obtain a continuous longitudinal sounding of the study reach.

Restigouche River, New Brunswick

This case study has already been reported by Beltaos and Burrell (1990*a*, 1990*b*) and it will be briefly covered here because of the grounding condition that it represents.

In the afternoon of April 5, 1988, a relatively short jam formed in the lower Restigouche River. Water levels along this jam were recorded photographically at a few locations and surveyed later during open-water conditions. In the following morning, evidence was found that more ice had released in upstream reaches and joined the jam, to make it extend for some 20 km upstream of the toe. This new jam remained in place till the morning of April 9, thus permitting several detailed surveys to be made of the water level profile near the toe. The results indicated little change with time.

After the jam released, detailed measurements of the shear wall heights were carried out at various locations to obtain an approximate jam thickness profile (see also Calkins (1983)). These measurements revealed an "equilibrium" thickness of 3–4 m throughout most of the length of the jam and a rapid increase to 6 m in the vicinity of the toe (almost full grounding), with a slower decrease past the toe.

For the relatively steady condition of April 6–8, the river flow was estimated to be between 290 and 350 m^3/s (Beltaos and Burrell 1990*b*). Numerous runs of RIVJAM were performed, following the procedure outlined earlier. Because of the extensive grounding near the toe, and the good definition of the local water surface profile, it was possible to directly estimate λ using [8]; this gave $\lambda \approx 2.3$ m/s. Only small deviations from this value proved satisfactory in the model runs. Reducing λ to near 1 m/s, a value closer to what would be expected from [A3], clearly overpredicted the water level. Satisfactory model results (Fig. 6) were obtained with $p = 0.4$, $c = 0.4$, $m_1 = m_2 = 1.0$, $\beta_2 = 0.5$, $K_x = 12$, $\mu = 0.80$, $\lambda = 2.5$ m/s, and $Q_T = 330\ m^3/s$. It was mentioned earlier that, to be consistent with what is known about the jam roughness–thickness relationship, m_1 should approach zero when a jam becomes very thick. This is certainly the case near the toe of the jam (Fig. 6) and, to examine what the effect might be on the results, an additional run was executed by changing m_1 to 0, and c to 1.28 (so that the f_o values away from the toe are comparable). The results of this run were hardly distinguishable from those of Fig. 6. As indicated earlier, the program places limits on f_o to ensure that unreasonably low or high values, calculated by [9] when $t_s/h \to 0$ or ∞, are not used in the computation. This feature likely accounts for the lack of sensitivity to m_1 when the jam is very thick.

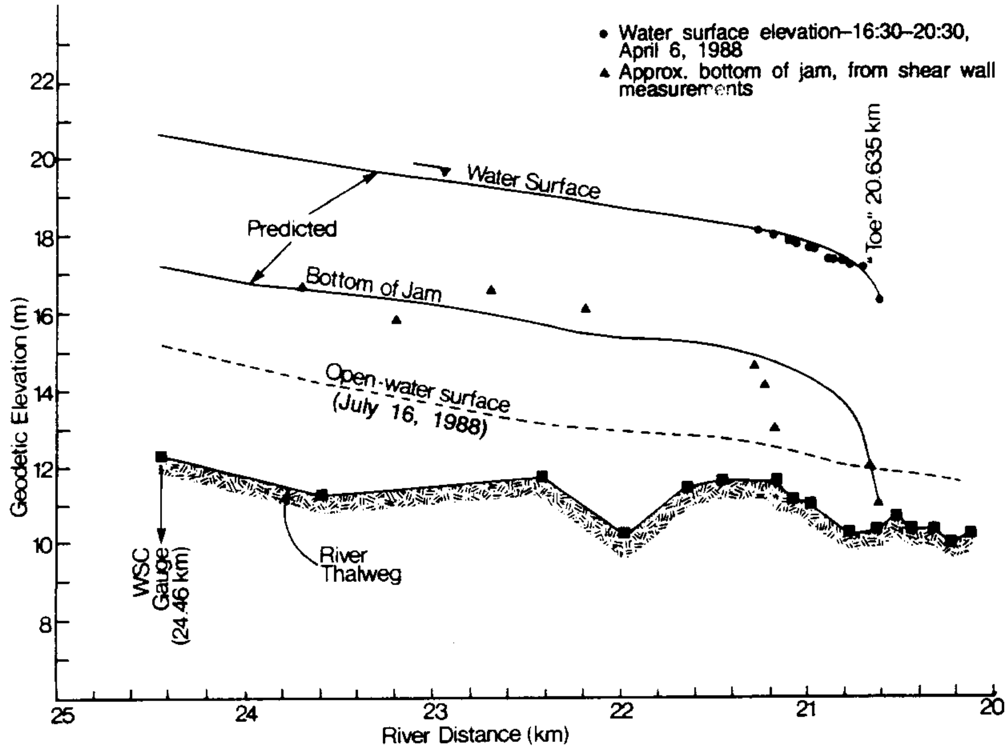

FIG. 6. Results of RIVJAM application to Restigouche River jam for April 6, 1988. After Beltaos and Burrell (1990*a*).

The model was next applied to the April 5 jam which was too short to have an equilibrium reach. The water level data are rather crude in this case, as they were obtained from photos, and there are no indications of jam thickness. Figure 7 shows that it was possible to approximately reproduce the water levels and length of this jam (observed head location = 24.4 km). However, it was necessary to reduce the discharge to 315 m^3/s and increase c to 0.6. The slight reduction in Q_T is reasonable (see Beltaos and Burrell 1990*b*). The increase in c is qualitatively plausible because jams should be roughest when they first form; it is not possible to comment on the magnitude of the change, owing to lack of pertinent data.

While this case study has produced some encouraging results, the model-deduced value of λ is too high relative to what would be obtained by extrapolating small-scale test data (the use of [A3] gives $\lambda = 0.9$ m/s, corresponding to $p = 0.4$). No satisfactory explanation can be furnished at this time for the discrepancy. Clearly, many more case studies are needed to resolve this question, particularly in wide, steep rivers where grounding is likely.

Rushoon River, Newfoundland

The lower Rushoon River has caused serious flooding in the community of Rushoon during breakup events occurring in 1973, 1983, and 1989. These events instigated hydrotechnical studies to define and reduce the problem (Shawmont Newfoundland Limited 1986; Lasalle Hydraulic Laboratory 1990). All the measurements and observations quoted herein derive from these two reports.

The three ice jams considered herein formed at Salmon Hole Point, a prime ice jamming site, as explained in the 1986 report quoted above. Following the 1973 flood, a fender wall was constructed alongside the river and consists of successive cribs filled with rock. It is highly permeable but its main function is to keep ice blocks and slabs from entering the community of Rushoon. For computation purposes, river cross sections have been truncated at the fender wall on the assumptions that the ice jam will abut against the wall and the water escaping through the wall toward Rushoon does not flow in significant quantities. The first assumption is well documented by observations and photographs, but the second is probably incorrect when major flooding is taking place. However, given the uncertainties involved in estimating the river flow in the first place, as explained next, the neglect of any bypass flow seems reasonable.

Accurate flows are unavailable. Estimates have been provided in the above quoted reports, based on regional analysis and comparisons with known flows in nearby basins. The corresponding values are Q_T = 21.4, 15, and 40 m^3/s for the 1973, 1983, and 1989 jams. The following values were selected for the model parameters: $p = 0.4$, $\mu = 1.2$, $K_x = 10$, $\lambda = 1$ m/s, $f_i/2f_o = 0.6$, $c = 0.5$, and $m_1 = m_2 = 1.0$. For each jam, the toe values of water elevation and jam thickness were adjusted until optimal agreement with the available data was obtained.

The most comprehensively documented case is the 1983 flood for which several water levels are known along the jam, including that at the toe; the latter restricts the "choices" for RIVJAM because now it is only the jam thickness that can be adjusted. The results of the simulation are depicted in Fig. 8 and seen to provide a good description of the observed water level profile. Moreover, it is of interest to note that the model predicts a non-equilibrium jam, slightly longer than what was observed (the theory predicts a profile that tapers to zero, but, for practical purposes, the profile should be truncated where the thickness becomes comparable to that of a single ice block). Another interesting feature in Fig. 8 is the shape of the jam

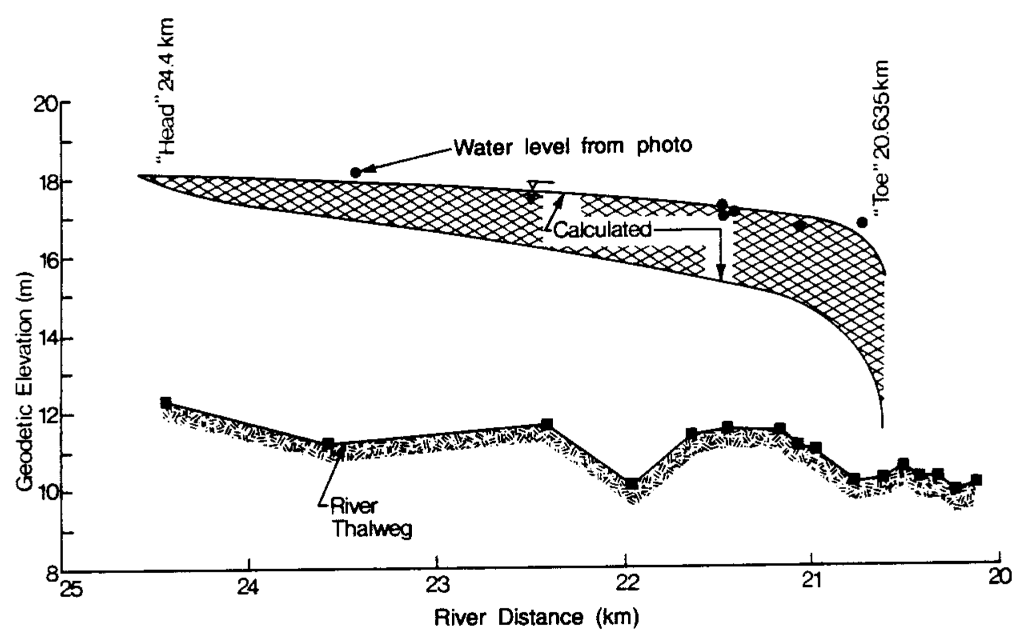

FIG. 7. Results of RIVJAM application to Restigouche River jam for April 5, 1988. After Beltaos and Burrell (1990*b*).

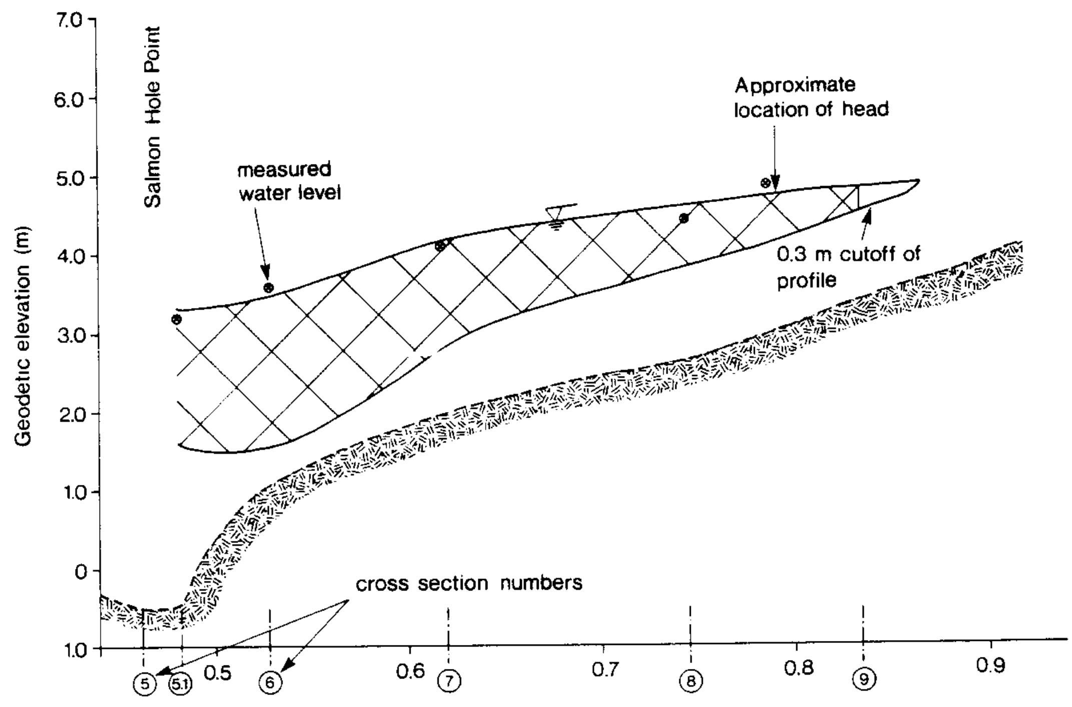

FIG. 8. Calculated profile of 1983 jam in Rushoon River. Discharge = 15 m^3/s.

very near the toe. Usually, the thickness decreases continuously in the upstream direction, but in this case the reverse is true for the first 30 m of the profile. This is caused by the abrupt change in slope at the toe. About 70 m upstream of the toe, a nearly grounded condition prevails, with merely 0.4 m "clearance" between the jam and the channel invert.

Figure 9 shows the results of the computation for the 1973 flood. The two available water levels are reasonably well reproduced.

The results of the computation for the 1989 event are shown in Fig. 10. No water level data exist in this case, but it is known that the water came very near the top of the fender wall, which is in agreement with the predicted profile. Moreover, there is good agreement between the predicted and actual locations of the head of the jam. Extensive grounding is predicted near the toe, in agreement with visual observations (Lasalle Hydraulic Laboratory 1989). This is further illustrated in Fig. 11, which shows the channel cross section 46 m above the toe, along with the calculated water level profile and the bottom elevation of the jam.

The values of the various coefficients used for the Rushoon runs are comparable to what has been found elsewhere. The seepage parameter, λ, was 1.0 m/s, which

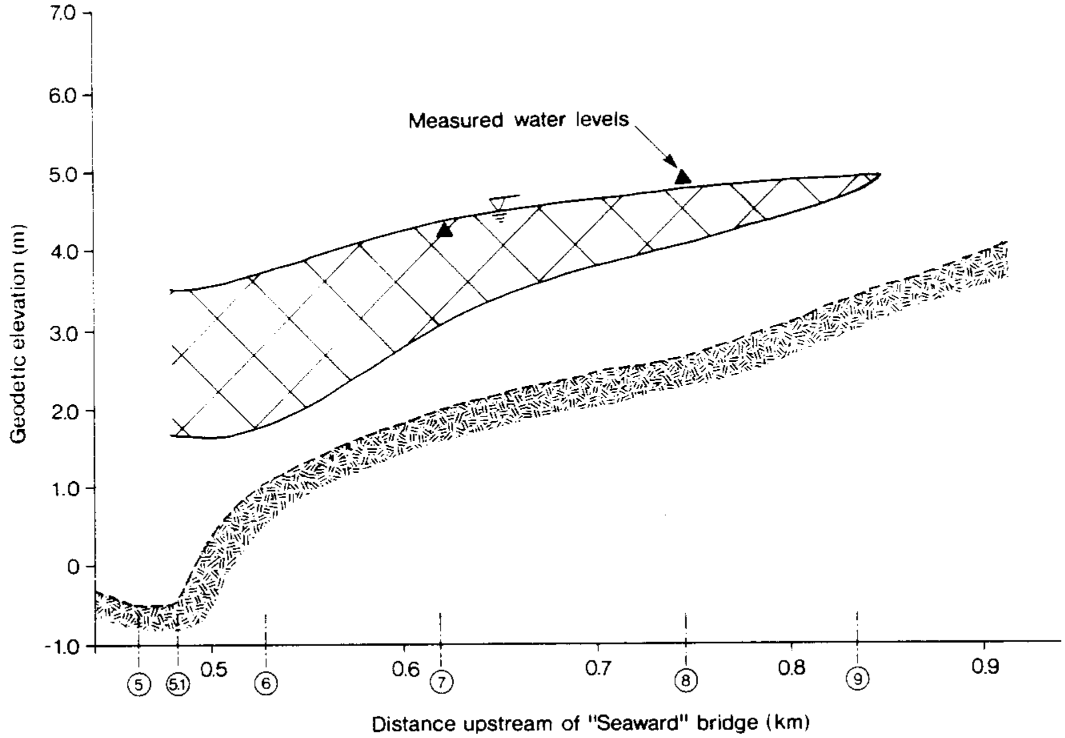

FIG. 9. Calculated profile of 1973 jam in Rushoon River. Discharge = 21.4 m^3/s.

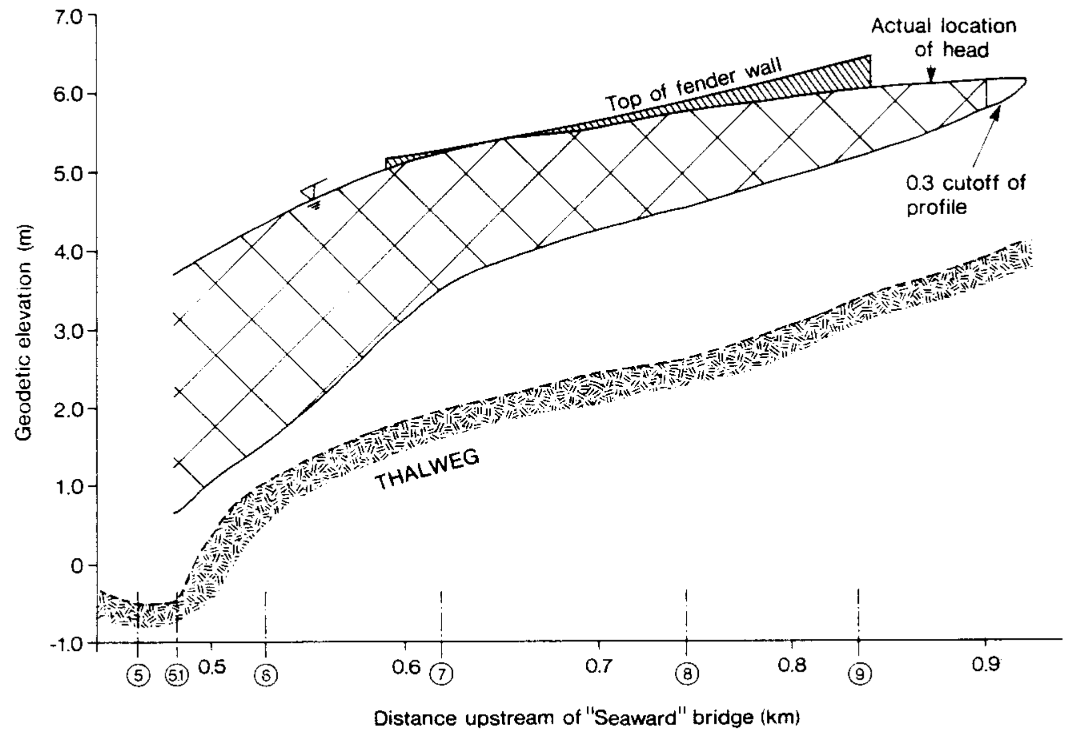

FIG. 10. Calculated profile of 1989 jam in Rushoon River. Discharge = 40 m^3/s.

is not far from what we would expect from an extrapolation of the lab test results (assuming an ice block thickness of 0.3 m, [A3] gives λ = 0.7 m/s which applies to a porosity of 0.4; if p = 0.5, then λ becomes 1.0 m/s).

Discussion

We have seen so far that RIVJAM provides reasonably good predictions of the configuration of ice jams and of the associated water levels, with appropriate choices of the model parameters. So far, these values have been plausible in terms of previous knowledge, and consistent in the sense that they do not change by much from one application to another. The one exception is the seepage parameter, λ. In the two applications where λ is a significant factor in the computed ice jam profiles (Restigouche and Rushoon rivers), the values of 2.5 and 1.0 m/s were found to give the best

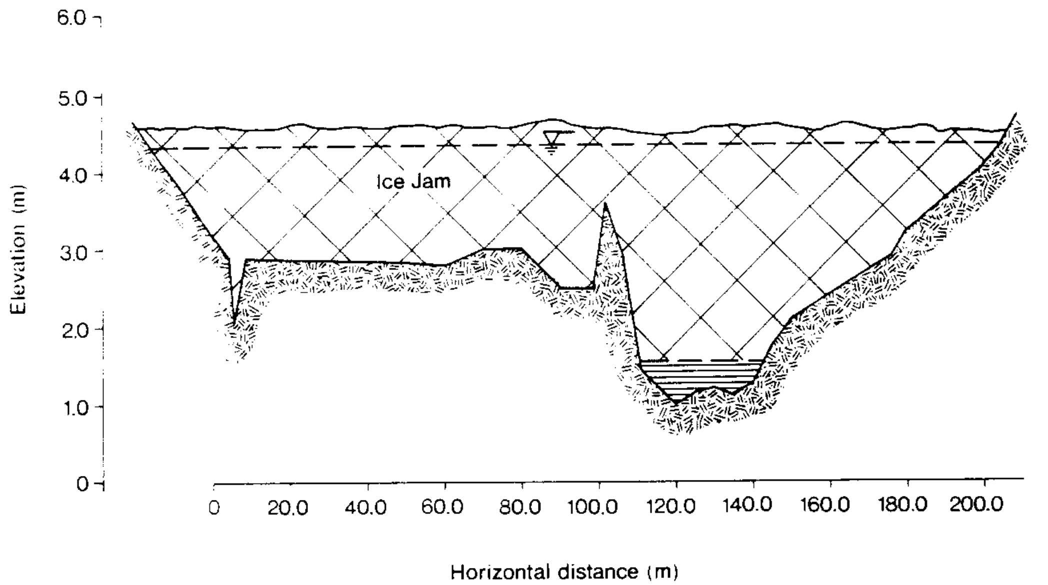

FIG. 11. Ice jam configuration at a section 46 m upstream of the toe, as determined by RIVJAM. Rushoon River, 1989 event (Sect. 6).

results. The first is about double what would be expected from extrapolating the lab test results; the second is comparable. As discussed earlier, a higher-than-expected value of λ could be due to a scale effect; this is evident in small-scale experimental results (see also Appendix A). However, this explanation would be irrelevant in the case of the Rushoon River. It appears that more measurements are needed to resolve this matter.

From the preceding results and discussion, it may be concluded that the structure of the model adequately describes the important features of ice jams, but current knowledge of the coefficients remains incomplete. Consequently, the use of the model for predictive purposes at a particular site should be preceded by local field observations and model calibration. Without calibration, model predictions will have to be combined with considerable judgment to ensure that uncertainties and errors are on the conservative side.

As already pointed out, RIVJAM only considers the "wide" type of jam. While this is generally adequate in practice, completeness would require that a subroutine be added to compute the "narrow" portion of the profile near the head and to identify the conditions under which the jam will revert to a single layer of blocks.

Another interesting question pertains to reaches with islands. At present, this question is ignored in the "hope" that the effect of islands on the overall configuration of a jam would be minimal, given their limited length. Where very long islands are present, one could consider separate applications of RIVJAM; the main problem is how to make the end conditions compatible.

