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Ice Jams and Flood Forecasting, Hay River, N.W.T.

R. Gerard and S. Stanley

Prepared for
Environment Canada and
Indian and Northern Affairs Canada
Yellowknife, N.W.T.

Final Report

Phase I

ICE JAMS AND FLOOD FORECASTING
HAY RIVER, N.W.T.

prepared by

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for

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Yellowknife, N.W.T.

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Indian and Northern Affairs Canada
Water Resources Division
Yellowknife, N.W.T.

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SUMMARY

The Town of Hay River, N.W.T., is situated at the mouth of the Hay River on the south shore of Great Slave Lake. A significant portion of the Town is located on the low-lying land of the Hay River delta and is subject to severe ice jam floods every decade or so. The most recent was in 1985, when an ice jam flood that exceeded the designated flood risk elevation occurred suddenly, with significant risk to life. As a first line of defence against a repetition of such an event, it was proposed that the ice jam flood forecast procedure traditionally undertaken by the Town be formalized and, if possible, refined. To do this the present two-phase study was commissioned. This report presents the results of the first phase.

The primary objective of the first phase was to identify and assess processes that precede flooding in Hay River and to propose a flood forecast procedure. There were six major components of the study: review and analysis of historical ice jam flood data; field surveys of the delta channels and nearshore lake bathymetry; field observations of the delta ice regime; calibration of an algorithm for calculating water level profiles through an ice jam; and, based on the results of these, development of a first-generation flood forecast procedure for three salient locations within the delta.

The Hay River delta consists of one main island, Vale Island, bounded by the East and West Channels. Typically the ice breaks up first in the lower reaches of the river and causes an ice run that moves through town and stalls in each channel at or near the still-solid lake ice. Hence ice jams can be expected to form almost every year in the delta channels. Given this, the prime parameter that governs whether flooding will occur in a given year in the delta is the peak discharge that occurs while ice jams are in place. The hydrology of the Hay River catchment is such that the maximum snowmelt discharge, which is the peak discharge of the year, can occur at this time, so ice jam flooding can be expected. This snowmelt discharge can be significantly augmented by surges released by ice jam failure in the mid-reaches of the river and, rarely but importantly, by runoff from spring rain.

A two-day forecast of discharge in Hay River can be directly determined from discharges measured at the Water Survey of Canada gauging station on the Hay River at the Alberta-Northwest Territories border. From this, an

understanding of the break-up ice regime developed from the study, and water level-discharge relations developed for ice jams located at the three locations in the delta, it was possible to develop a first-generation flood forecast procedure that gave two days warning of high water at each of the three locations. The procedure was evaluated against the break-up events of 1988 with success.

Because the extent of flooding along the East Channel is very sensitive to the location of the jam toe, a major limitation of the procedure is an inability to predict if and when the East Channel jam will move to the mouth. Only the maximum likely water level, rather than the actual water level, can be forecast for this site. Other limitations include the semi-empirical allowance for the effects of surges released by ice jam failure during break-up in the upper reach, no allowance for the mitigating influence of pack melt that can occur before the peak discharge arrives in the delta, and the limitation of the forecast period to the approximately two-day travel time of flow between the WSC station at the Alberta-NWT border and Hay River.

The recommendations for future action are aimed at removing some of the more important and simplest of the limitations. They include further evaluation of the first-generation procedure against the 1989 and future break-ups; development of simple unsteady flow routing and attenuation relations for surges from the mid-reaches of the river; and investigation of a simple ice jam melt algorithm tied to water temperature measurements at the Hay River WSC station. The two-day forecast period could be extended by one or two days by development of a satisfactory precipitation-runoff algorithm. However the viability of this depends on the installation, and operation during break-up, of new meteorological stations in the Caribou and Cameron Hills of the lower catchment. An alternative is the upgrading of some of the existing WSC stations on tributaries in the lower catchment. It was clear that this portion of the catchment can make a critical contribution to the discharge, particularly in 'event' years, but it is as yet uninstrumented during spring.

TABLE OF CONTENTS

TABLE OF CONTENTS (contents)

APPENDICES

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (Continued)

ACKNOWLEDGEMENTS

Many people and organizations have contributed effort, information or funds to this investigation. Principal among these are the residents of Hay River. In particular, this study would be very much poorer without the benefit of the experience related to ice jams and break-up ice processes in the Hay River of Mr. 'Red' McBryan, long-term resident, Town Flood Watch coordinator and ex-mayor of Hay River; the support and encouragment of Mr. John Pollard MLA, then Mayor of Hay River; the on-site liaison and logistic support arranged by Mr. Lloyd Brunes, Town Superintendent; and the research on the history of Hay River carried out and willingly made available by Dr. David Harrison. Mr. Pat Bobinski of Fisheries and Oceans Canada provided field support during the summer surveys and advice on the ice jams and lake ice regime.