Summary

RIVJAM is a one-dimensional numerical model to compute the configuration of "wide" cohesionless ice jams. It can compute in both the upstream and downstream directions, starting at a site of known thickness and water level. Irregular channel bathymetry, typical of natural streams, can be accommodated as a series of surveyed cross sections with linear interpolation performed by the model between successive sections. A major departure from earlier theoretical work is the consideration of the flow seeping through the voids of the jam. Invariably neglected in the past, this flow could represent a significant portion or even the entirety of the river discharge in cases of thick or grounded jams. Accounting for seepage enables the model to function in the downstream transition leading to the toe of the jam, and to predict grounding in accordance with observations. Neglect of seepage would, at some point, lead to infinitely high velocities for the flow under the jam. The model is easy to apply, requiring specification of relatively few coefficients. Already, we have a fair idea as to the numerical values of these coefficients, with the exception of the seepage parameter, λ.

Acknowledgments

Dr. B.G. Krishnappan's help in formulating the subroutine for user-specified limits of the friction factor is gratefully acknowledged.

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Appendix A. Flow through porous ice accumulations

Flow through porous media has three regimes, the "laminar," transitional, and "turbulent," depending on the flow Reynolds number, R. For low R, the seepage velocity is proportional to the pressure gradient or, in the case of gravity flow, to the water surface slope. This is the laminar regime, usually describing flow through frazil and slush accumulations that have voids of relatively small dimensions, such as hanging dams (see also Beltaos and Dean (1981)). Laminar seepage is extremely slow and could generally be neglected in comparison with the flow under the ice cover. On the other hand, large values of R imply turbulent conditions and the seepage velocity is now proportional to the square root of the pressure gradient or slope. For the large void dimensions encountered in accumulations of ice blocks, the seepage is in the turbulent regime which is what equation [8] expresses.

Various theoretical formulations exist to provide a physical basis for porous media flow (e.g., see Bear (1972)). For turbulent seepage, the coefficient that appears in [8] is given by

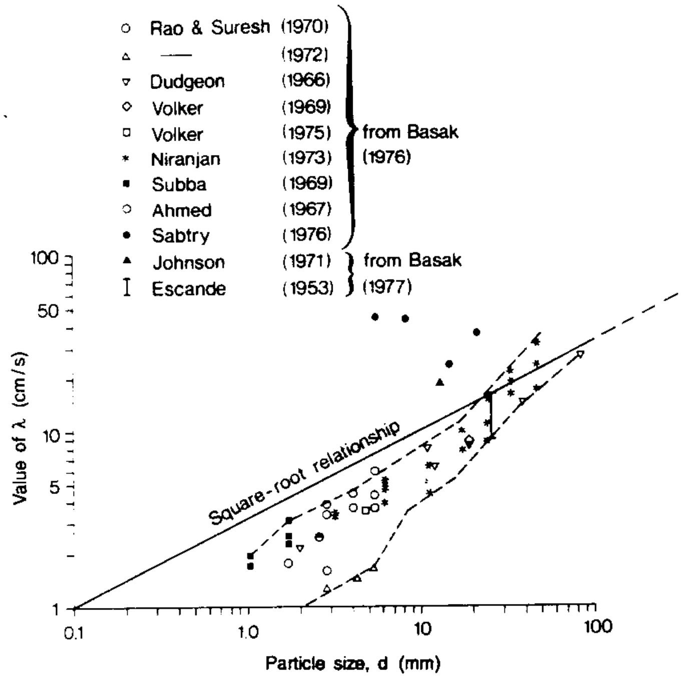


FIG. A1. Variation of λ with size of gravel and rock.

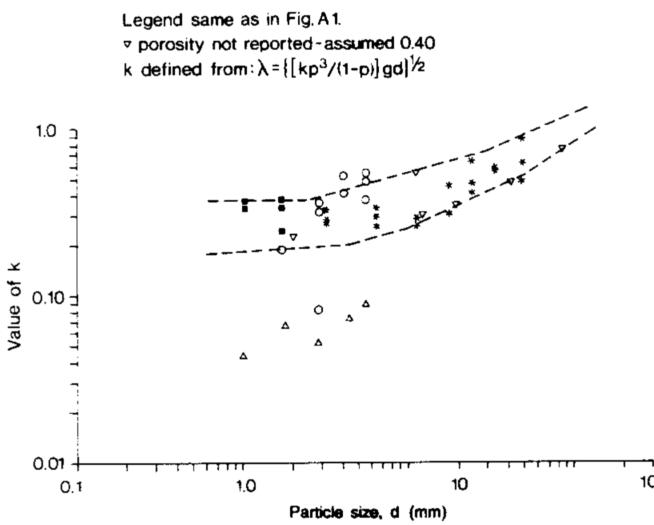


FIG. A2. Variation of dimensionless seepage coefficient, k, with size of gravel and rock.

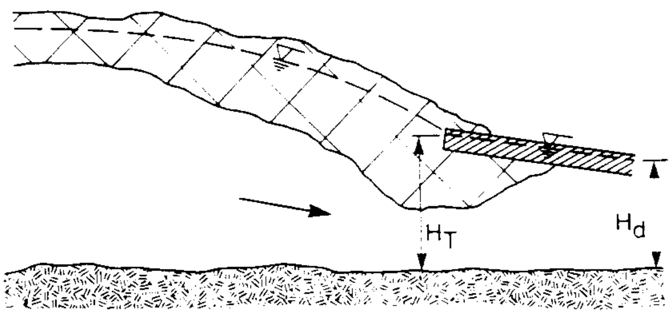


FIG. B1. Schematic illustration of a floating toe condition.

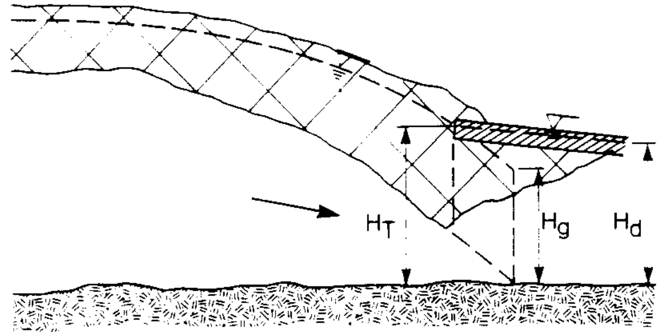


FIG. B2. Illustration of RIVJAM profile truncation when the toe is floating.

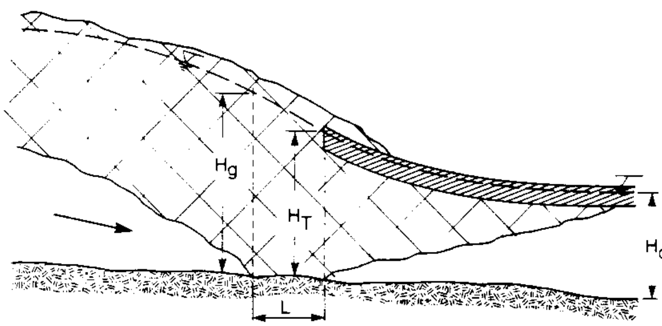


FIG. B3. Schematic illustration of grounded toe conditions.

[A1] $$\lambda = \sqrt{K\frac{p^3}{1-p}gd_s}$$

in which d_s = 6 × volume of solids/surface area of solids, which is a characteristic dimension of the porous medium, related to the hydraulic radius of the flow in the voids. The dimensionless coefficient K was found to be 0.70 for randomly placed square blocks (5 × 5 × 0.6 cm and 10 × 10 × 1.3 cm) by Beltaos and Wong (1986*b*). For gravel particles, Ergun recommended a value of 0.57 (as quoted in Bear (1972)). There is no information on the actual, field values of λ. If we extrapolate using [A1] and K = 0.70, and assume that the ratio of ice block diameter to thickness equals 4, we find that

[A2] $$\frac{\lambda}{\sqrt{gt_i}} = \sqrt{\frac{1.4p^3}{1-p}}$$

in which t_i is the ice block thickness. The porosity of natural jams is not well known; there is some evidence in favour of p = 0.40 for accumulations of ice blocks during breakup (Prowse 1990). Then [A2] gives

[A3] $$\frac{\lambda}{\sqrt{gt_i}} = 0.4$$

For a typical thickness of 0.5 m, we then have λ = 0.9 m/s. If the porosity were taken as 0.60, then λ = 2.0 m/s.

Relevant information may also be found in literature regarding flow through rockfill, e.g., Leps (1973). Several data sets were reanalyzed by Basak (1976), for gravel sizes of up to 8.4 cm. Assuming that d_s = constant × d (d is gravel diameter), we can study these data on the basis of [A1] where we substitute d_s with d and K with k. Then, we would expect λ to vary as the square root of d, but Fig. A1 suggests that this may not be the case. The same is implied in Fig. A2 where the possible influence of porosity is accounted for. Here, the data suggest that there may be a scale effect on k so that extrapolations to natural ice accumulations using small-scale laboratory data would tend to underestimate the value of λ. However, the available information is too limited to permit speculation as to what the magnitude of this effect might be.

Appendix B. Toe conditions

As an introduction to this problem, consider Fig. B1, depicting the toe conditions when no grounding occurs (based on field measurements reported by Beltaos (1988*b*)). The jam is essentially held in place by friction between the rubble and the relatively intact ice cover downstream of the toe. This force also enables the thickness of the rubble to taper down to nil some distance downstream. The water level and sheet ice at the toe will be slightly higher than farther downstream, respectively owing to higher hydraulic roughness and buoyancy of the rubble. Unless the rubble is exceedingly thick, these effects are negligible. Therefore, when the grounding depth, H_g, is less than H_d, it is reasonable to truncate the computed profile at the section where $t_s + h = H_T$, as shown in Fig. B2. This is the type of toe that one might expect in relatively deep, flat, and not too wide rivers.

Consider now the case where H_g is well in excess of H_d. From what has already been outlined, we expect the configuration depicted in Fig. B3. Here, the water depth at the toe, H_T, is less than H_g but more than H_d. The length of grounding, L, depends on H_g, H_T, and Q_T. For a very wide rectangular channel, it can be shown that (Wong and Beltaos 1985)

[B1] $$L = \lambda^2\frac{H_g^3 - H_T^3}{3q_T^2}$$

in which q_T is the discharge per unit width. Using [B1], the grounding length can be shown to be in the order of tens of metres. Where grounding is much more extensive, it is more likely due to drastic flow reduction after a thick jam has formed.

At present, we have no way of computing the value of H_T and there is no hard evidence that Fig. B3 is correct in its details. It is very important in this context to measure water level profiles of ice jams in the vicinity of the toe, both upstream and downstream, particularly in steep, wide rivers.

appendix d

Exploits River Frazil Ice Production Frequency Analysis

WSC STATION NO=1
WSC STATION NAME=Exploits River Slush Rate Freqency Analysis

MONTH (1)	YEAR (2)	DATA (3) (CMS)	ORDERED (4) (CMS)	RANK (5)	PROB. (6) (%)	RET. PERIOD (7) (YEARS)
**	36	2250.000	2500.000	1	1.46	68.667
**	44	100.100	2250.000	2	3.88	25.750
**	46	800.000	2230.000	3	6.31	15.846
**	50	1300.000	1670.000	4	8.74	11.444
**	53	1560.000	1560.000	5	11.17	8.957
**	54	100.200	1300.000	6	13.59	7.357
**	55	570.000	1230.000	7	16.02	6.242
**	56	1670.000	1180.000	8	18.45	5.421
**	57	100.300	1130.000	9	20.87	4.791
**	58	1040.300	1040.300	10	23.30	4.292
**	59	1000.000	1020.000	11	25.73	3.887
**	60	900.000	1000.000	12	28.16	3.552
**	61	740.000	999.900	13	30.58	3.270
**	62	1230.000	960.000	14	33.01	3.029
**	63	299.000	930.000	15	35.44	2.822
**	64	500.000	900.000	16	37.86	2.641
**	65	1130.000	820.000	17	40.29	2.482
**	66	999.900	800.000	18	42.72	2.341
**	67	100.400	800.000	19	45.15	2.215
**	68	100.500	760.000	20	47.57	2.102
**	69	100.600	750.000	21	50.00	2.000
**	70	560.000	740.000	22	52.43	1.907
**	71	650.000	650.000	23	54.85	1.823
**	72	960.000	650.000	24	57.28	1.746
**	73	401.000	640.000	25	59.71	1.675
**	74	1180.000	570.000	26	62.14	1.609
**	75	650.000	560.000	27	64.56	1.549
**	76	2500.000	520.000	28	66.99	1.493
**	77	100.700	500.000	29	69.42	1.441
**	78	750.000	401.000	30	71.84	1.392
**	80	100.800	380.000	31	74.27	1.346
**	81	380.000	301.000	32	76.70	1.304
**	82	2230.000	299.000	33	79.13	1.264
**	83	301.000	100.800	34	81.55	1.226
**	86	820.000	100.700	35	83.98	1.191
**	87	760.000	100.600	36	86.41	1.157
**	89	520.000	100.500	37	88.83	1.126
**	90	1020.000	100.400	38	91.26	1.096
**	91	930.000	100.300	39	93.69	1.067
**	92	640.000	100.200	40	96.12	1.040
**	93	800.000	100.100	41	98.54	1.015

FREQUENCY ANALYSIS - THREE-PARAMETER LOGNORMAL DISTRIBUTION

1 Exploits River Slush Rate Freqency Analysis

SAMPLE STATISTICS

	MEAN	S.D.	C.V.	C.S.	C.K.
X SERIES	801.093	600.142	0.749	1.102	4.496
LN X SERIES	6.325	0.978	0.155	-0.743	2.755
LN(X-A) SERIES	7.383	0.334	0.045	0.261	2.910

X(MIN)= 100.100 TOTAL SAMPLE SIZE= 41

X(MAX)= 2500.000 NO. OF LOW OUTLIERS= 0

LOWER OUTLIER LIMIT OF X= 40.132 NO. OF ZERO FLOWS= 0

SOLUTION OBTAINED VIA MOMENTS

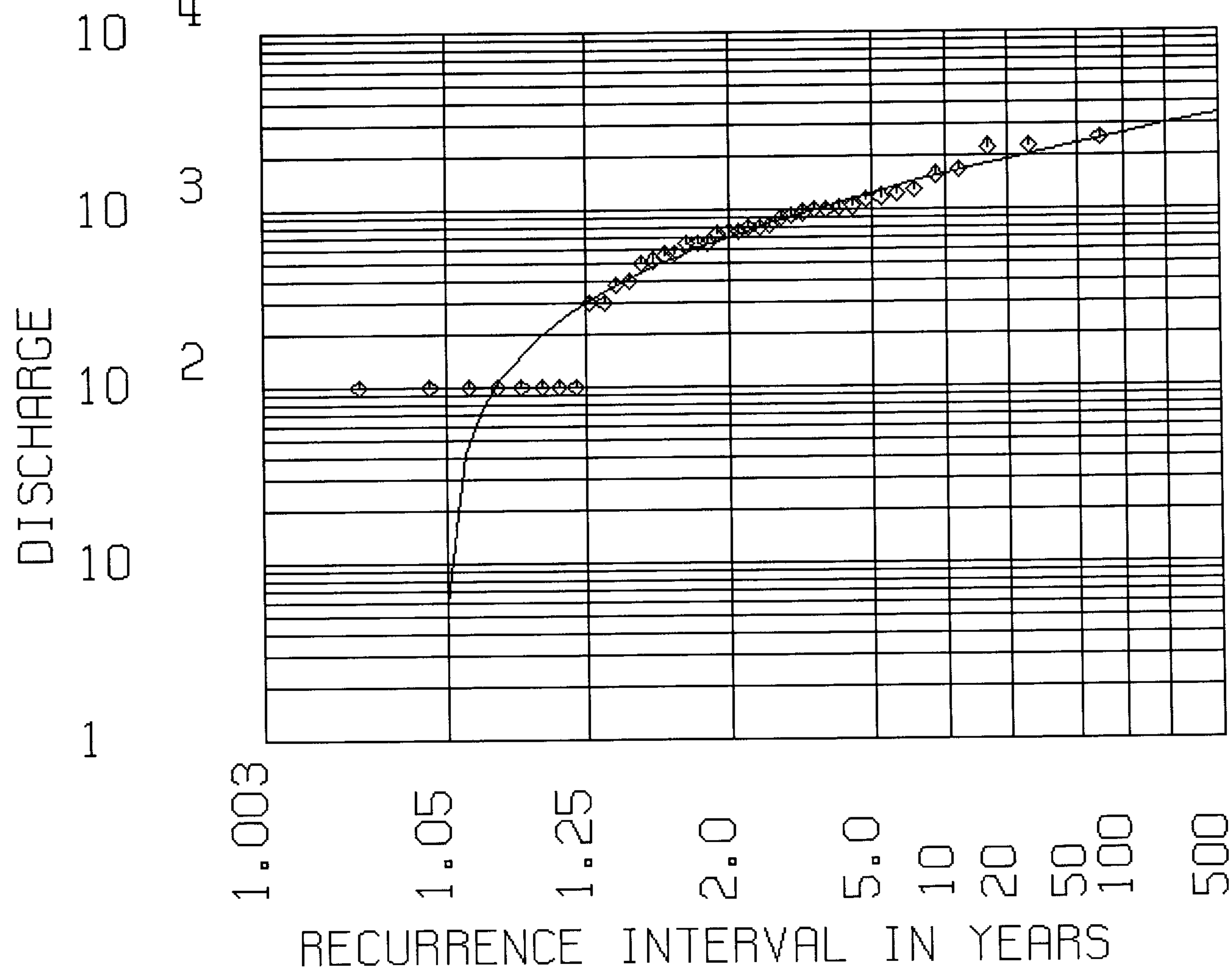
3LN PARAMETERS: A= -899.840 M= 7.380 S= 0.343

FLOOD FREQUENCY REGIME

RETURN PERIOD	EXCEEDANCE PROBABILITY	FLOOD
1.003	0.997	-
1.050	0.952	5.82
1.250	0.800	303.00
2.000	0.500	704.00
5.000	0.200	1240.00
10.000	0.100	1590.00
20.000	0.050	1920.00
50.000	0.020	2340.00
100.000	0.010	2660.00
200.000	0.005	2980.00
500.000	0.002	3400.00

FREQUENCY ANALYSIS - 1

THREE PARAMETER LØGNØRMAL-MØMENT



appendix e

River Ice Model Data Files: 1986-87 to 1994-95

(provided digitally)

DISKETTE 1

Directory of \RIVJAM93

DRKGS.FOR
FNDWA.FOR
FCLOSE.FOR
PROP.FOR
WROUT.FOR
FCT2.FOR
SOLVE2.FOR
FILEIO.FOR
READIN.FOR
MAIN.FOR
CHNGXS.FOR
FILEIO_B.FOR
CNVRTXS.FOR
89RESTXS.DAT
89RESTIN.DAT
RIVJAM.EXE
CNVRTXS.EXE
STA19453.DAT
STR19453.DAT
README.FIR
CNVRTXS.OBJ
SOLVE2M.FOR
89RESOUT
89RESPLO

Directory of \RIVICE

RIVICE

Directory of \ICEMODEL

ICE4I2.BAS
ICE4I2.EXE

Directory of \INPUT

ICE86.PRN
ICE87.PRN
ICE88.PRN
ICE89.PRN
ICE90.PRN
ICE91.PRN
ICE92.PRN
ICE93.PRN
ICE94.PRN

Directory of \OUTPUT

ICE8687A.OUT
ICE8788G.OUT
ICE8889A.OUT
ICE8990D.OUT
ICE9091P.OUT

DISKETTE 2

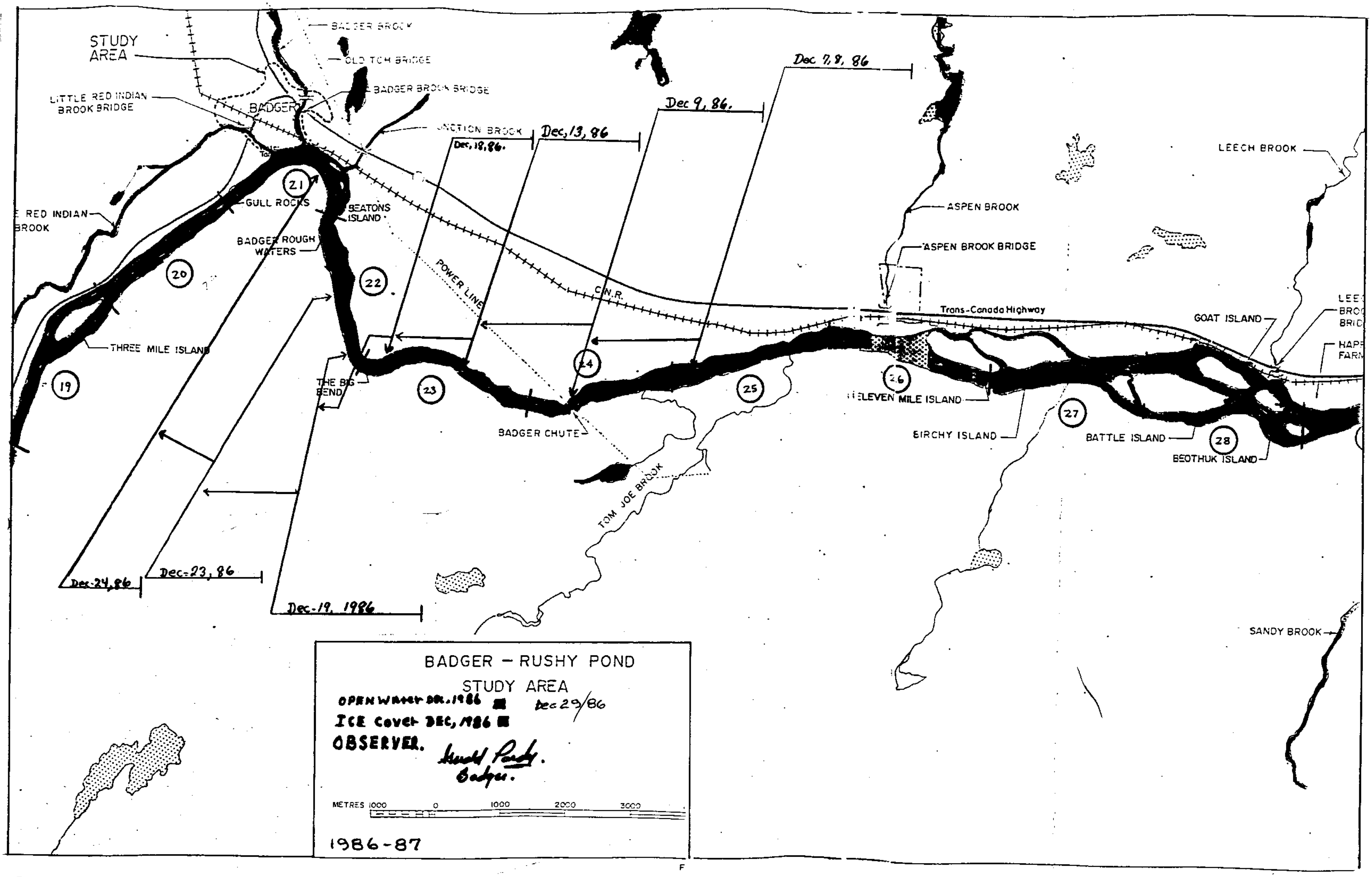
Directory of \OUTPUT

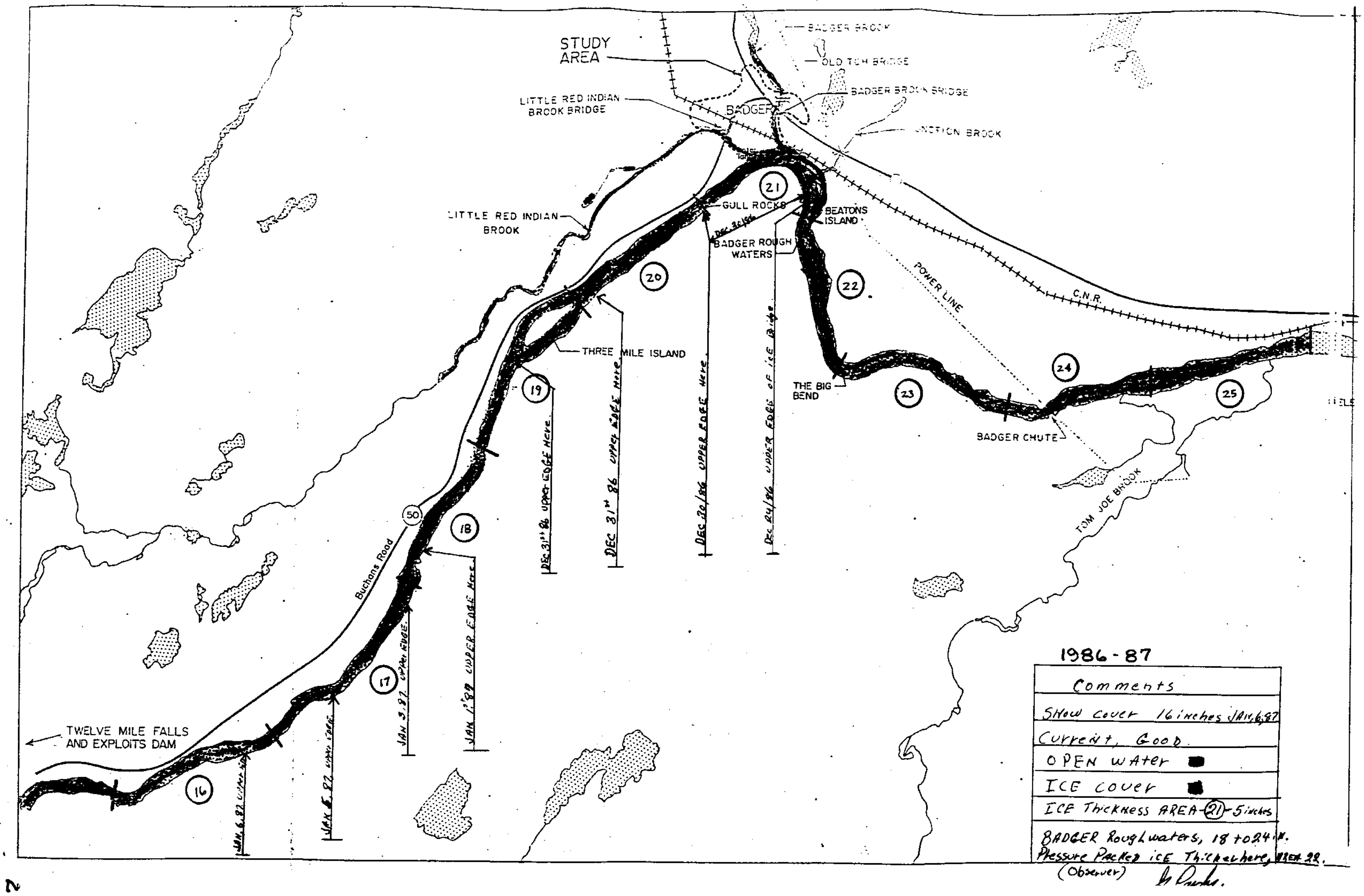
ICE9192A.OUT
ICE9293A.OUT
ICE9394C.OUT
ICE94 .OUT

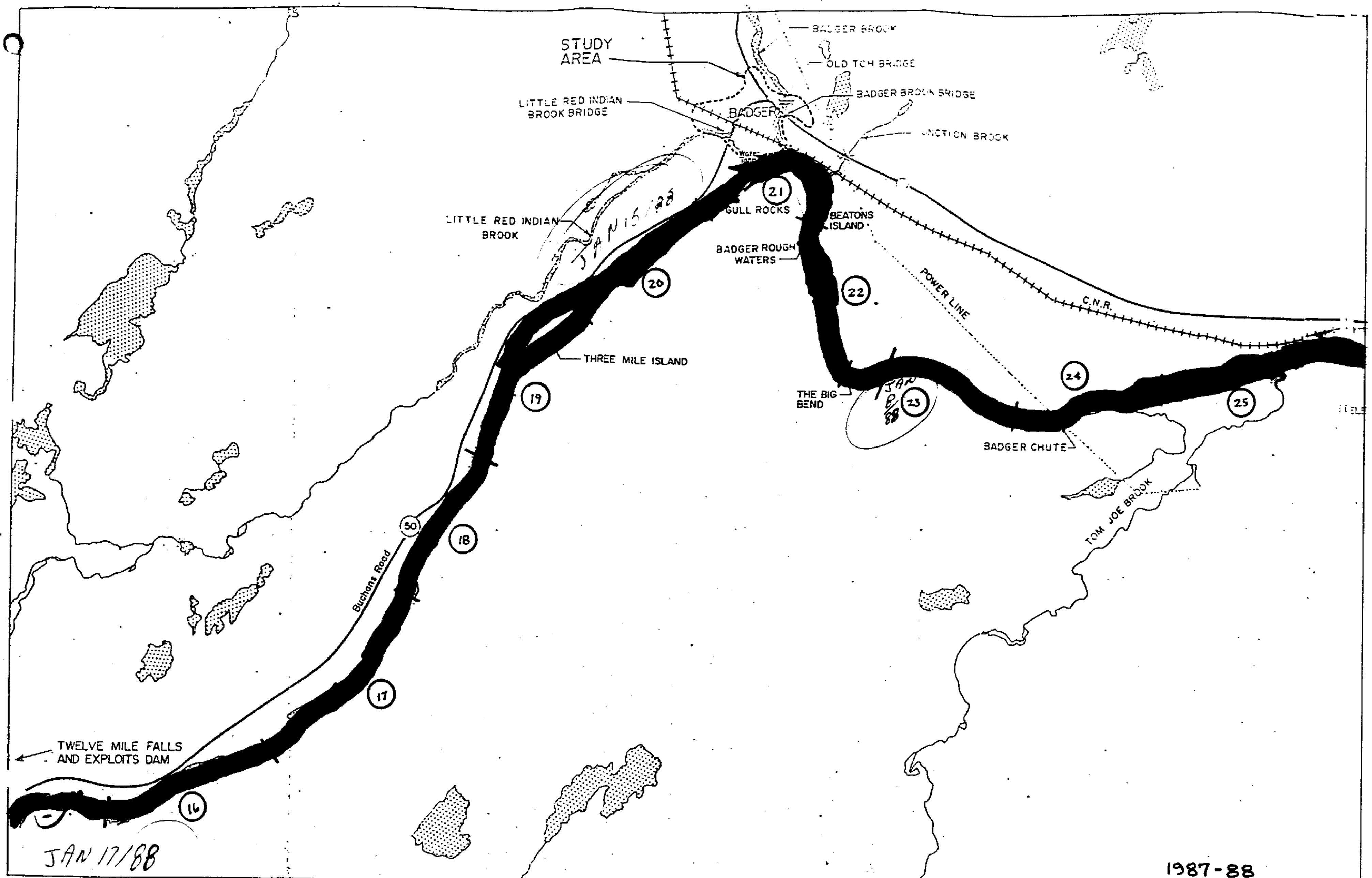
appendix f

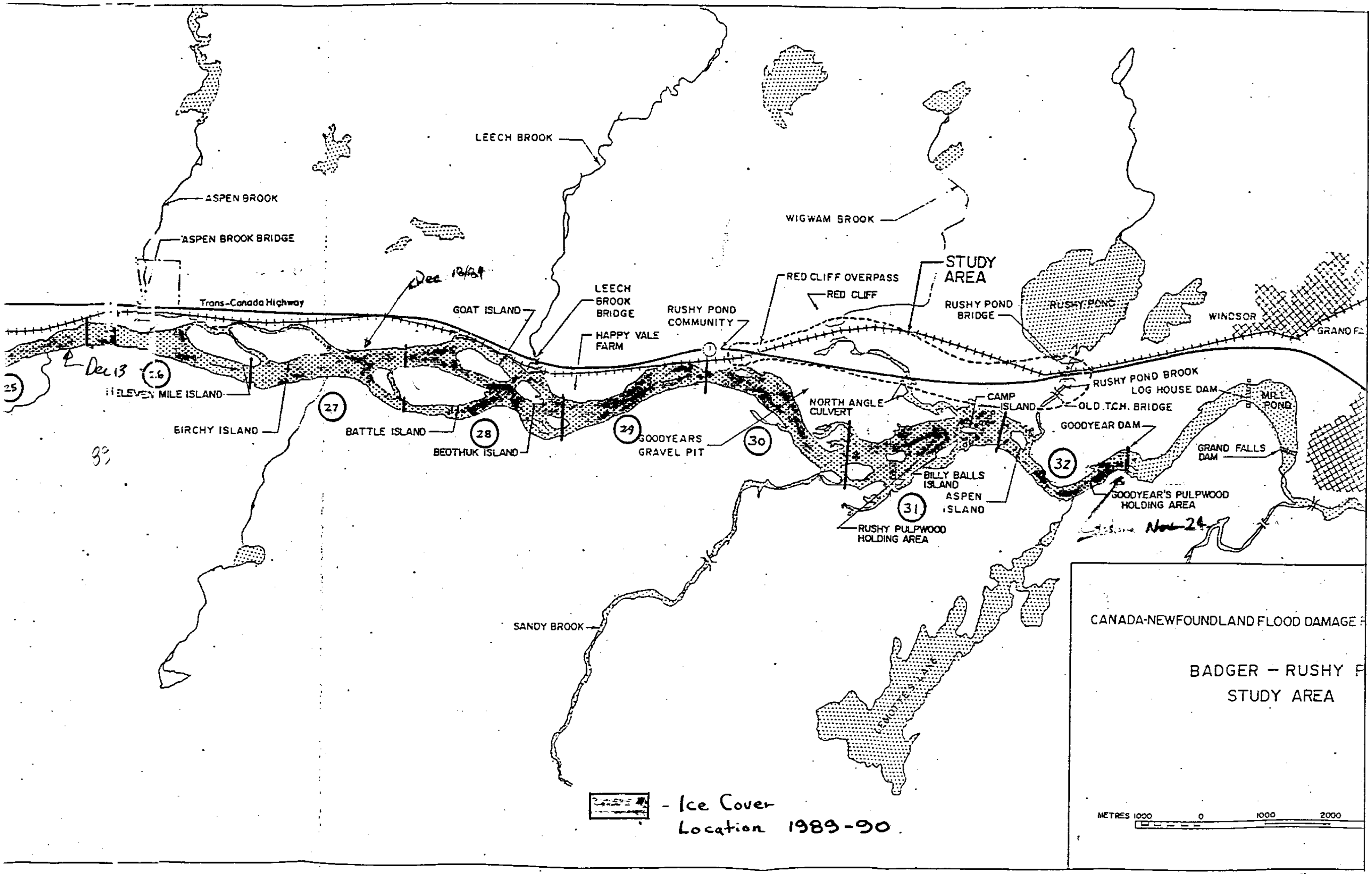
Ice Progression Mapping

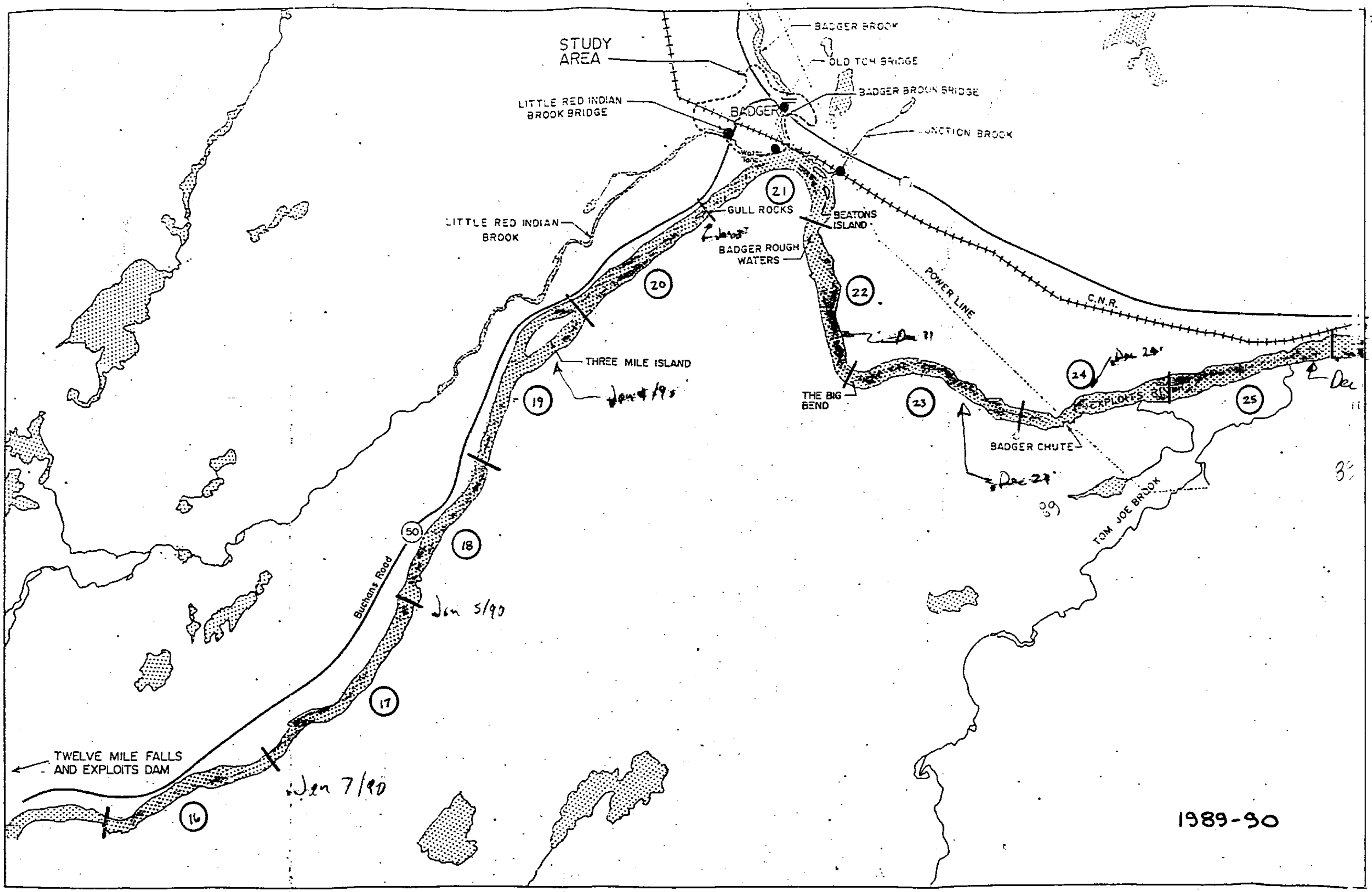
1986-87
1987-88
1989-90
1992-93
1993-94


BADGER – RUSHY POND
STUDY AREA
OPEN WATER DEC. 1986
Dec 29/86
ICE COVER DEC, 1986
OBSERVER.
Badger.
METRES 1000 0 1000 2000 3000
1986-87
STUDY AREA
LITTLE RED INDIAN BROOK BRIDGE
RED INDIAN BROOK
BADGER
BADGER BROOK
OLD TCH BRIDGE
BADGER BROOK BRIDGE
JUNCTION BROOK
GULL ROCKS
BEATONS ISLAND
BADGER ROUGH WATERS
THREE MILE ISLAND
THE BIG BEND
POWER LINE
C.N.R.
BADGER CHUTE
TOM JOE BROOK
ASPEN BROOK
ASPEN BROOK BRIDGE
Trans-Canada Highway
ELEVEN MILE ISLAND
BIRCHY ISLAND
BATTLE ISLAND
BEOTHUK ISLAND
GOAT ISLAND
LEECH BROOK
SANDY BROOK
19
20
21
22
23
24
25
26
27
28
Dec 7, 8, 86
Dec 9, 86.
Dec, 13, 86
Dec, 18, 86.
Dec-19, 1986
Dec-23, 86
Dec-24, 86


STUDY AREA
LITTLE RED INDIAN BROOK BRIDGE
BADGER BROOK
OLD TOWN BRIDGE
BADGER BROOK BRIDGE
JUNCTION BROOK
BADGER
LITTLE RED INDIAN BROOK
GULL ROCKS
BEATONS ISLAND
BADGER ROUGH WATERS
POWER LINE
C.N.R.
THREE MILE ISLAND
THE BIG BEND
BADGER CHUTE
TOM JOE BROOK
Buchans Road
50
TWELVE MILE FALLS AND EXPLOITS DAM
16
17
18
19
20
21
22
23
24
25
DEC 31st 86 upper edge here
DEC 31st 86 upper edge here
DEC 30/86 upper edge here
DEC 24/86 upper edge of ice bridge
JAN 1st 87 upper edge here
JAN 3.87 upper edge
JAN 6.87 upper edge
JAN 6.87 upper edge
1986-87
Comments
Snow cover 16 inches JAN 6.87
Current, Good
OPEN water
ICE cover
ICE Thickness AREA (21) - 5 inches
BADGER Roughwaters, 18 to 24 in.
Pressure Packed ice Thicker here, AREA 22.
(Observer)


STUDY AREA
BADGER BROOK
OLD TCH BRIDGE
BADGER BROOK BRIDGE
LITTLE RED INDIAN BROOK BRIDGE
BADGER
JUNCTION BROOK
LITTLE RED INDIAN BROOK
JAN 15/88
GULL ROCKS
BEATONS ISLAND
BADGER ROUGH WATERS
POWER LINE
C.N.R.
THREE MILE ISLAND
THE BIG BEND
JAN 8/88
BADGER CHUTE
TOM JOE BROOK
Buchans Road
50
TWELVE MILE FALLS AND EXPLOITS DAM
16
17
18
19
20
21
22
23
24
25
JAN 17/88
1987-88


CANADA-NEWFOUNDLAND FLOOD DAMAGE
BADGER – RUSHY
STUDY AREA
METRES 1000 0 1000 2000
Ice Cover Location 1989-90
STUDY AREA
Trans-Canada Highway
ASPEN BROOK
ASPEN BROOK BRIDGE
LEECH BROOK
WIGWAM BROOK
RED CLIFF OVERPASS
RED CLIFF
RUSHY POND
RUSHY POND BRIDGE
WINDSOR
GOAT ISLAND
LEECH BROOK BRIDGE
HAPPY VALE FARM
RUSHY POND COMMUNITY
RUSHY POND BROOK
LOG HOUSE DAM
MILL POND
OLD T.C.H. BRIDGE
CAMP ISLAND
NORTH ANGLE CULVERT
GOODYEAR DAM
GRAND FALLS DAM
GOODYEAR'S PULPWOOD HOLDING AREA
BILLY BALLS ISLAND
ASPEN ISLAND
RUSHY PULPWOOD HOLDING AREA
GOODYEARS GRAVEL PIT
BEOTHUK ISLAND
BATTLE ISLAND
BIRCHY ISLAND
ELEVEN MILE ISLAND
SANDY BROOK
25
26
27
28
29
30
31
32
Dec 13
Nov 24


STUDY AREA
BADGER BROOK
OLD TCH BRIDGE
BADGER BROOK BRIDGE
LITTLE RED INDIAN BROOK BRIDGE
BADGER
JUNCTION BROOK
LITTLE RED INDIAN BROOK
GULL ROCKS
BEATONS ISLAND
BADGER ROUGH WATERS
POWER LINE
C.N.R.
THREE MILE ISLAND
THE BIG BEND
BADGER CHUTE
EXPLOITS
TOM JOE BROOK
Buchans Road
50
TWELVE MILE FALLS AND EXPLOITS DAM
16
17
18
19
20
21
22
23
24
25
Jan 5/90
Jan 7/90
Dec 27
Dec 24
1989-90