Throughout the investigation Mr. Brian Latham, of Indian and Northern Affairs Canada, Yellowknife, provided sage advice and timely and thoughtful liaison with the various organizations involved, and actively participated in the break-up observations. The study was initiated, funded and guided by the efforts of Mr. Jesse Jasper of Indian and Northern Affairs Canada, Yellowknife; Mr. Jack Wedel, Inland Waters Directorate, Environment Canada, Yellowknife; and Dr. Terry Prowse, National Hydrology Research Institute, Saskatoon. Through many hours of stream gauging, Mr. Murray Jones of Water Survey of Canada, Fort Smith, provided the information on the discharge variation throughout break-up that is so vital in an ice jam study.

Other staff and graduate students of the Department of Civil Engineering, University of Alberta, provided aid during the study. Messrs. Joe Groenveld and Des Williamson assisted with field observations, compilation of meteorological data, and adaptation and application of the ice jam computer model. Mr. Sid Lodewyk participated in the winter field work and Messrs. Sheldon Lovell and Roy Gitzel helped prepare equipment for the field. Mrs. Donna Salvian typed the manuscript.

This report is based on an M.Sc. thesis prepared by S. Stanley under the supervision of R. Gerard.

1. INTRODUCTION

1.1 Background

As shown in Figure 1, the Town of Hay River lies at the mouth of the Hay River on the southwest shore of Great Slave Lake. A significant portion of the town is on the low-lying Hay River delta, which consists of one main island, Vale Island, bounded by the East and West channels.

The regional climate is boreal, being characterized by long cold winters and short cool summers.

Because of its location in a cold region and at a river mouth, the Town of Hay River is threatened almost every year by ice jams that form at break-up against the thick, solid ice of Great Slave Lake. The occurrence of these ice jams can coincide with the peak snowmelt flood which, in this region, is usually the maximum discharge of the year. Ice jam flooding of low-lying land is therefore to be expected and indeed serious flooding has occurred somewhere in the Town of Hay River on an average of about 1 in 9 years over the past century.

The most recent flood was in 1985. In this year water levels exceeded declared flood risk water levels (Environment Canada, 1983) by about 1 m in some areas. A particularly ominous feature of this flood was the rapidity with which it occurred. The next spring, 1986, saw a near-flood.

These two events in quick succession and, particularly, the threat to life posed by the rapid onset of the high water in 1985, emphasized the need for some form of flood mitigation for the Town of Hay River. An appropriate first line of defence against this threat is an effective flood forecast procedure. This report describes the results of Phase 1 of a two phase study aimed at developing such a procedure. The basic intent of Phase 1 was to 'identify and assess the processes that precede flooding in the community and to propose a prototype flood prediction model'.

1.2 Scope of Work

Work on Phase 1 of the study was begun in April 1987. The tasks defined in the Statement of Work were as follows:

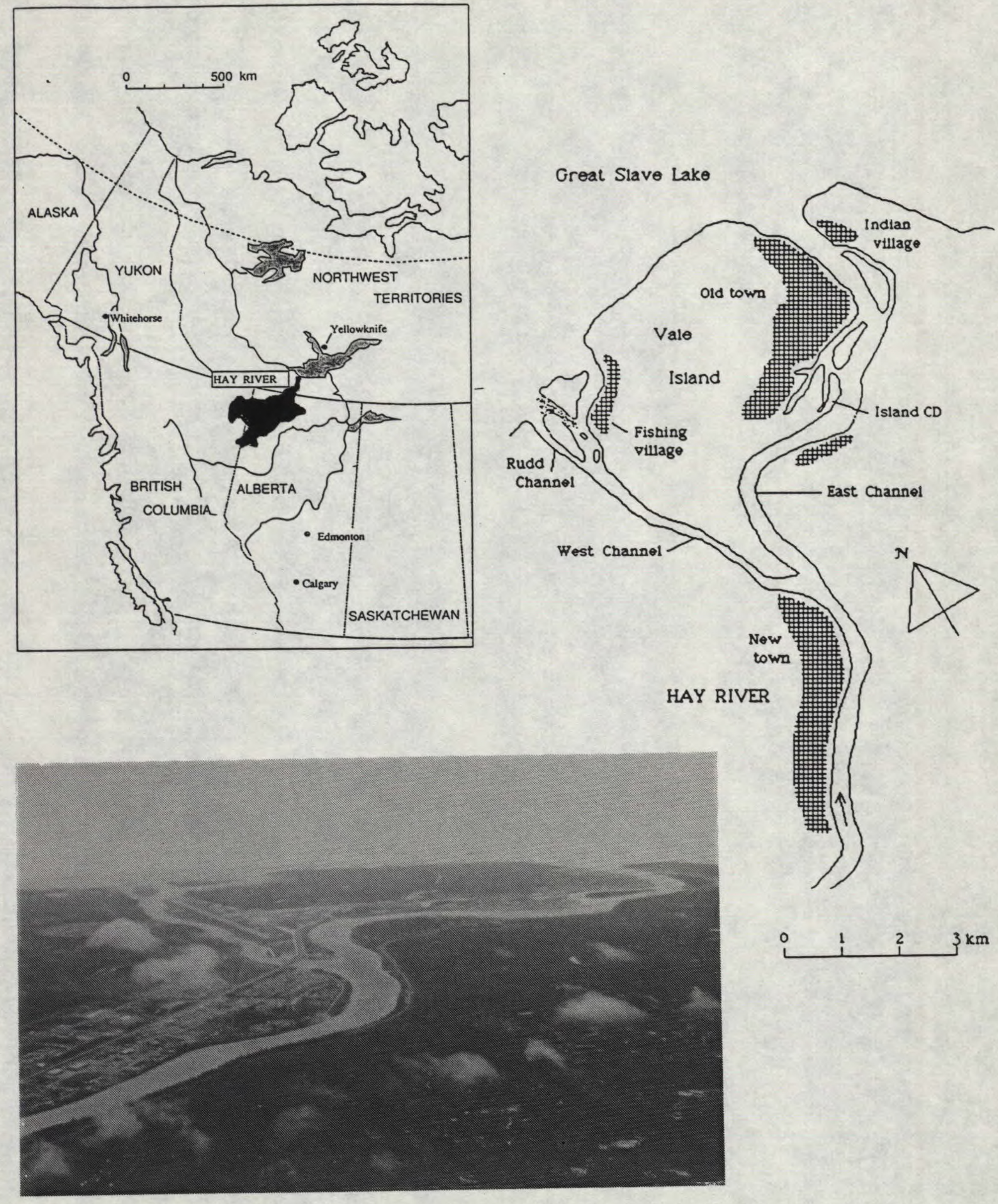

Figure 1 The Town of Hay River, N.W.T.: (a) Location (b) General plan of the town (c) Photograph looking downstream over the town with Great Slave Lake in the background (continued overleaf).