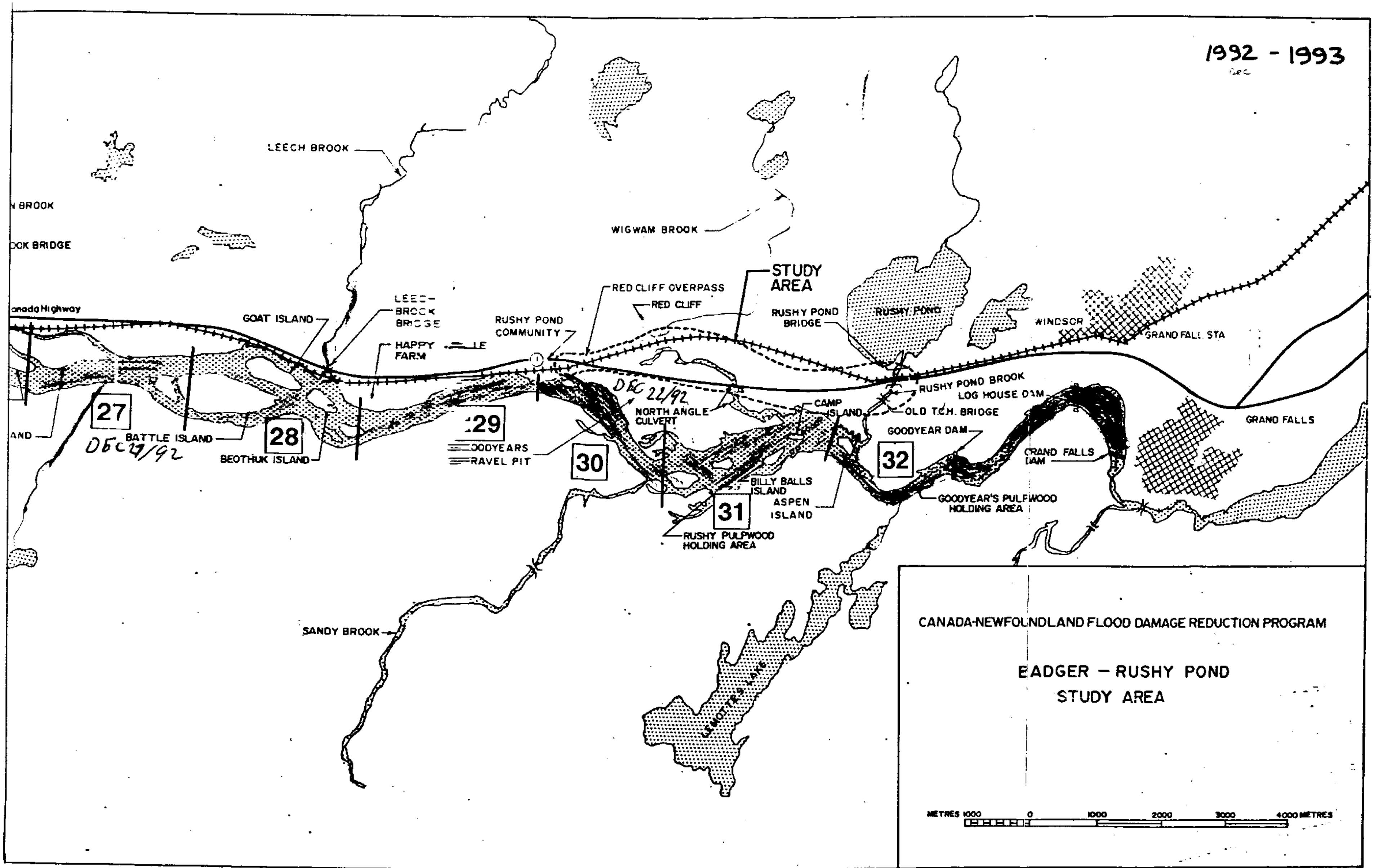
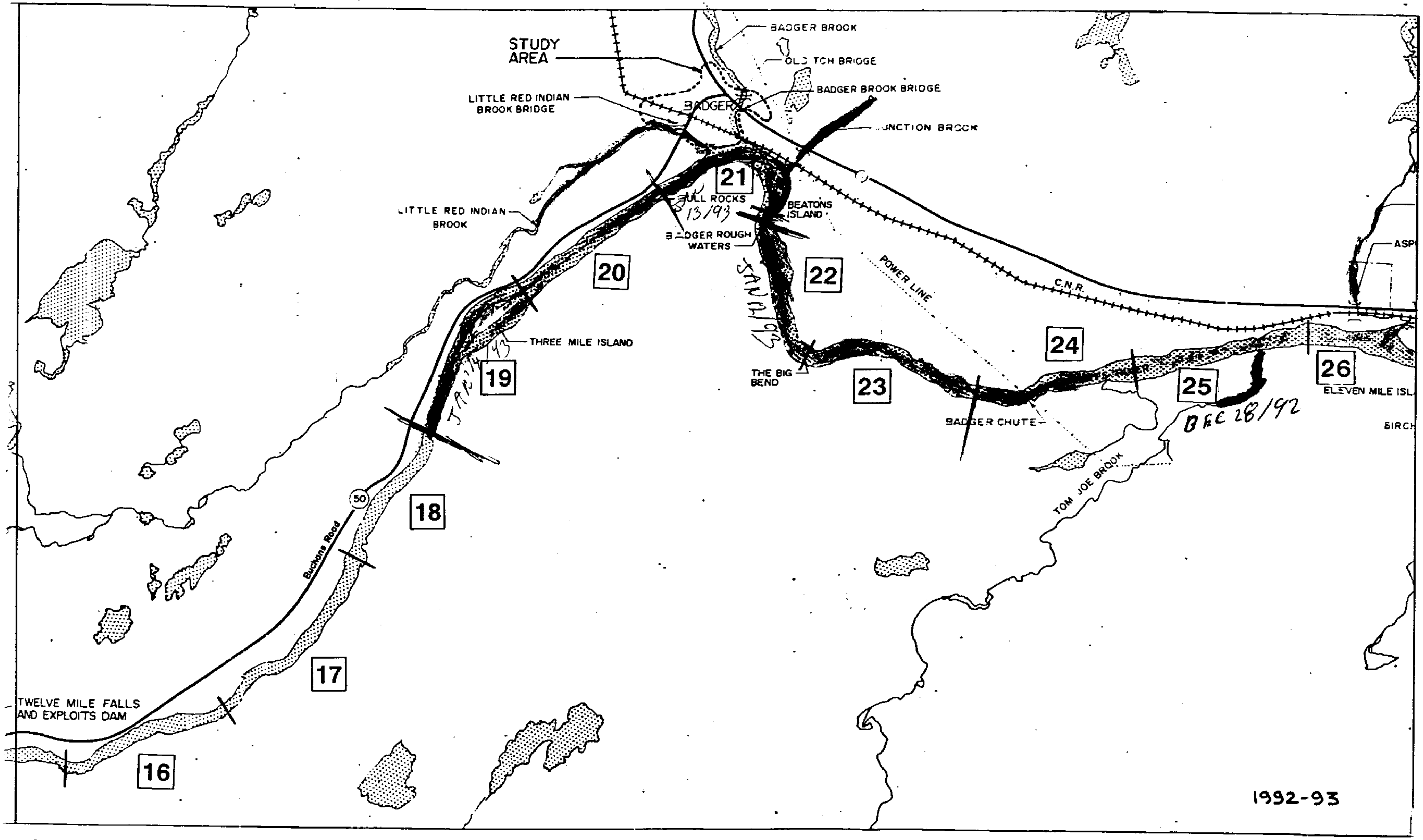
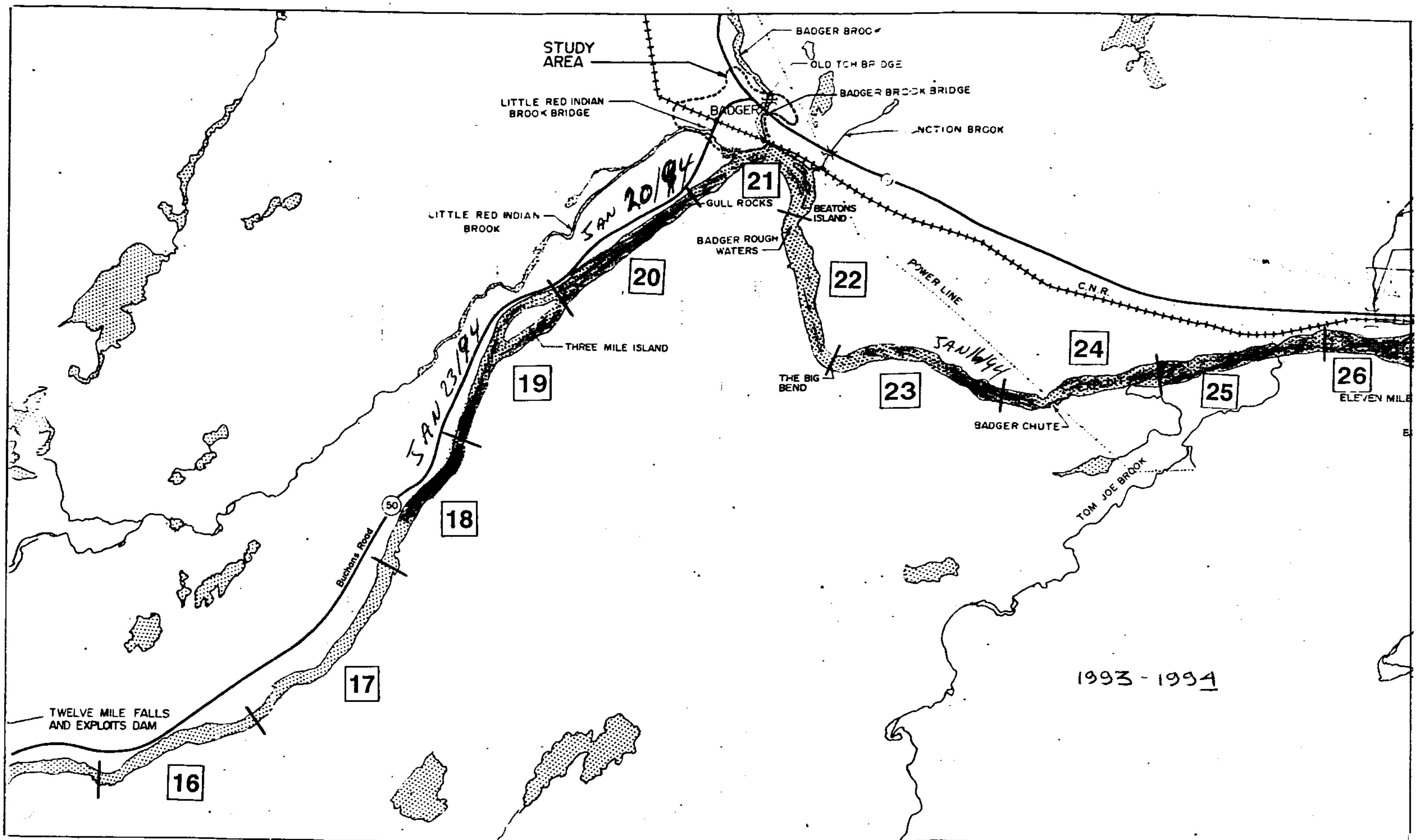

1992 - 1993
LEECH BROOK
BROOK
OK BROOK BRIDGE
Canada Highway
WIGWAM BROOK
STUDY AREA
RED CLIFF OVERPASS
RED CLIFF
RUSHY POND BRIDGE
RUSHY POND
WINDSOR
GRAND FALL STA
GOAT ISLAND
LEECH BROOK BRIDGE
HAPPY FARM
RUSHY POND COMMUNITY
RUSHY POND BROOK
LOG HOUSE DAM
OLD T.C.H. BRIDGE
GRAND FALLS
27
AND
BATTLE ISLAND
DEC 29/92
28
BEOTHUK ISLAND
29
GOODYEARS GRAVEL PIT
DEC 22/92
NORTH ANGLE CULVERT
30
CAMP ISLAND
GOODYEAR DAM
GRAND FALLS DAM
32
BILLY BALLS ISLAND
ASPEN ISLAND
31
RUSHY PULPWOOD HOLDING AREA
GOODYEAR'S PULPWOOD HOLDING AREA
SANDY BROOK
CANADA-NEWFOUNDLAND FLOOD DAMAGE REDUCTION PROGRAM
BADGER – RUSHY POND STUDY AREA
METRES 1000 0 1000 2000 3000 4000 METRES

FIGURE 2.2



STUDY AREA
BADGER BROOK
OLD TCH BRIDGE
BADGER BROOK BRIDGE
JUNCTION BROOK
LITTLE RED INDIAN BROOK BRIDGE
BADGER
LITTLE RED INDIAN BROOK
21
BULL ROCKS
13/93
BEATONS ISLAND
BADGER ROUGH WATERS
JAN 12/93
20
22
POWER LINE
C.N.R.
ASP
THREE MILE ISLAND
JAN 14/93
19
THE BIG BEND
23
24
BADGER CHUTE
25
26
ELEVEN MILE ISL
DEC 28/92
BIRCH
TOM JOE BROOK
50
18
Buchans Road
17
TWELVE MILE FALLS AND EXPLOITS DAM
16
1992-93

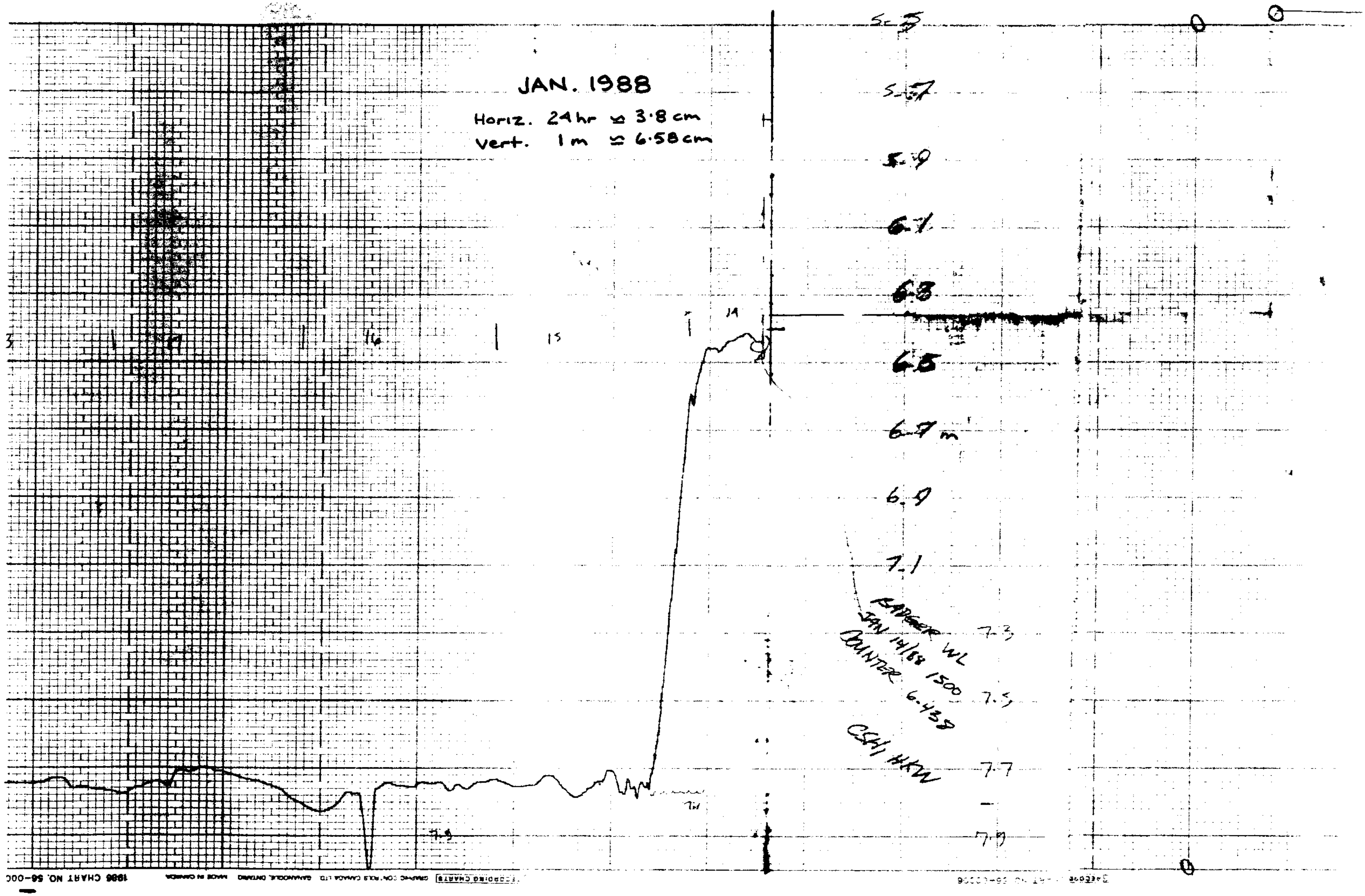

STUDY AREA
LITTLE RED INDIAN BROOK BRIDGE
LITTLE RED INDIAN BROOK
BADGER
BADGER BROOK
OLD TCH BRIDGE
BADGER BROOK BRIDGE
NCTION BROOK
C.N.R.
POWER LINE
GULL ROCKS
BEATONS ISLAND
BADGER ROUGH WATERS
THREE MILE ISLAND
THE BIG BEND
BADGER CHUTE
TOM JOE BROOK
ELEVEN MILE
TWELVE MILE FALLS AND EXPLOITS DAM
Buchans Road
50
16
17
18
19
20
21
22
23
24
25
26
JAN 23/94
JAN 20/94
JAN 1/94
1993 - 1994

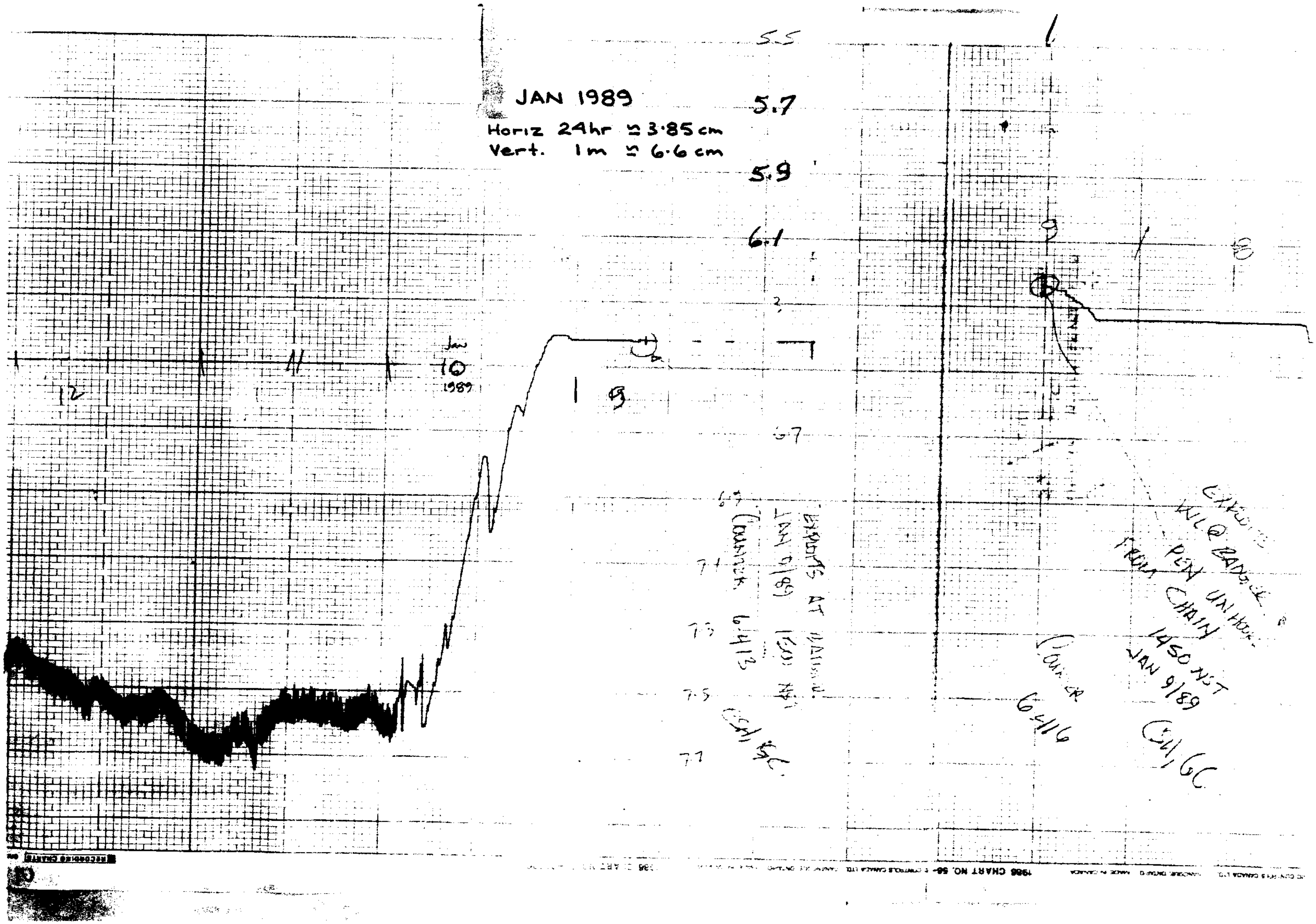
8

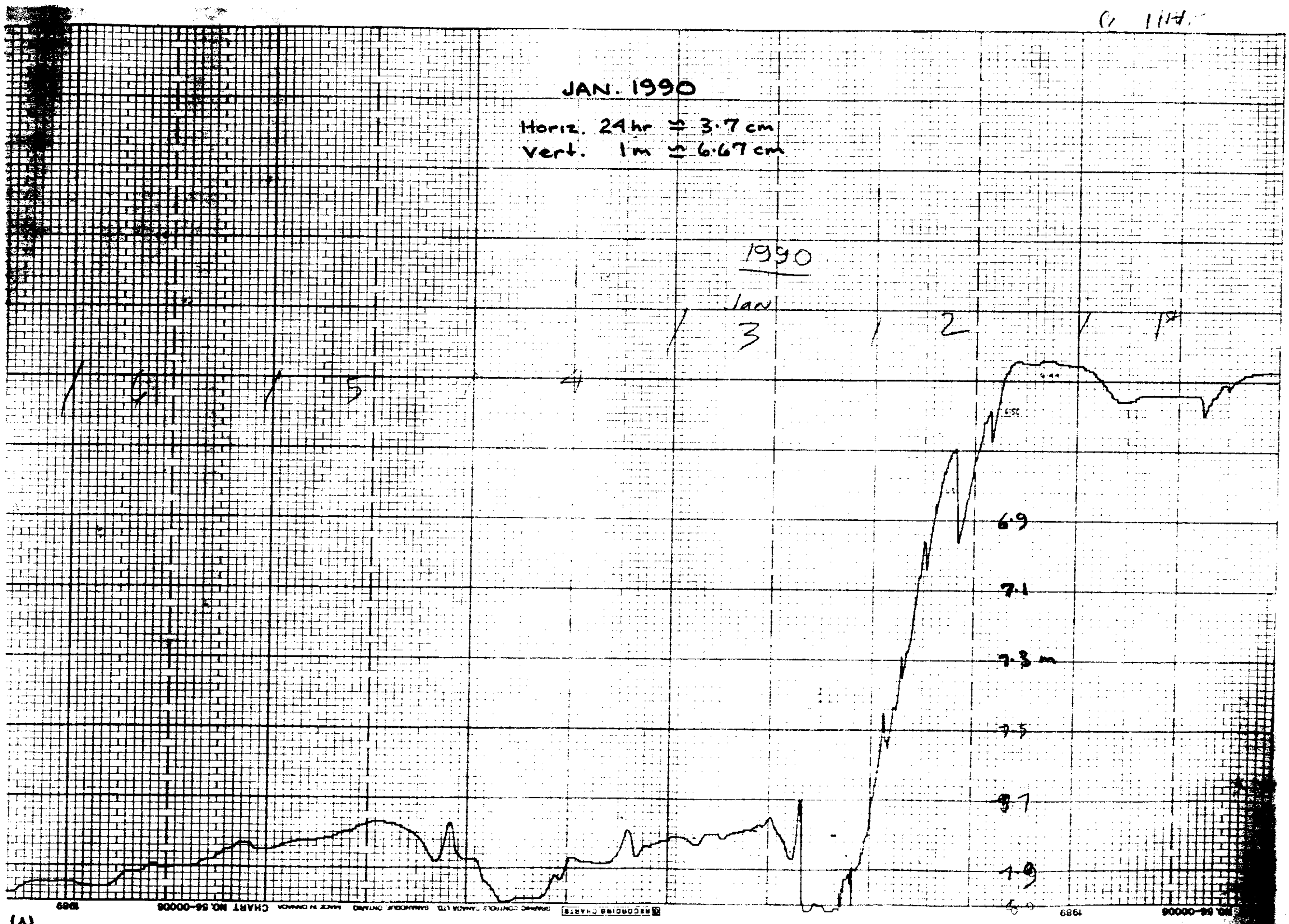
appendix g

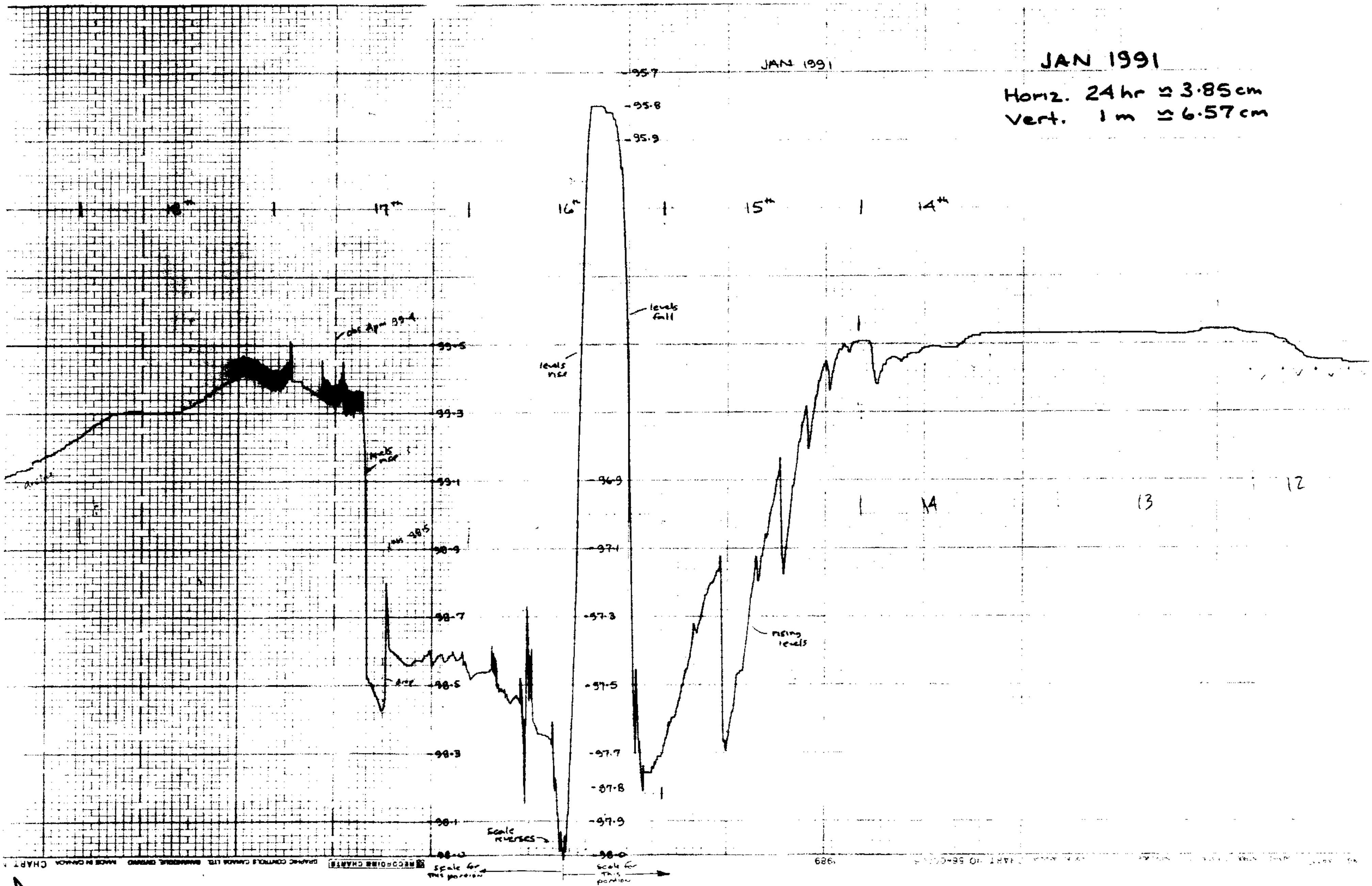
Strip Chart Water Level Records

January 1988
January 1989
January 1990
January 1992


JAN. 1988
Horiz. 24hr ≃ 3.8 cm
Vert. 1m ≃ 6.58 cm
5.5
5.7
5.9
6.1
6.3
6.5
6.7 m
6.9
7.1
7.3
7.5
7.7
7.9
14
15
16
BADGER WL
JAN 14/88 1500
COUNTER 6.438
CSH/HKW
1986 CHART NO. 58-00C