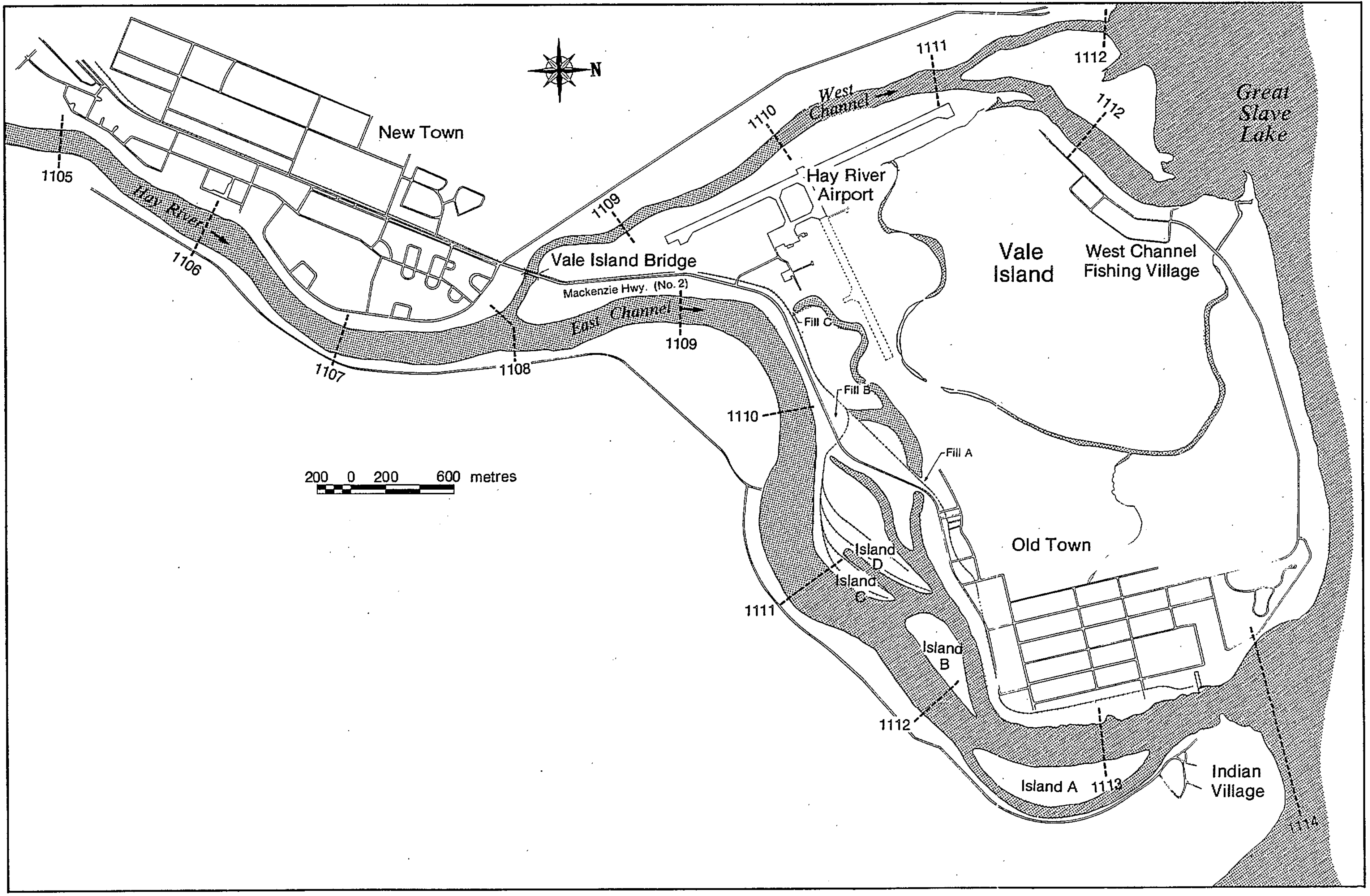

Figure 1 (continued) (d) Detailed town plan (base map from UMA, 1979)

"1. Review and evaluate historic information and data for floods at Hay River.

2. Conduct field programs in the lower Hay River Basin during freeze-up and break-up in each year of the study.

3. Investigate the factors which determine the location of offshore ice-pressure ridges and their magnitude in the Hay River vicinity.

4. Investigate factors which determine the location and strength of ice jams in the Hay River vicinity.

5. Establish linkages between break-up timing, discharge magnitude and antecedent hydrometeorological conditions.

6. Investigate models or techniques of combining the effects of river ice jams, discharge, and flow blockage by offshore pressure ridges with significant hydrometeorological factors to predict flood stages in Hay River.

7. Provide first estimates of the predictive capabilities of a prototype model."

The complete Statement of Work for Phase 1 is included in Appendix A.

1.3 Outline of Phase 1 studies

The Phase 1 study had six major components reflecting portions of one or more of the tasks outlined in the Statement of Work. These components were:

1.3.1 A review and evaluation of the history of ice jam flooding in Hay River.

This involved a review of previous consultant and Government reports, relevant files made available by the Town and Government Departments, and interviews with selected local residents and Town personnel who had had long involvement with ice jam flooding in Hay River. Water levels determined from these generally qualitative descriptions were defined and tied to geodetic datum during the summer field survey described in Section 1.3.3.

Using this information an effort was made to define events during each break-up over the period of record. The results are given in Appendix B and the general picture that emerged of the break-up ice regime in Hay River is described in Section 2.3.

The quantitative results of this historical review formed the basis of the probability analysis of ice jam floods at Hay River detailed in Sections 4.2 and 4.3. The purpose of this analysis was to place the various flood events in perspective, and to get a first indication of whether the several man-made changes in the delta had had a perceptable effect on the ice jam regime.

1.3.2 Field observations of the delta ice regime.

Four field trips were undertaken over the course of the Phase 1 study to observe various aspects of the delta ice regime: in fall 1987 to assess the freeze-up process; in late winter 1988 to document the ice ridges off the West Channel mouth; and in spring 1987 and 1988 to observe break-up. The emphasis was placed on the break-up observations. During each field trip appropriate water level and ice thickness surveys were carried out. During the 1988 break-up observations, an attempt was made to measure water temperatures at several sites in the catchment but, due to instrument malfunction, this was unsuccessful.

In all instances the Town provided on-site support in the form of transport, equipment, personnel and encouragement. During the break-up observations a near-continuous record of discharge entering the delta was obtained through the frequent direct discharge measurements carried out by Water Survey of Canada and Indian and Northern Affairs Canada personnel.