JAN 1989
Horiz 24hr ≃ 3·85 cm
Vert. 1m ≃ 6·6 cm
5.5
5.7
5.9
6.1
6.7
7.1
7.3
7.5
7.7
12
11
Jan 10 1989
EXPLOITS AT BADGER
JAN 9/89
COUNTER 6.413
PEN UNHOOK FROM CHAIN
1450 NST
JAN 9/89
COUNTER 6.416
1986 CHART NO. 58


JAN. 1990
Horiz. 24 hr ≃ 3.7 cm
Vert. 1 m ≃ 6.67 cm
1990
Jan
1
2
3
4
5
6
6.9
7.1
7.3 m
7.5
7.7
7.9
CHART NO. 56-00006
RECORDING CHARTS
MADE IN CANADA
1989


JAN 1991
Horiz. 24 hr ≃ 3.85 cm
Vert. 1 m ≃ 6.57 cm
JAN 1991
17th
16th
15th
14th
14
13
12
levels fall
levels rise
rising levels
Scale reverses
scale for this portion
scale for this portion
-95.7
-95.8
-95.9
-96.9
-97.1
-97.3
-97.5
-97.7
-97.8
-97.9
-98.0
99.5
99.3
99.1
98.9
98.7
98.5
98.3
98.1
98.0
RECORDING CHARTS
GRAPHIC CONTROLS CANADA LTD. GANANOQUE, ONTARIO MADE IN CANADA CHART

4

appendix h

Climatic Normals - Dew Point

BUCHANS (A), NFLD.

MEAN VALUES AT HOURS SHOWN — VALEURS MOYENNES AUX HEURES SYNOPTIQUES

	JAN JANV	FEB FEV	MAR MARS	APR AVR	MAY MAI	JUN JUIN	JUL JUIL	AUG AOUT	SEP SEPT	OCT OCT	NOV NOV	DEC DEC	
02 NST													
Dry Bulb Temperature (°F)	16	14	20	27	35	44	52	52	46	39	32	22	Température du thermomètre sec (°F)
Dew Point Temperature (°F)	12	9	15	24	32	40	49	50	43	36	29	18	Température du point de rosée (°F)
Relative Humidity (%)	84	82	82	87	87	87	89	91	88	91	88	85	Humidité relative (p. 100)
08 NST													
Dry Bulb Temperature (°F)	16	13	20	30	41	49	57	56	50	40	32	21	Température du thermomètre sec (°F)
Dew Point Temperature (°F)	12	8	16	25	34	42	51	51	45	36	29	17	Température du point de rosée (°F)
Relative Humidity (%)	85	82	84	82	77	76	81	82	84	87	89	83	Humidité relative (p. 100)
14 NST													
Dry Bulb Temperature (°F)	20	19	27	35	49	58	66	65	57	46	35	25	Température du thermomètre sec (°F)
Dew Point Temperature (°F)	15	14	21	28	36	43	52	51	45	37	31	20	Température du point de rosée (°F)
Relative Humidity (%)	81	80	79	74	62	56	60	60	63	70	84	81	Humidité relative (p. 100)
20 NST													
Dry Bulb Temperature (°F)	17	15	22	31	41	52	59	57	49	40	33	22	Température du thermomètre sec (°F)
Dew Point Temperature (°F)	13	11	18	26	34	43	52	51	44	36	29	18	Température du point de rosée (°F)
Relative Humidity (%)	84	83	85	83	75	72	77	79	82	81	87	83	Humidité relative (p. 100)

MEAN VALUES (Mean of four synoptic observations) — VALEURS MOYENNES (Moyenne des quatre observations synoptiques)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Dry Bulb Temperature (°F)	17	15	22	31	42	51	59	58	51	41	33	23	Température du thermomètre sec (°F)
Dew Point Temperature (°F)	13	11	18	26	34	42	51	51	44	36	30	18	Température du point de rosée (°F)
Wet Bulb Temperature (°F)	16	14	21	29	38	46	54	54	47	39	32	22	Température du thermomètre mouillé (°F)
Mixing Ratio (gr/lb)	11	10	14	21	30	41	57	57	44	32	25	14	Rapport de mélange (g/liv.)
Relative Humidity (%)	84	83	85	82	74	72	76	78	78	84	88	82	Humidité relative (p. 100)

DEW POINT EXTREMES — EXTRÊMES DU POINT DE ROSÉE

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Mean of Highest Dew Point each month	38	36	36	40	52	53	64	64	63	57	52	43	Moyenne du point de rosée maximal chaque mois

Highest Dew Point Recorded (°F)	68	Point de rosée maximal enregistré (°F)
Corresponding Dry Bulb Temperature (°F)	70	Température du thermomètre sec correspondante (°F)
Corresponding Wet Bulb Temperature (°F)	69	Température du thermomètre mouillé correspondante (°F)
Corresponding Mixing Ratio (gr/lb)	107	Rapport de mélange correspondante (g/liv.)

CAPE RACE, NFLD.

MEAN VALUES AT HOURS SHOWN — VALEURS MOYENNES AUX HEURES SYNOPTIQUES

	JAN JANV	FEB FEV	MAR MARS	APR AVR	MAY MAI	JUN JUIN	JUL JUIL	AUG AOUT	SEP SEPT	OCT OCT	NOV NOV	DEC DEC	
02 NST													
Dry Bulb Temperature (°F)	27	25	27	31	36	42	50	54	50	44	38	31	Température du thermomètre sec (°F)
Dew Point Temperature (°F)	24	22	24	29	34	40	49	53	48	41	36	28	Température du point de rosée (°F)
Relative Humidity (%)	87	88	88	92	94	94	97	98	91	90	93	87	Humidité relative (p. 100)
08 NST													
Dry Bulb Temperature (°F)	27	25	27	34	39	45	53	57	54	46	39	31	Température du thermomètre sec (°F)
Dew Point Temperature (°F)	24	22	25	31	36	42	51	54	50	43	36	28	Température du point de rosée (°F)
Relative Humidity (%)	90	88	91	90	89	88	93	91	88	88	89	87	Humidité relative (p. 100)
14 NST													
Dry Bulb Temperature (°F)	29	27	31	36	41	47	55	59	56	48	41	33	Température du thermomètre sec (°F)
Dew Point Temperature (°F)	25	24	27	32	36	42	52	55	50	43	37	29	Température du point de rosée (°F)
Relative Humidity (%)	86	87	87	85	82	83	89	87	80	81	86	86	Humidité relative (p. 100)
20 NST													
Dry Bulb Temperature (°F)	27	26	28	32	37	43	51	55	51	45	39	31	Température du thermomètre sec (°F)
Dew Point Temperature (°F)	24	22	25	30	35	41	49	53	49	42	36	28	Température du point de rosée (°F)
Relative Humidity (%)	87	86	89	91	93	94	94	94	91	91	91	87	Humidité relative (p. 100)

MEAN VALUES (Mean of four synoptic observations) — VALEURS MOYENNES (Moyenne des quatre observations synoptiques)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Dry Bulb Temperature (°F)	28	26	28	33	38	44	52	56	53	46	39	32	Température du thermomètre sec (°F)
Dew Point Temperature (°F)	24	23	25	31	35	41	50	54	49	42	36	28	Température du point de rosée (°F)
Wet Bulb Temperature (°F)	27	25	27	32	37	43	51	55	51	44	38	30	Température du thermomètre mouillé (°F)
Mixing Ratio (gr/lb)	18	17	19	25	30	38	53	62	51	39	31	22	Rapport de mélange (g/liv.)
Relative Humidity (%)	87	89	88	91	88	89	92	93	87	87	89	86	Humidité relative (p. 100)

DEW POINT EXTREMES — EXTRÊMES DU POINT DE ROSÉE

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Mean of Highest Dew Point each month	41	38	38	39	47	53	61	62	61	56	56	45	Moyenne du point de rosée maximal chaque mois

Highest Dew Point Recorded (°F)	73	Point de rosée maximal enregistré (°F)
Corresponding Dry Bulb Temperature (°F)	74	Température du thermomètre sec correspondante (°F)
Corresponding Wet Bulb Temperature (°F)	73	Température du thermomètre mouillé correspondante (°F)
Corresponding Mixing Ratio (gr/lb)	122	Rapport de mélange correspondante (g/liv.)

GANDER INT. (A), NFLD.

MEAN VALUES AT HOURS SHOWN — VALEURS MOYENNES AUX HEURES SYNOPTIQUES

	JAN JANV	FEB FEV	MAR MARS	APR AVR	MAY MAI	JUN JUIN	JUL JUIL	AUG AOUT	SEP SEPT	OCT OCT	NOV NOV	DEC DEC	
02 AST													
Dry Bulb Temperature (°F)	20	18	23	30	38	45	55	55	48	41	34	25	Température du thermomètre sec (°F)
Dew Point Temperature (°F)	17	14	20	27	34	41	51	51	45	38	31	22	Température du point de rosée (°F)
Relative Humidity (%)	87	84	88	88	85	84	86	86	88	90	88	87	Humidité relative (p. 100)
08 AST													
Dry Bulb Temperature (°F)	20	18	24	32	42	50	59	58	51	42	34	25	Température du thermomètre sec (°F)
Dew Point Temperature (°F)	16	14	19	28	35	43	53	52	46	38	31	22	Température du point de rosée (°F)
Relative Humidity (%)	86	86	81	85	76	76	81	80	84	86	88	89	Humidité relative (p. 100)
14 AST													
Dry Bulb Temperature (°F)	24	23	30	38	50	59	68	67	58	48	38	28	Température du thermomètre sec (°F)
Dew Point Temperature (°F)	18	18	24	29	36	43	52	52	45	38	33	23	Température du point de rosée (°F)
Relative Humidity (%)	79	80	79	71	58	55	57	60	61	68	81	80	Humidité relative (p. 100)
20 AST													
Dry Bulb Temperature (°F)	21	20	25	33	43	52	61	59	51	42	35	26	Température du thermomètre sec (°F)
Dew Point Temperature (°F)	17	15	22	28	35	43	52	52	45	37	32	22	Température du point de rosée (°F)
Relative Humidity (%)	84	81	86	82	74	72	72	77	79	81	88	85	Humidité relative (p. 100)

MEAN VALUES (Mean of four synoptic observations) — VALEURS MOYENNES (Moyenne des quatre observations synoptiques)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Dry Bulb Temperature (°F)	21	20	26	33	43	52	61	60	52	43	35	26	Température du thermomètre sec (°F)
→ Dew Point Temperature (°F)	17	15	21	28	35	43	52	52	45	38	32	22	Température du point de rosée (°F)
Wet Bulb Temperature (°F)	20	19	24	31	40	47	56	55	48	41	34	25	Température du thermomètre mouillé (°F)
Mixing Ratio (gr/lb)	13	12	16	22	30	41	58	58	44	34	26	17	Rapport de mélange (g/liv.)
Relative Humidity (%)	84	81	83	81	72	72	73	76	76	82	87	84	Humidité relative (p. 100)

DEW POINT EXTREMES — EXTRÊMES DU POINT DE ROSÉE

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Mean of Highest Dew Point each month	40	38	38	42	54	61	65	65	65	58	54	47	Moyenne du point de rosée maximal chaque mois

Highest Dew Point Recorded (°F)	68	Point de rosée maximal enregistré (°F)
Corresponding Dry Bulb Temperature (°F)	79	Température du thermomètre sec correspondante (°F)
Corresponding Wet Bulb Temperature (°F)	71	Température du thermomètre mouillé correspondante (°F)
Corresponding Mixing Ratio (gr/lb)	103	Rapport de mélange correspondante (g/liv.)

GOOSE (A), NFLD.

MEAN VALUES AT HOURS SHOWN — VALEURS MOYENNES AUX HEURES SYNOPTIQUES

	JAN JANV	FEB FEV	MAR MARS	APR AVR	MAY MAI	JUN JUIN	JUL JUIL	AUG AOUT	SEP SEPT	OCT OCT	NOV NOV	DEC DEC	
02 NST													
Dry Bulb Temperature (°F)	3	4	15	26	37	46	54	53	45	35	25	10	Température du thermomètre sec (°F)
Dew Point Temperature (°F)	-4	-2	8	20	30	39	48	48	39	29	20	4	Température du point de rosée (°F)
Relative Humidity (%)	74	76	74	78	77	77	79	82	79	79	81	76	Humidité relative (p. 100)
08 NST													
Dry Bulb Temperature (°F)	2	2	14	27	40	50	57	56	46	35	24	9	Température du thermomètre sec (°F)
Dew Point Temperature (°F)	-4	-3	8	19	31	40	49	48	39	29	19	3	Température du point de rosée (°F)
Relative Humidity (%)	75	78	77	71	71	69	74	76	76	79	81	76	Humidité relative (p. 100)
14 NST													
Dry Bulb Temperature (°F)	8	12	25	36	48	59	66	64	55	42	29	14	Température du thermomètre sec (°F)
Dew Point Temperature (°F)	1	3	15	23	31	41	50	47	40	30	22	6	Température du point de rosée (°F)
Relative Humidity (%)	74	65	66	60	52	52	57	53	57	63	75	70	Humidité relative (p. 100)
20 NST													
Dry Bulb Temperature (°F)	5	8	20	32	43	54	62	60	50	37	26	11	Température du thermomètre sec (°F)
Dew Point Temperature (°F)	-1	0	12	23	31	41	50	49	41	30	21	5	Température du point de rosée (°F)
Relative Humidity (%)	77	71	71	70	62	60	65	67	70	75	80	75	Humidité relative (p. 100)

MEAN VALUES (Mean of four synoptic observations) — VALEURS MOYENNES (Moyenne des quatre observations synoptiques)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Dry Bulb Temperature (°F)	4	7	18	30	42	52	60	58	49	37	26	11	Température du thermomètre sec (°F)
Dew Point Temperature (°F)	-2	-1	11	21	31	40	49	48	40	30	21	5	Température du point de rosée (°F)
Wet Bulb Temperature (°F)	4	6	17	27	37	46	54	53	45	34	25	10	Température du thermomètre mouillé (°F)
Mixing Ratio (gr/lb)	5	5	10	16	25	36	51	50	36	24	16	7	Rapport de mélange (g/liv.)
Relative Humidity (%)	76	71	72	68	65	63	67	68	70	75	80	75	Humidité relative (p. 100)

DEW POINT EXTREMES — EXTRÊMES DU POINT DE ROSÉE

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Mean of Highest Dew Point each month	31	28	35	38	47	60	64	62	59	50	44	37	Moyenne du point de rosée maximal chaque mois

Highest Dew Point Recorded (°F)	70	Point de rosée maximal enregistré (°F)
Corresponding Dry Bulb Temperature (°F)	75	Température du thermomètre sec correspondante (°F)
Corresponding Wet Bulb Temperature (°F)	72	Température du thermomètre mouillé correspondante (°F)
Corresponding Mixing Ratio (gr/lb)	110	Rapport de mélange correspondante (g/liv.)

appendix i

Field Observations

APPENDIX I
FIELD OBSERVATIONS

An overflight reconnaissance was made of the river in March and August 1994 to gather additional ice-related and open water data, respectively. Records of these overflights are provided in the following pages and in a binder of photographs, and a binder containing winter and summer video tapes.

Ice Reconnaissance - March 1994

The objective of this overflight was to obtain a photographic record of ice conditions along the river prior to break-up. Such a record had never been obtained and was considered important for comparison with partial records obtained in 1984. The principal reason for needing a comparative record was to determine if ice conditions (i.e., accumulation conditions) could be considered as one-dimensional, laterally averaged. If not, it would be extremely challenging to model ice conditions using laterally averaged ice models such as RIVICE or RIVMIX.

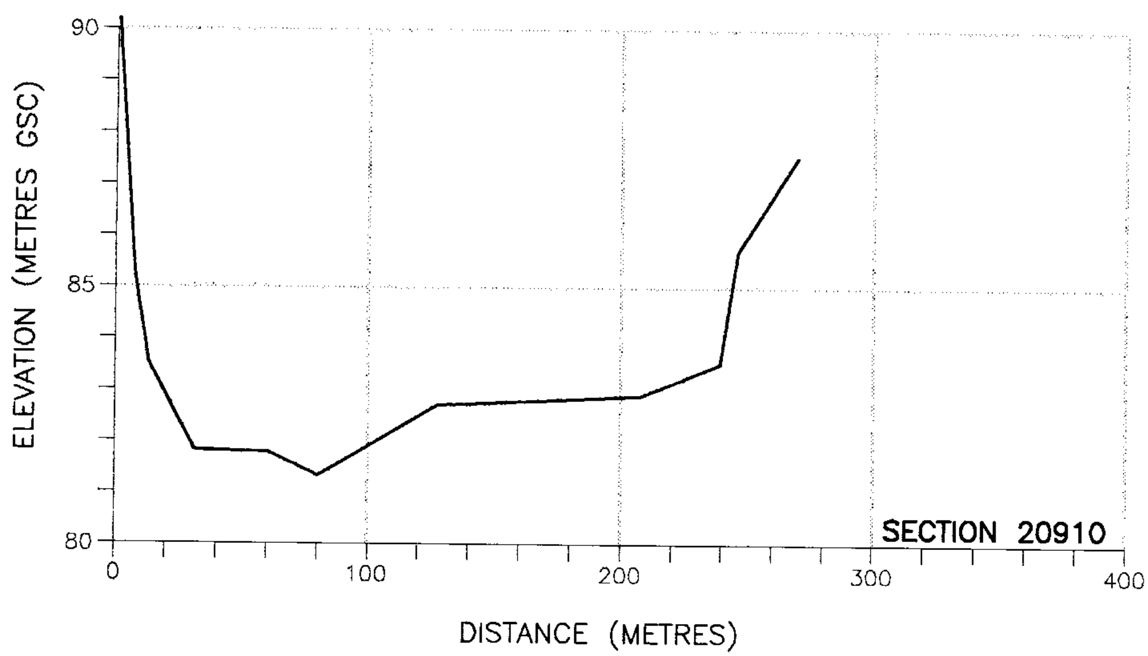
A second reason for the winter observations was to determine if ice conditions were generally similar to those of 1984. The focus of the flight was to locate areas of thick frazil accumulation, regions where under-ice passages were eroded in the cover, locations where shoves had occurred, locations where ice or ice-generated debris had pushed onto the banks, and the ice level at freeze-up. If conditions below Badger were similar to those observed in 1984, there would be potential for modelling using two-dimensional, vertically averaged approaches and potential to further refine the existing ice model.

River Reconnaissance - August 1994

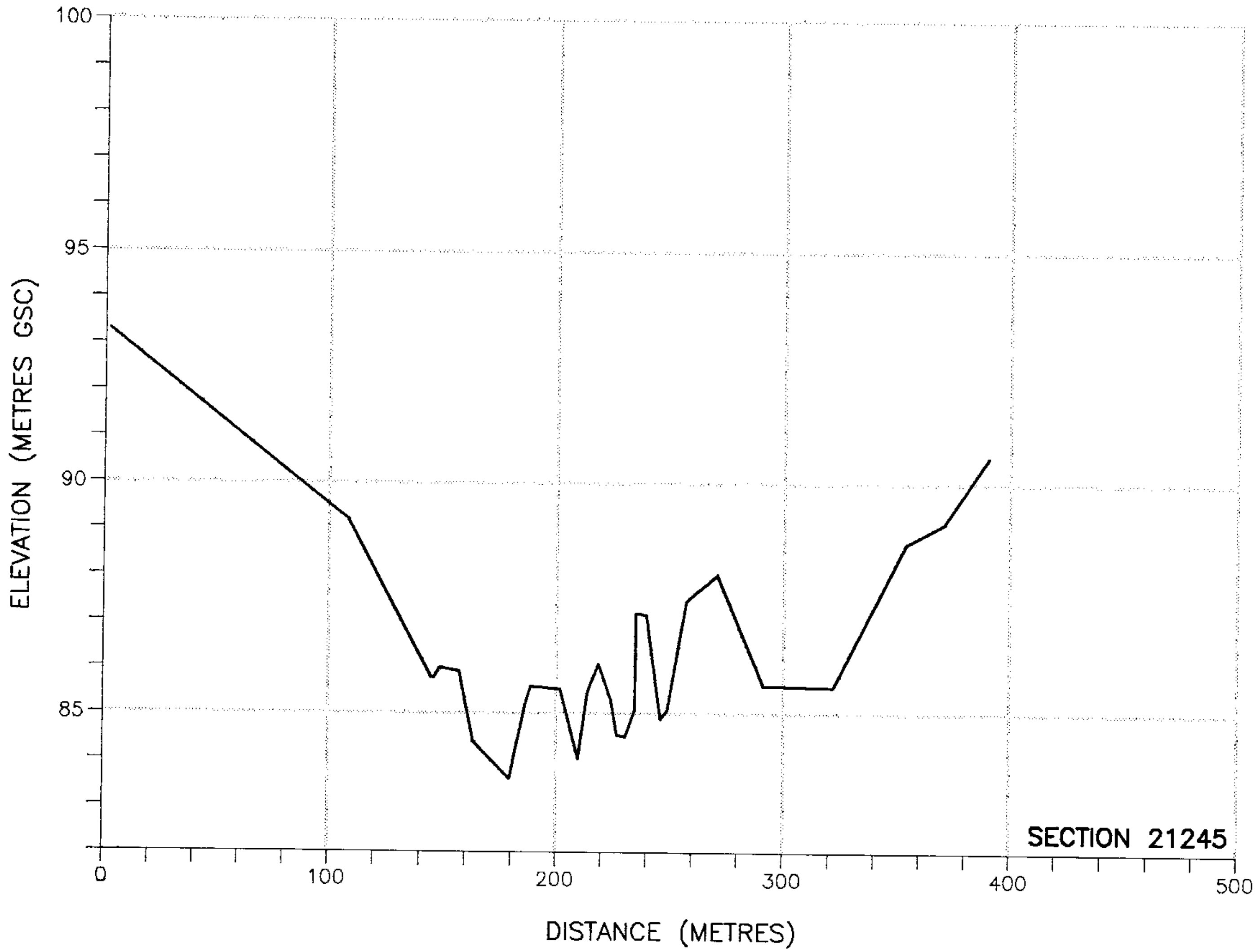
The purpose of this overflight was to obtain a record of open-water conditions at flow rates and depths which would be similar to conditions just prior to freeze-up (and representative of frazil-producing conditions). Such a record was not available except at a limited number of cross-sections measured in 1984 and would have application for refining the existing model or for use in other/future modelling.

The results of this survey are the records (noted above) and interpreted cross-sections plotted on the following pages. The location of cross-sections and their distance (m) upstream of Goodyear's Dam are shown on copies of airphotos prepared by the Province. All cross-sections are drawn looking downstream and correspond in datum and orientation to those presented in the 1985 report.

EXPLOITS RIVER - CROSS SECTIONS
BADGER CHUTE TO BADGER ROUGH WATERS



EXPLOITS RIVER – CROSS SECTIONS
BADGER CHUTE TO BADGER ROUGH WATERS



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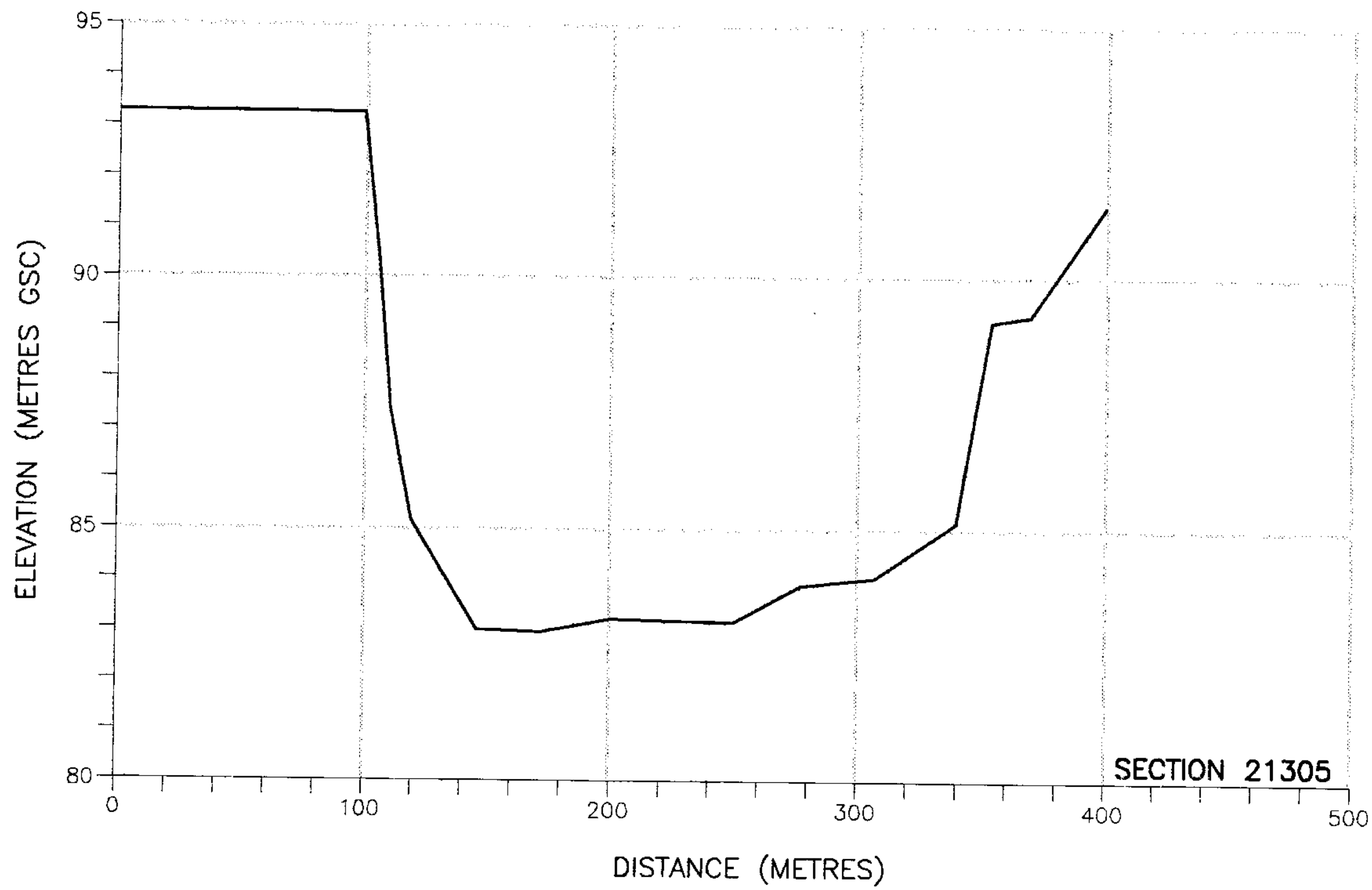
BADGER CHUTE TO BADGER ROUGH WATERS



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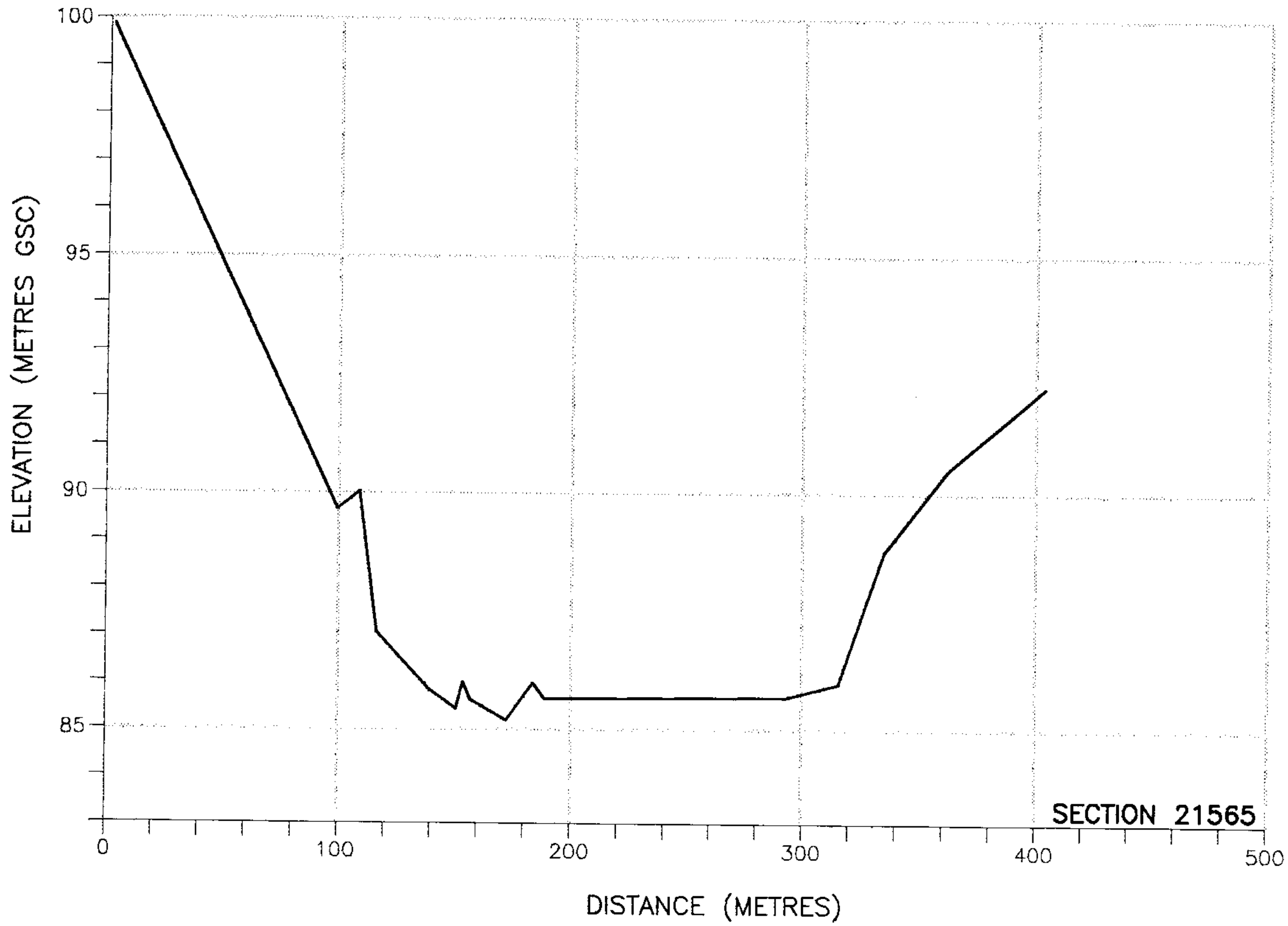
BADGER CHUTE TO BADGER ROUGH WATERS



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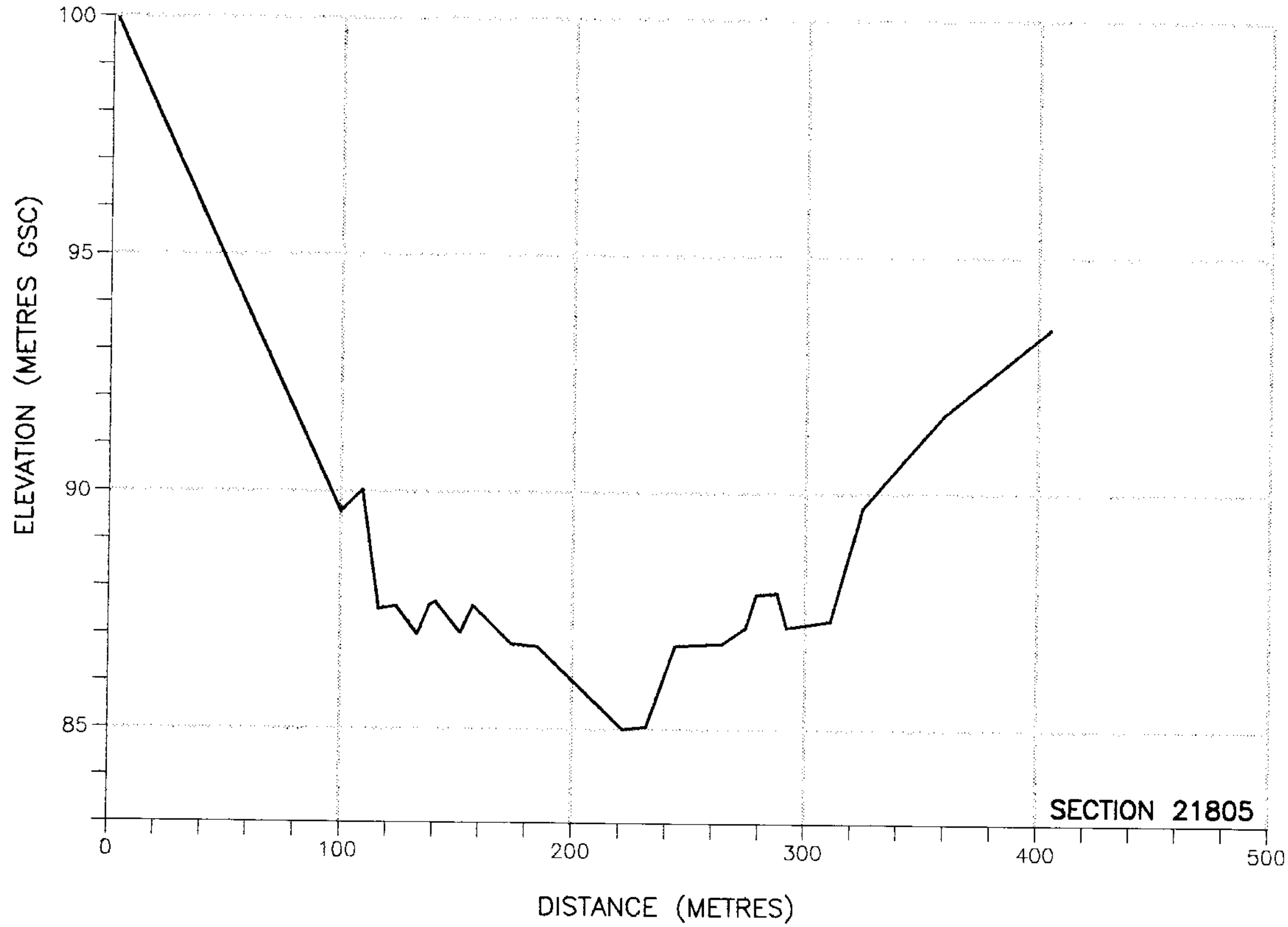
BADGER CHUTE TO BADGER ROUGH WATERS



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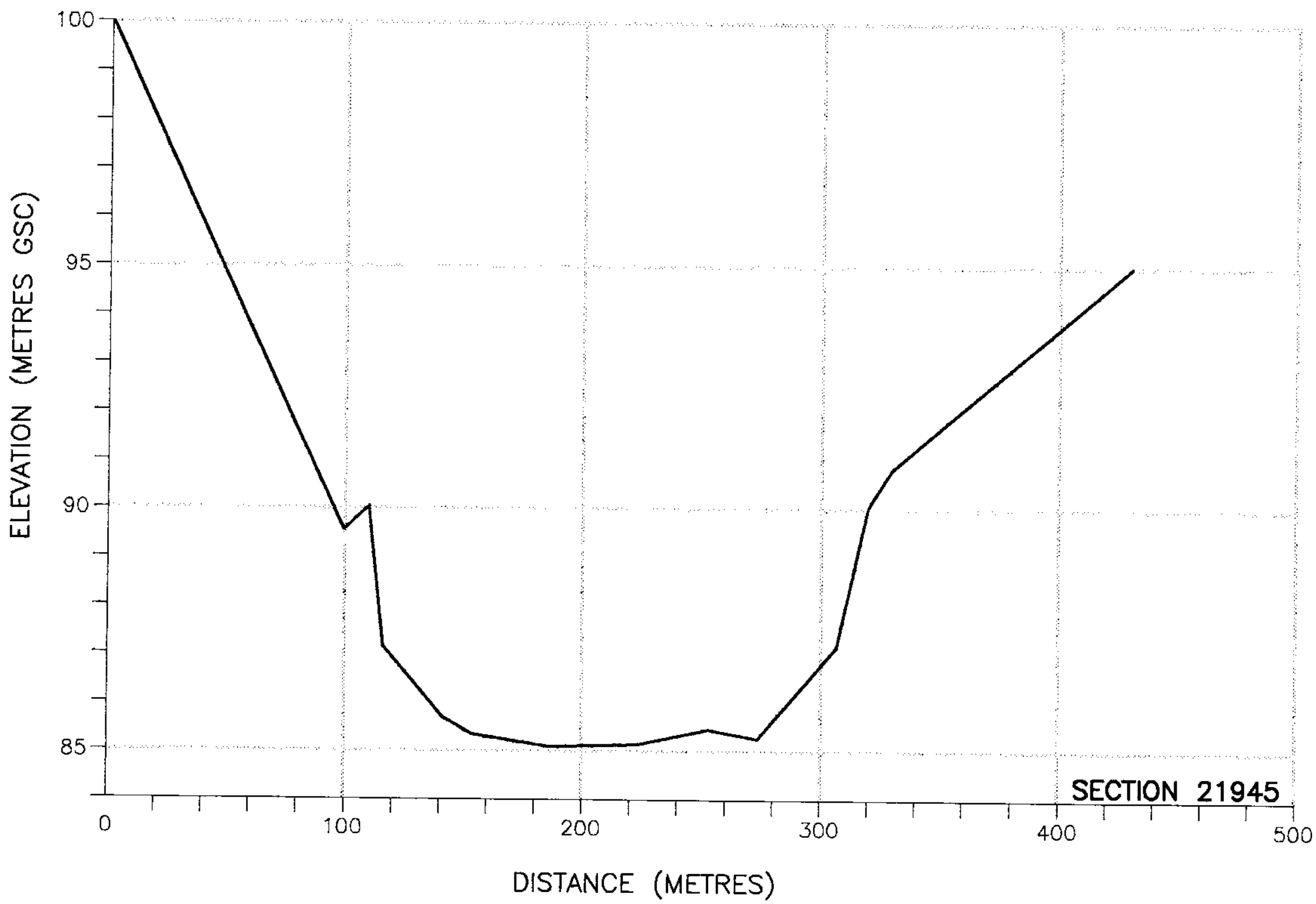
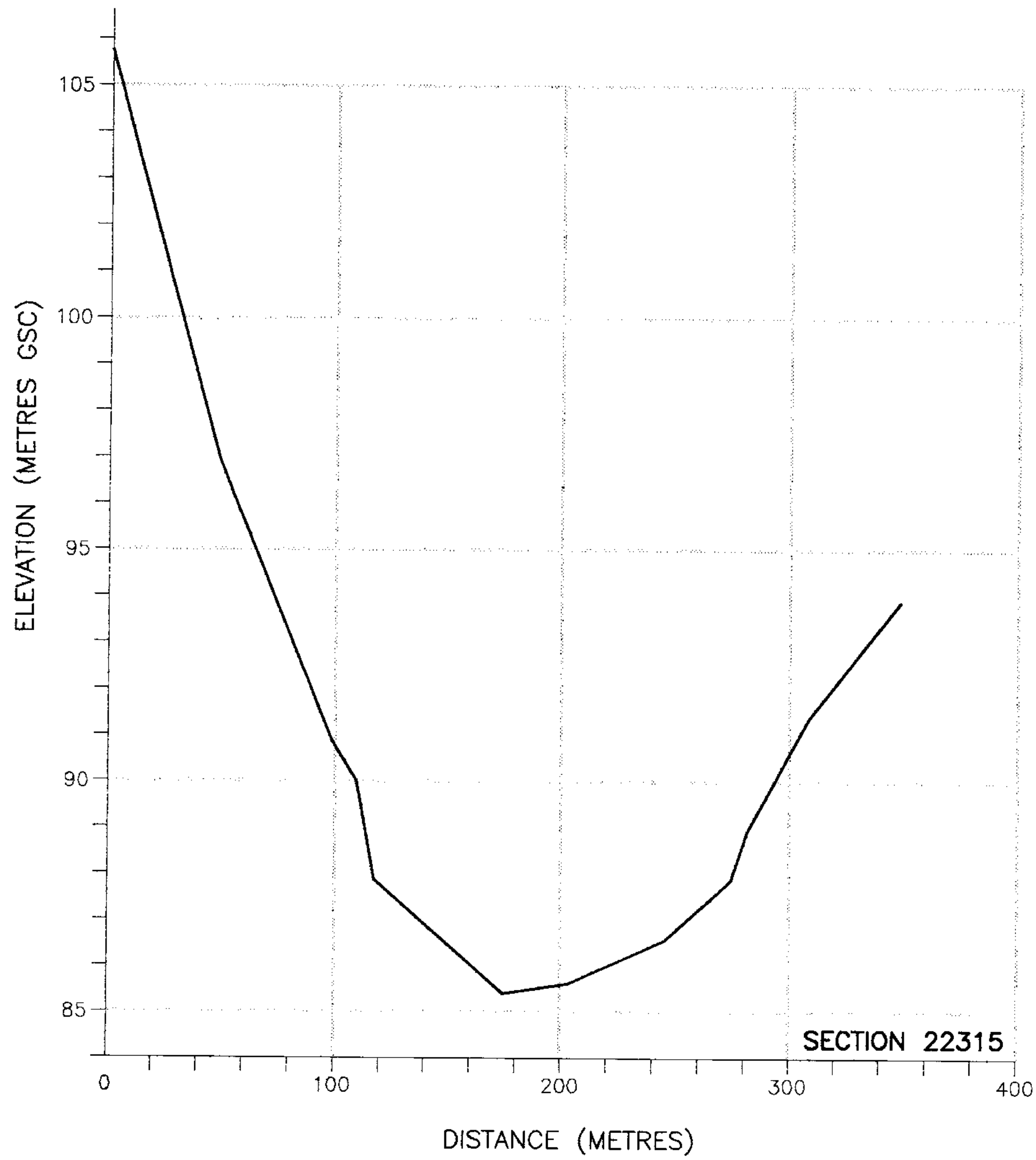
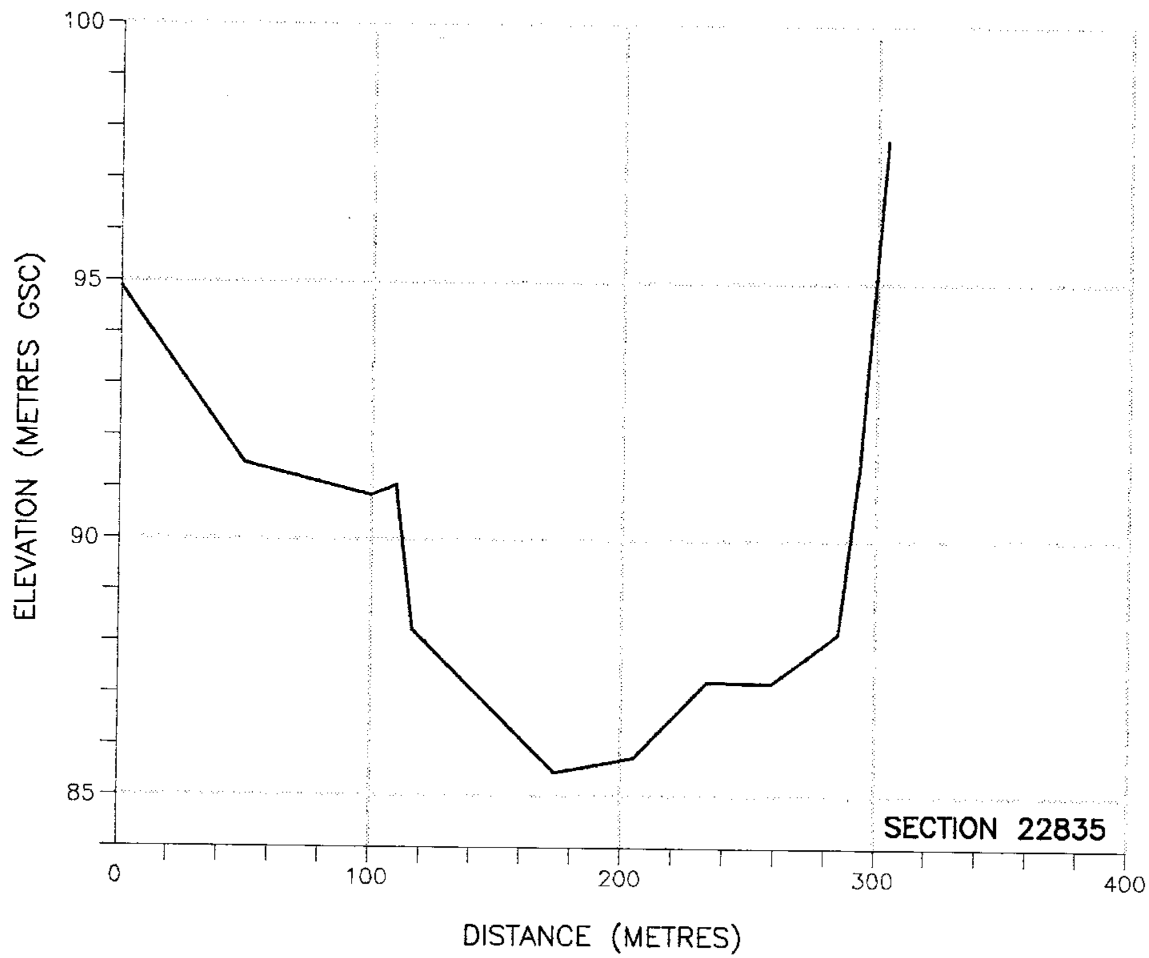
BADGER CHUTE TO BADGER ROUGH WATERS



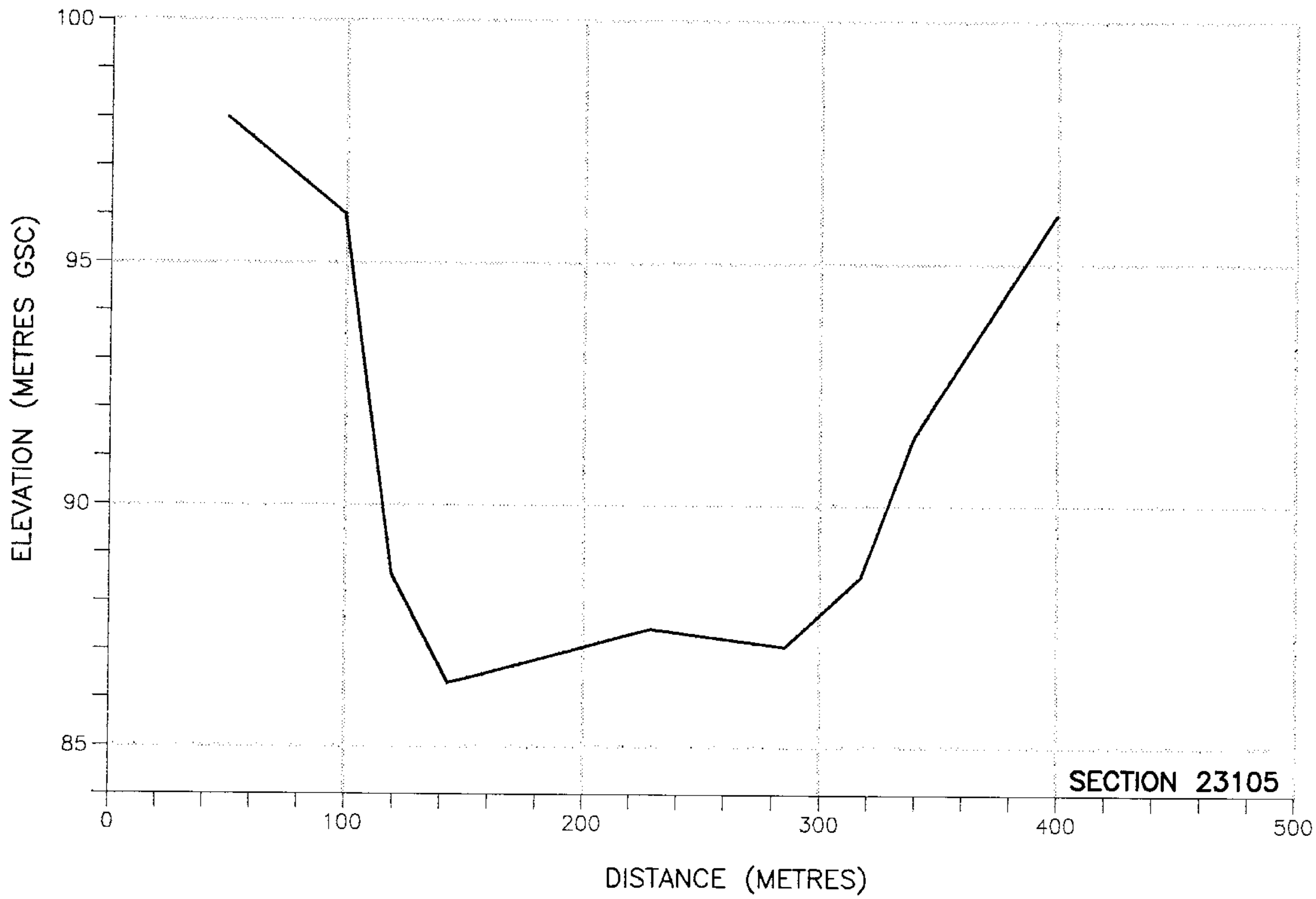
EXPLOITS RIVER - CROSS SECTIONS
BADGER CHUTE TO BADGER ROUGH WATERS



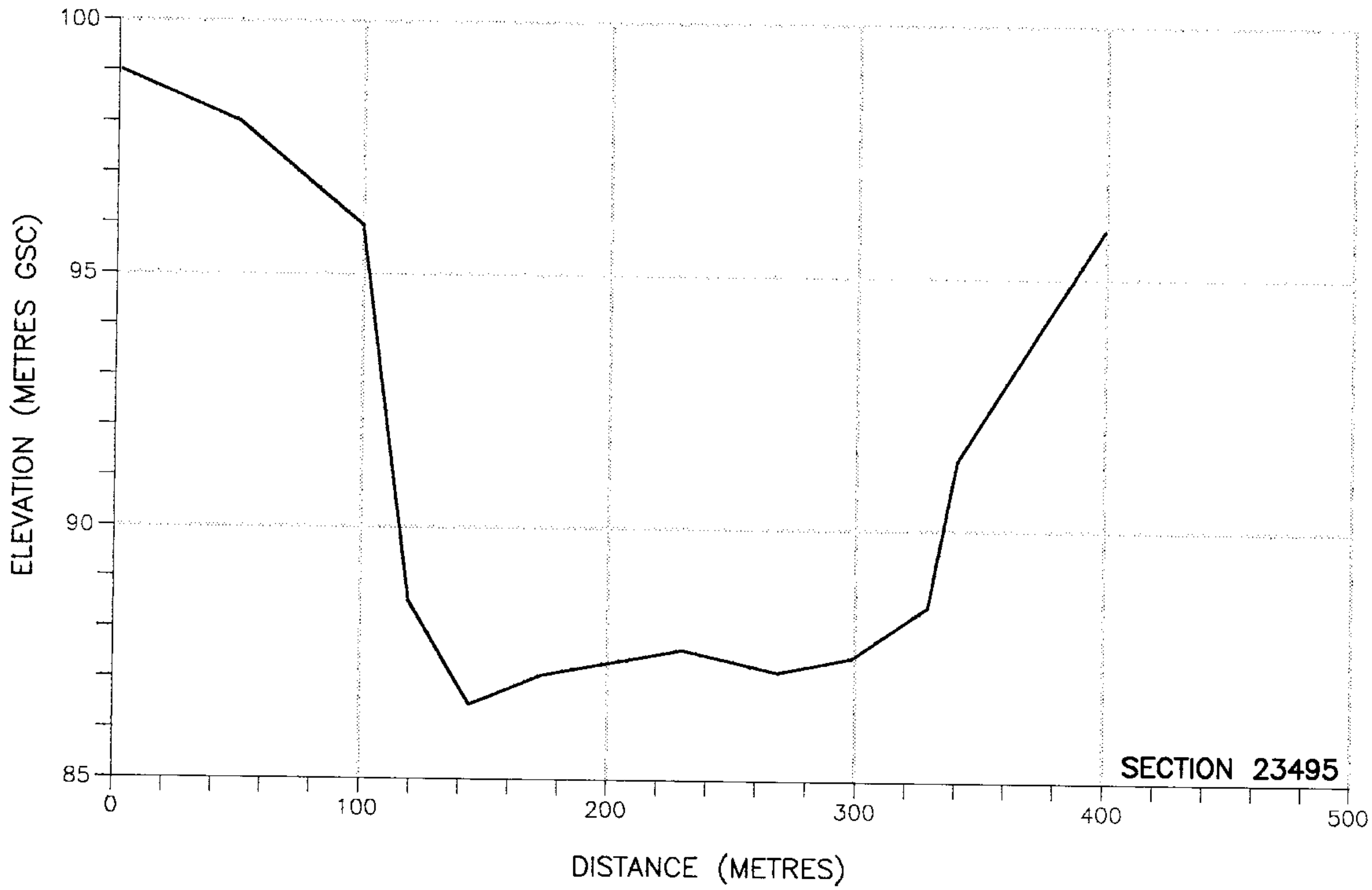
EXPLOITS RIVER - CROSS SECTIONS
BADGER CHUTE TO BADGER ROUGH WATERS



EXPLOITS RIVER – CROSS SECTIONS
BADGER CHUTE TO BADGER ROUGH WATERS



EXPLOITS RIVER - CROSS SECTIONS
BADGER CHUTE TO BADGER ROUGH WATERS



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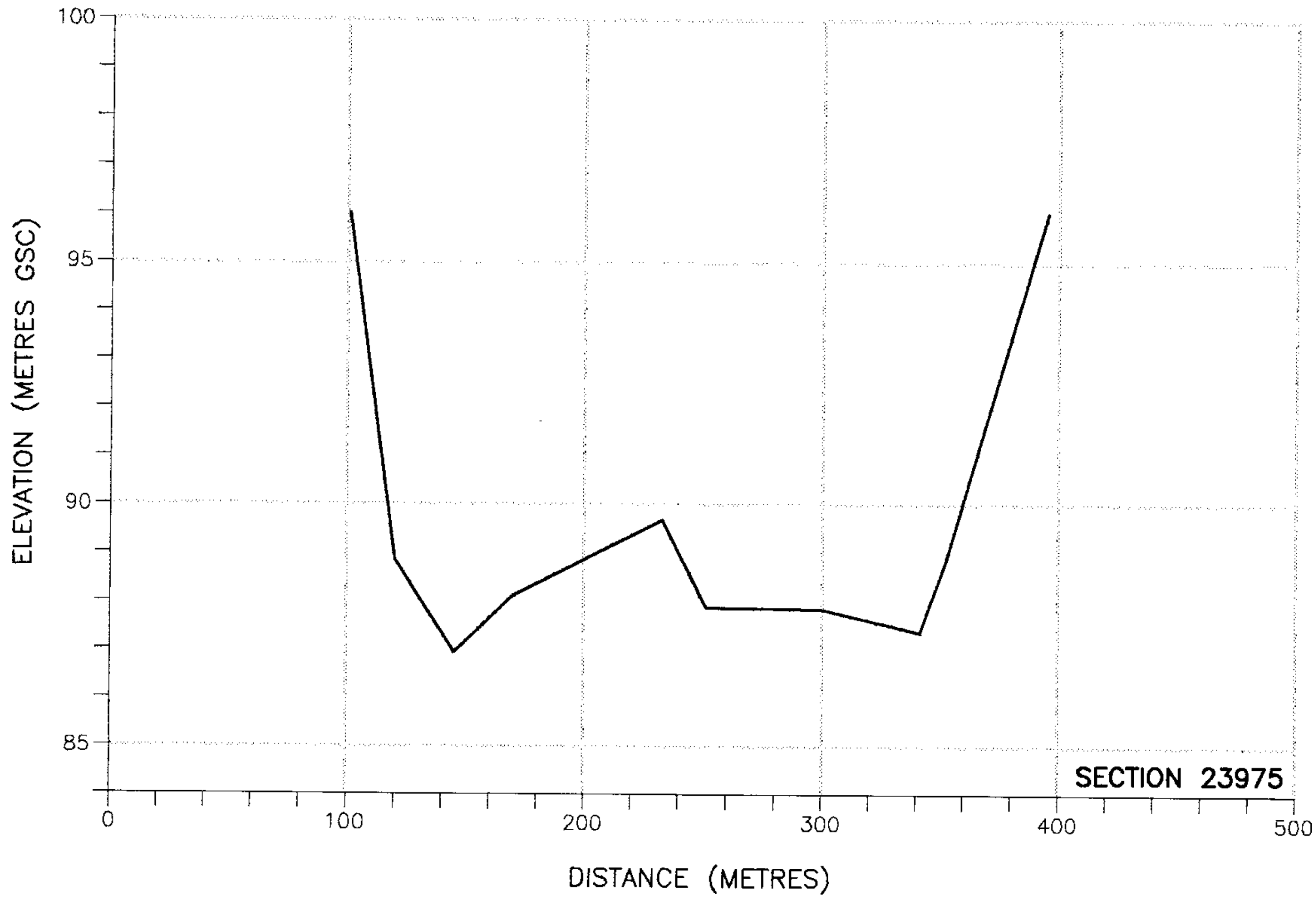
BADGER CHUTE TO BADGER ROUGH WATERS



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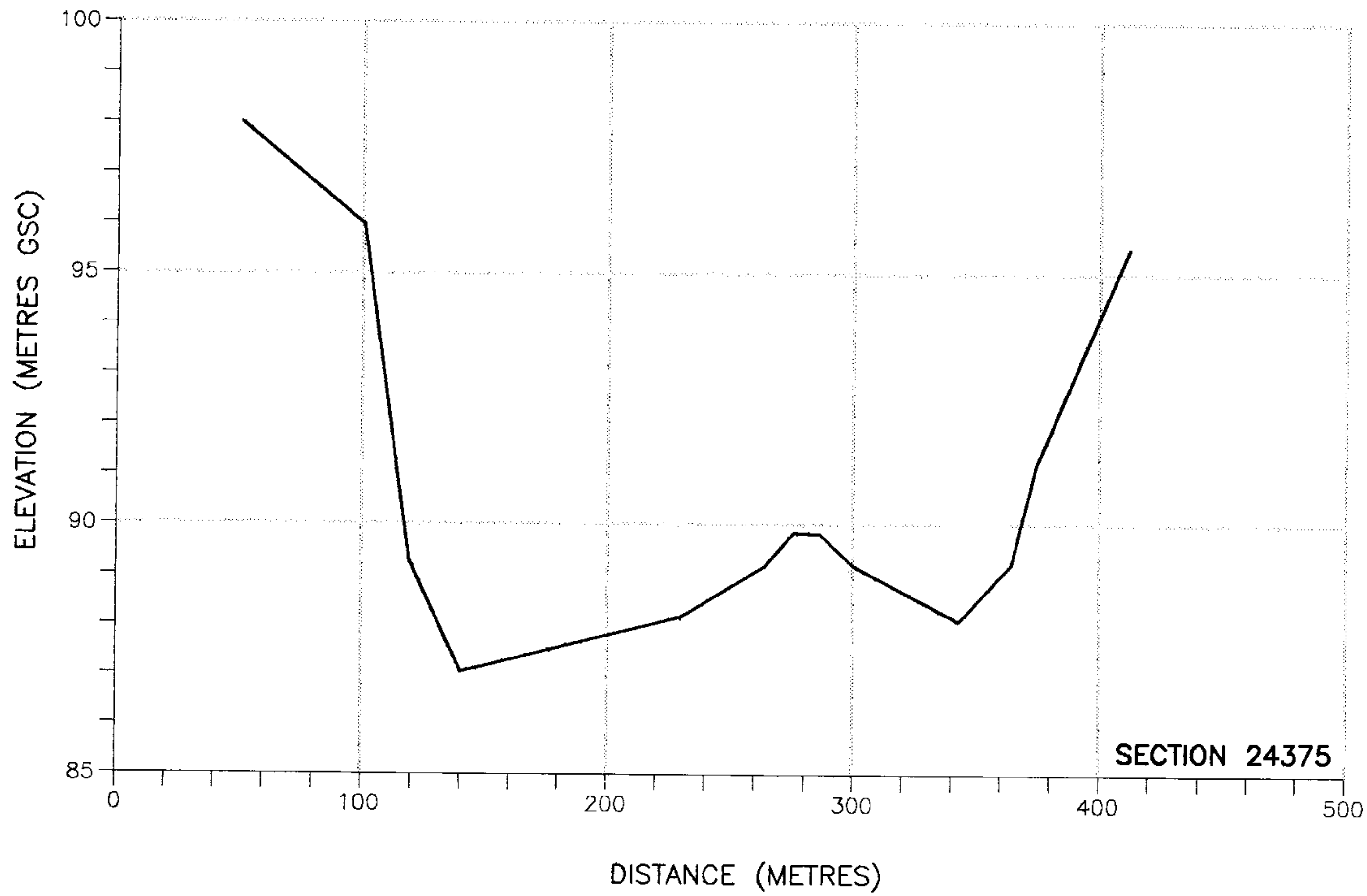
BADGER CHUTE TO BADGER ROUGH WATERS



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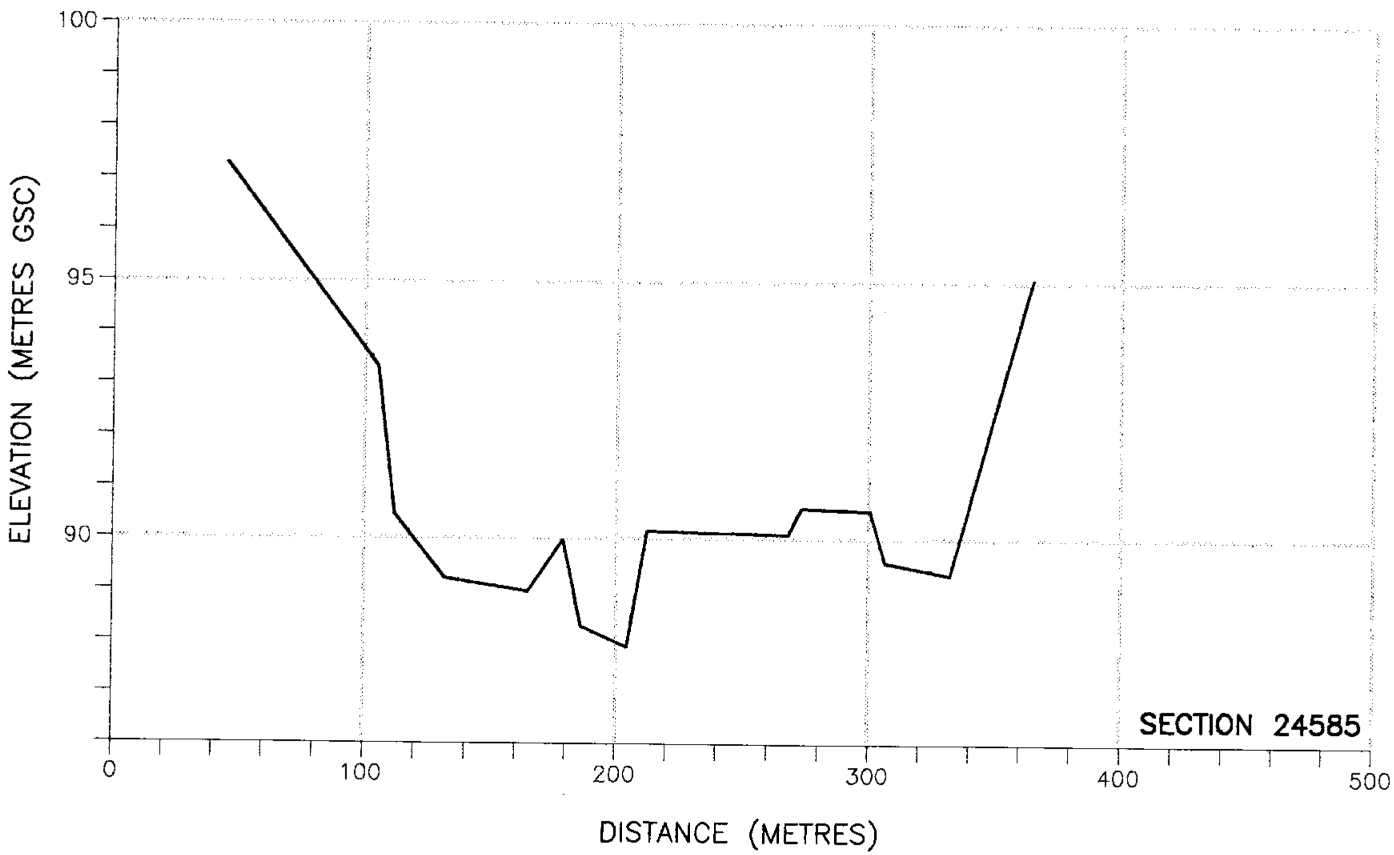
BADGER CHUTE TO BADGER ROUGH WATERS



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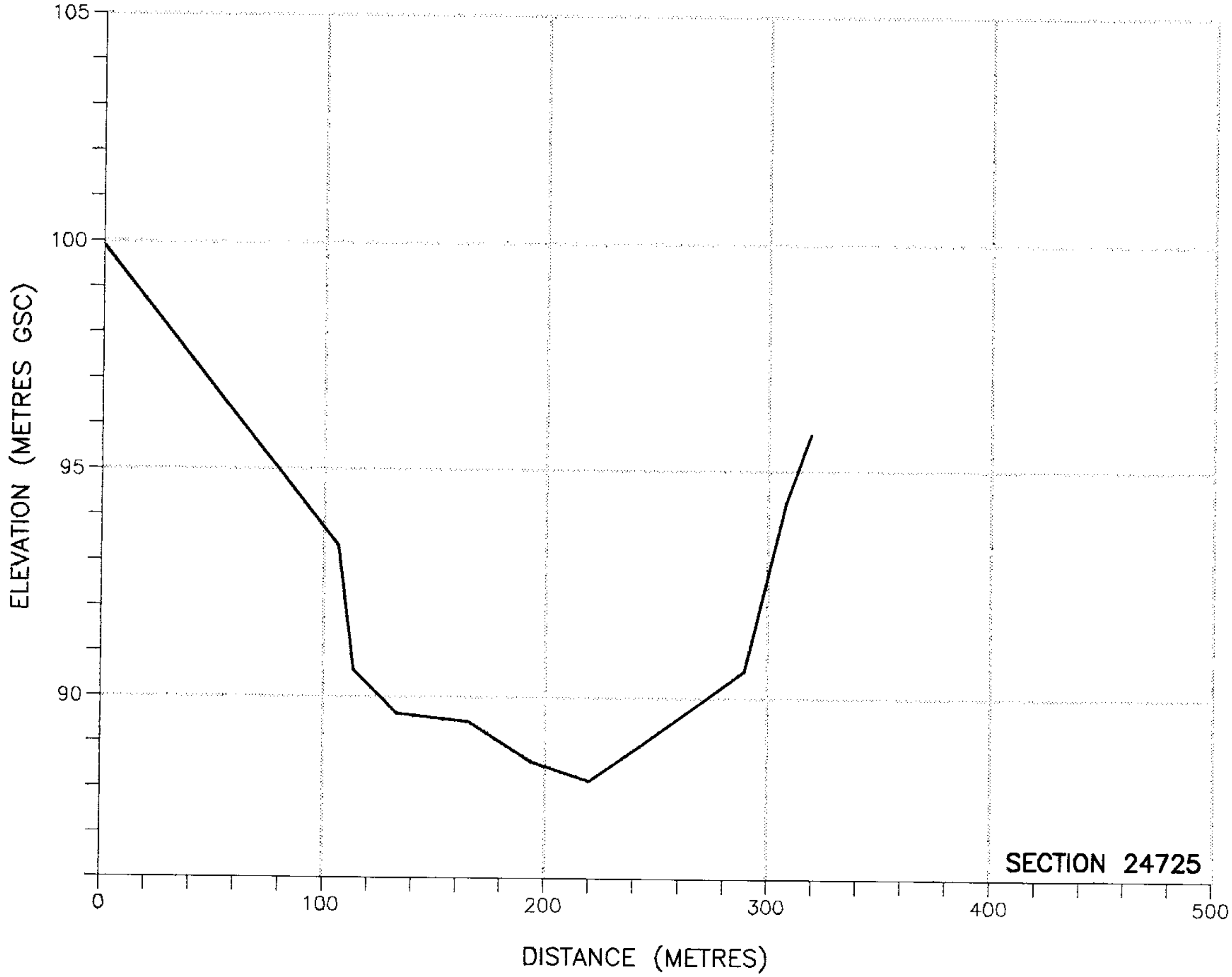
BADGER CHUTE TO BADGER ROUGH WATERS



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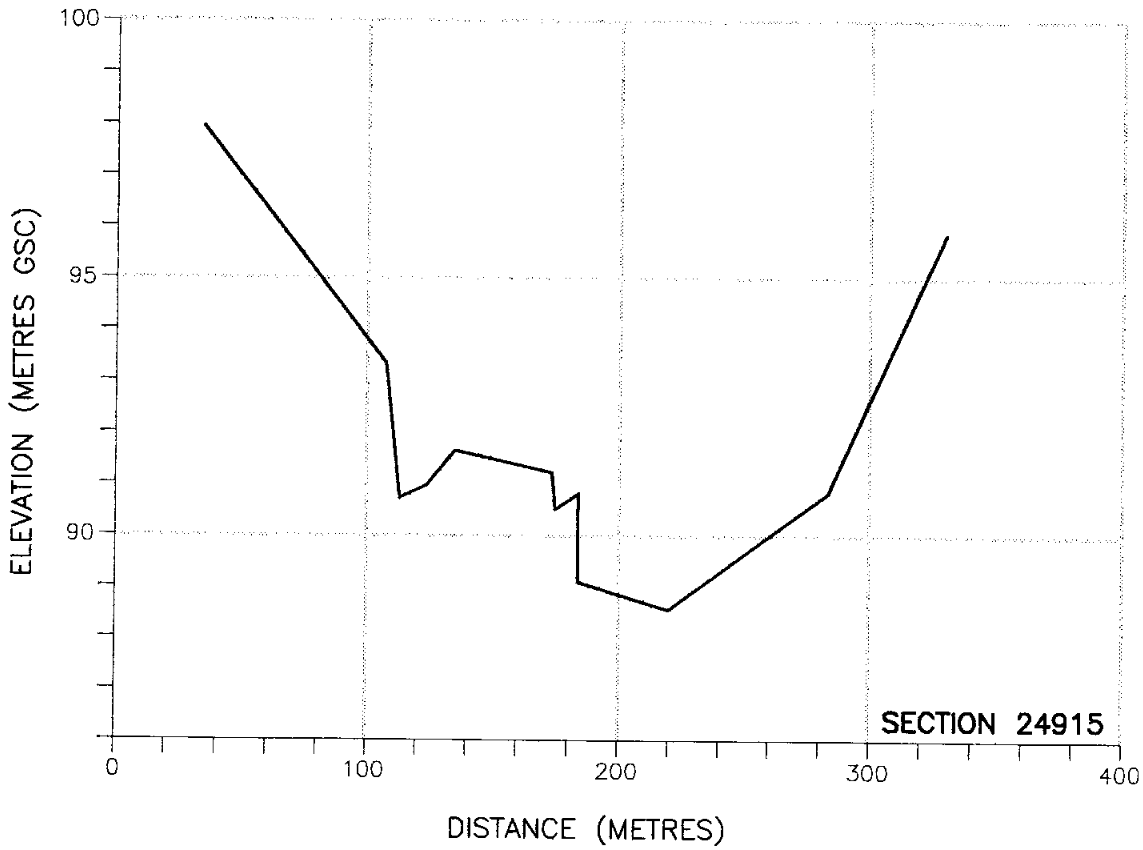
BADGER CHUTE TO BADGER ROUGH WATERS



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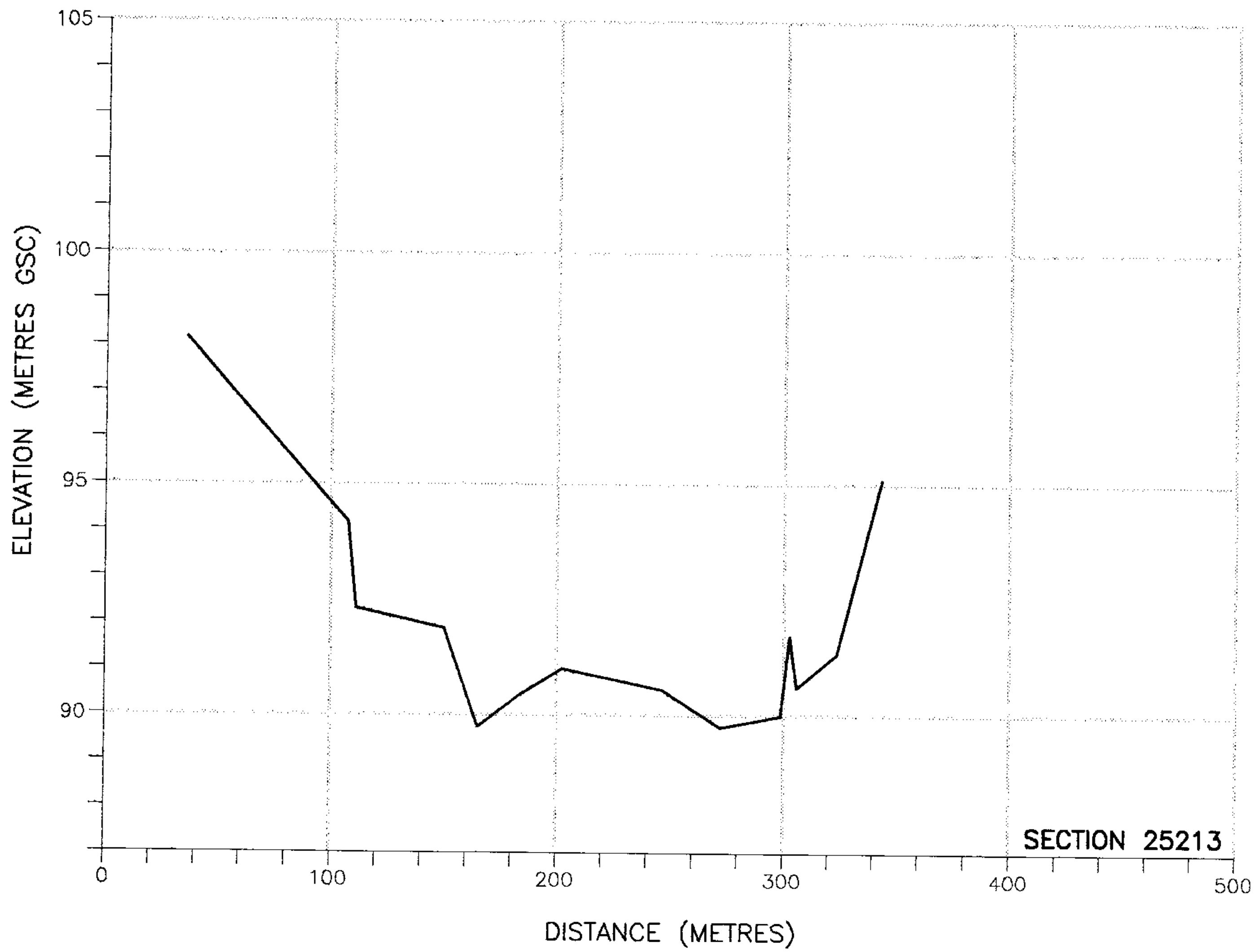
BADGER CHUTE TO BADGER ROUGH WATERS



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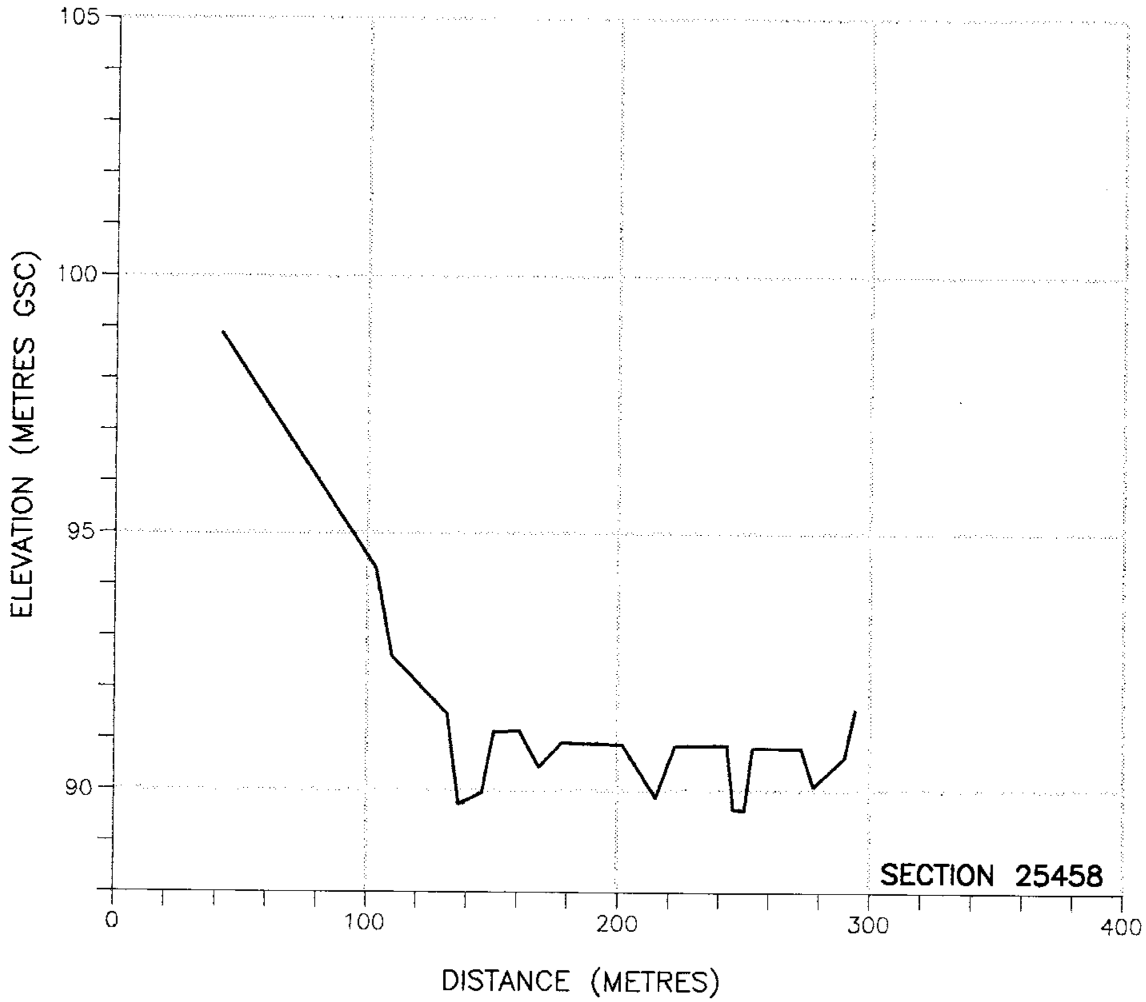

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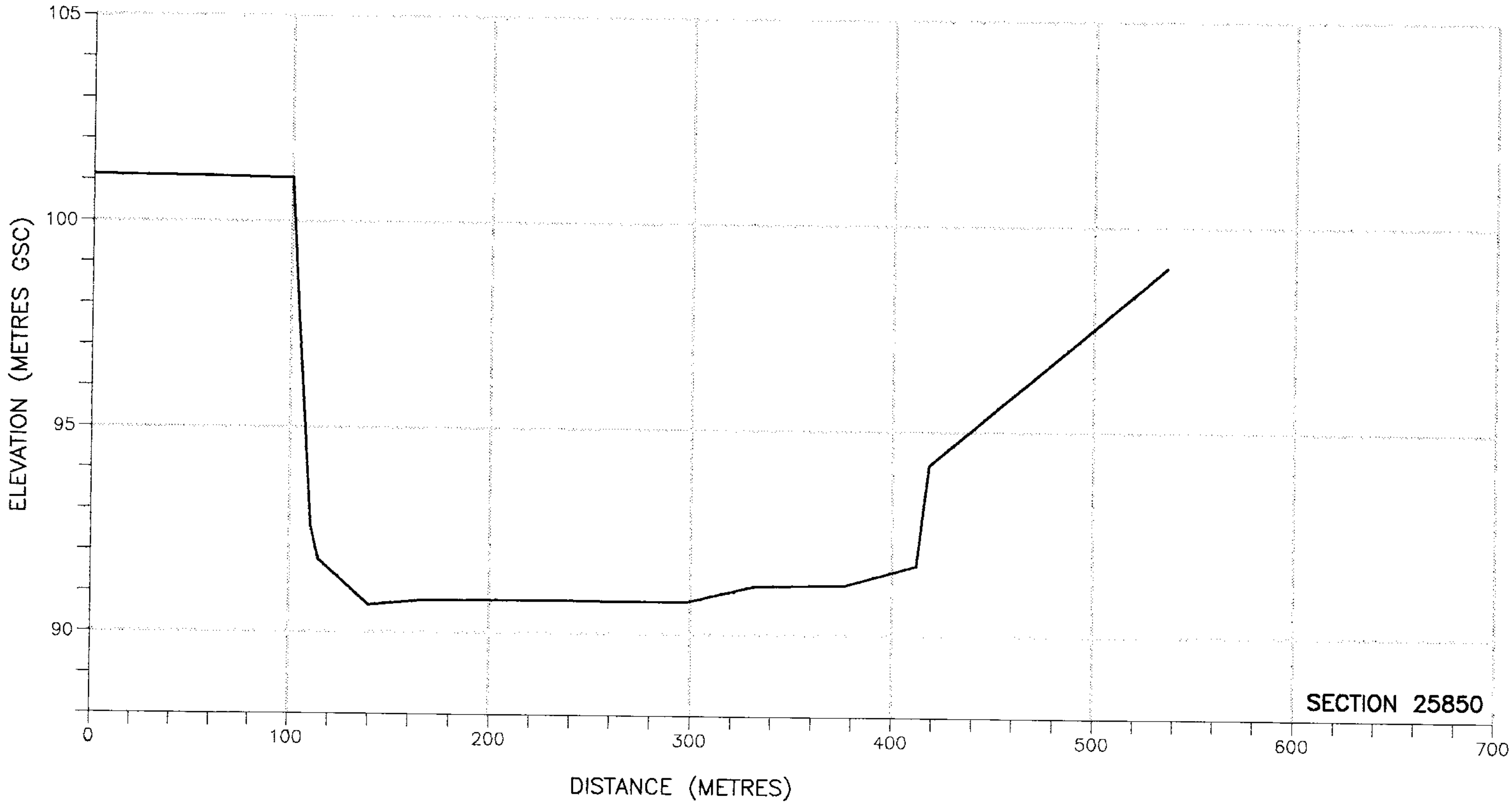

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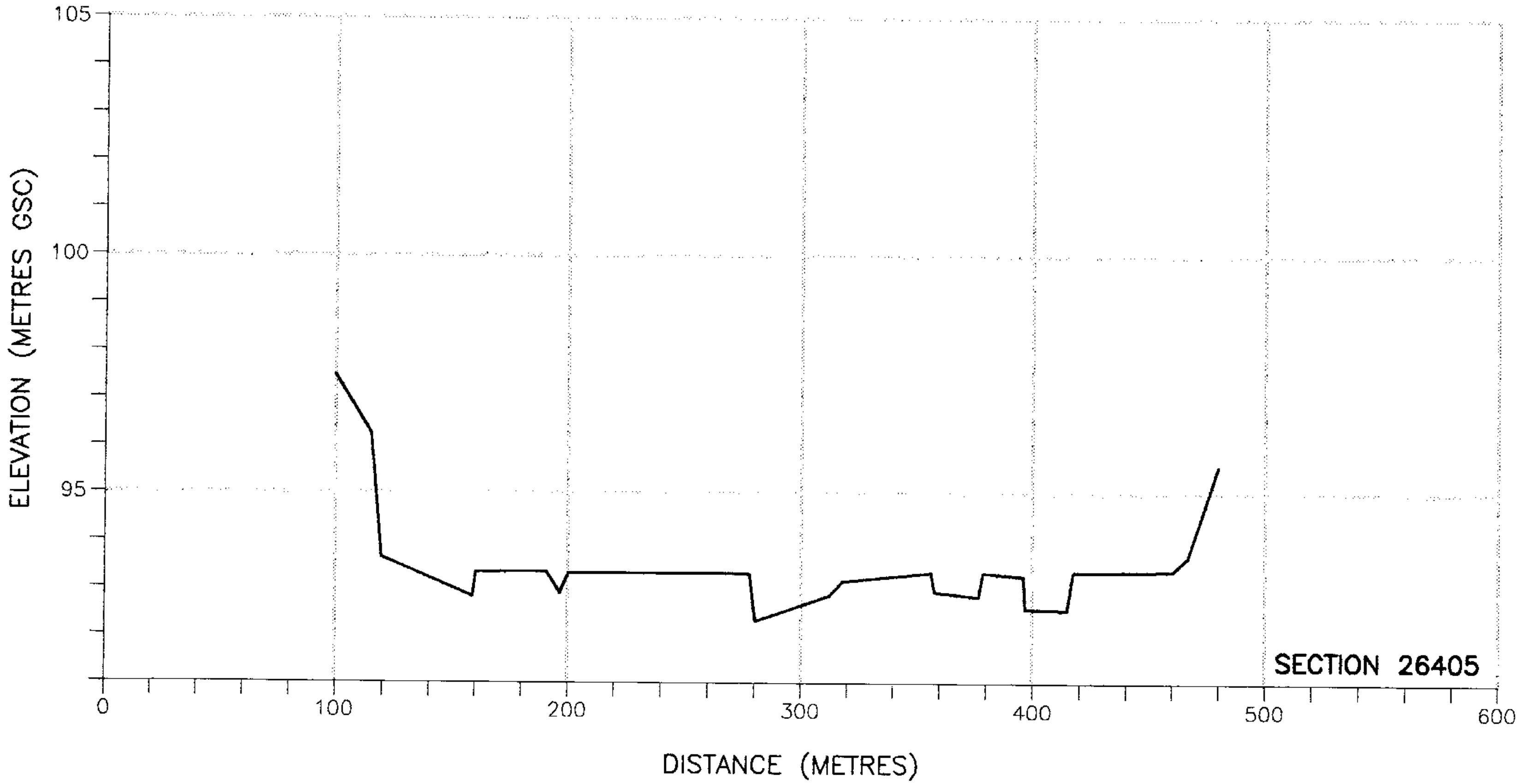

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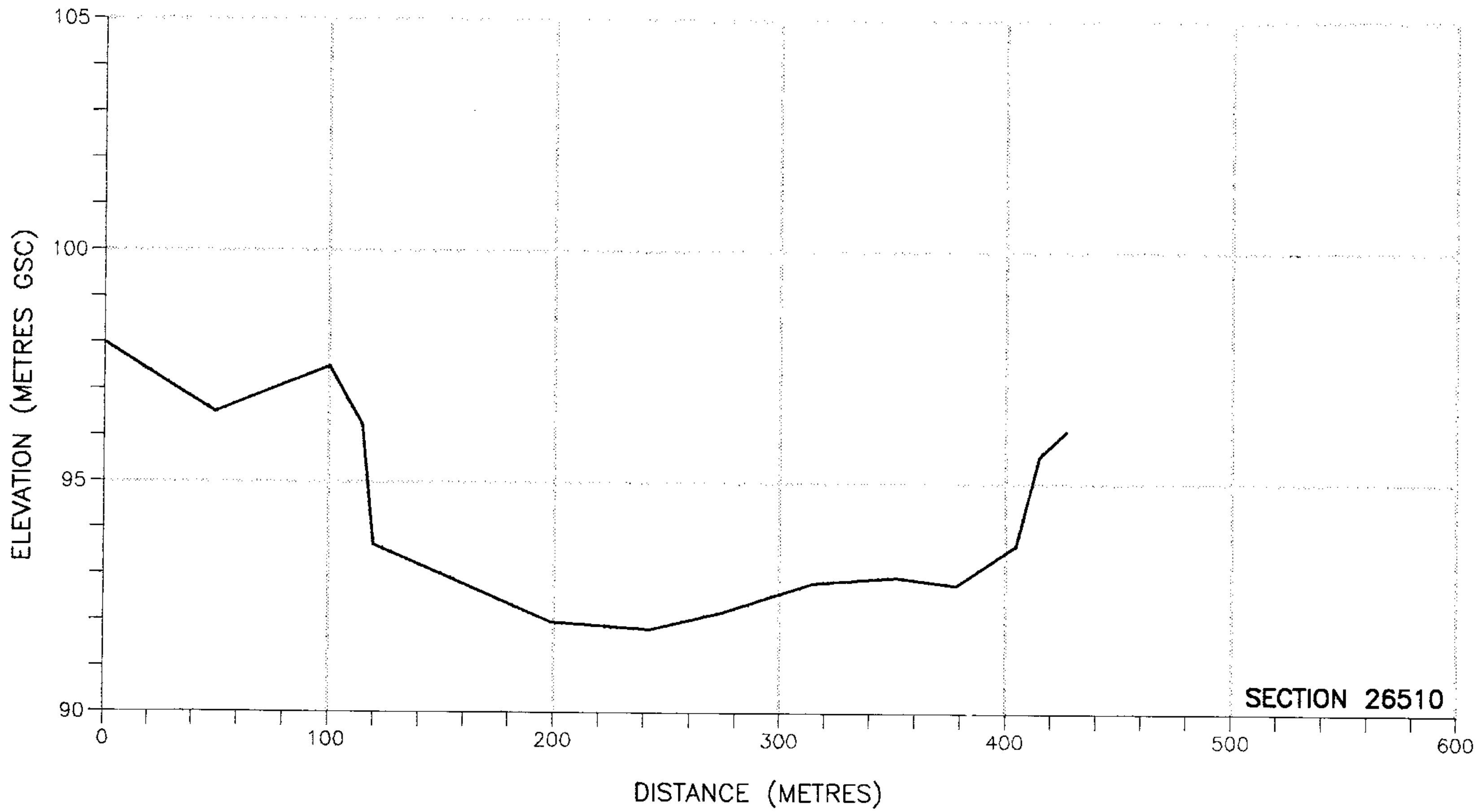

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