The details of these field observations and surveys are described in Appendix C.

1.3.3 Determination of the hydraulic geometry of the delta channels and the nearshore lake bathymetry

A fifth field trip was undertaken in summer 1987 to survey the hydraulic geometry of the delta channels and the nearshore lake bathymetry, and to tie into geodetic datum the temporary benchmarks established during the break-up observations.

The detailed channel geometry was needed to allow calculation of flow and ice jam water level profiles throughout the delta. Unfortunately use could not be made of cross-sections surveyed as part of earlier studies because of ambiguities about the locations and datums of these cross-sections. To try to avoid a repetition of this problem for future studies, considerable effort was devoted in the present study to establishing an unambiguous distance datum for the reach and to tie all levels into reliable geodetic benchmarks. Reference locations for the distance datum are given in Appendix D and the geodetic bench marks used are described in Appendix E.

Some 32 channel cross-sections and the thalweg profile of each channel were surveyed over the reach from the Water Survey of Canada gauge to the mouth. The detailed nearshore bathymetry was documented by hydrographic survey from just west of the West Channel mouth to just east of the East Channel mouth, extending offshore for approximately 0.7 km. The field techniques used and the results obtained are given in Appendix F.

1.3.4 Adaptation and refinement of an algorithm for calculating the water level profile through an ice jam.

Flooding that occurs at the East Channel mouth is caused by water levels associated with the very non-uniform toe region of an ice jam. When Phase 1 was initiated such water level profiles had not been calculated in practice. However an algorithm for this task had recently been developed as part of an on-going research program on ice jams in the Department of Civil Engineering, University of Alberta. As part of the Phase 1 study this algorithm was refined and calibrated for the East Channel and utilized when developing the portion of the flood forecast algorithm to be applied at the East Channel mouth.

The application of this algorithm is discussed in Section 5.5 and its calibration is described in Appendix G.

1.3.5 Discharge prediction

Review of the historical data, and preliminary analysis, confirmed that the major parameter governing ice jam floods in Hay River, other than ice jam formation itself, was the discharge entering the delta. A significant effort was initially devoted to developing a simple algorithm to predict this discharge but it became apparent that the available meteorological data for the Hay River catchment precluded **simple** prediction of the discharge hydrograph, both in magnitude and timing, with the required accuracy. Details of this preliminary investigation are given in Appendix H.

In view of this problem, the largely exploratory nature of the Phase 1 studies, and the likely availability of a 2 day warning of high discharge in Hay River from the Water Survey of Canada border station, it was agreed with Indian and Northern Affairs personnel to postpone further investigation of the discharge to Phase 2 of the study. However, a simple empirical relation was defined that would allow **long-term** prediction of a likely upper bound on the peak discharge to be expected in any given year. This relation is described in Section 5.1.

Although significant rainfall in spring appears to be unusual (it is difficult to tell because of the very sparse meteorological network operable at that time of year in the Hay River catchment) it has been argued that it was very important in the 1985 event and, indeed, the 1985 discharge is an outlier when plotted against winter snowfall. To investigate this a simple water balance was determined for 1985 and some 20 other spring runoff events. The analysis and results are described in Appendix I.

1.3.6 Flood forecast algorithm

Investigation of the feasibility of a flood forecast algorithm was taken as the prime objective of the Phase 1 study. Such a procedure was developed, and evaluated using the observations of the 1988 break-up, as described in Sections 5 and 6.

At the beginning of this study it was accepted that the ice ridges which form each winter off the delta mouth can play a major role in causing flooding at the mouth. However, as the study progressed, it became evident that the role of the ridges was likely more apparent than real, as detailed in Section 2.3. For this reason somewhat less attention was paid to the ice ridges in this Phase I study than was originally invisaged would be appropriate.

2.0 THE HAY RIVER

2.1 Catchment Characteristics

The Hay River has a catchment of some 48,100 km^2 and rises in the foothills of the Rocky Mountains to the southwest, as shown in Figure 2. The river flows generally northeast through mainly flat muskeg-ridden terrain before plunging over two quite dramatic waterfalls some 70 km upstream of the lake and then running through a gorge whose sides gradually decrease in height towards the lake. Just upstream of the lake the river banks are still quite high, with the result that the delta at the mouth is almost the only low-lying land along the lower reach of the river.

The Hay River catchment lies entirely in the north-western portion of the Great Central Plains and within the zone of discontinuous permafrost. Its physiography is shown in Figure 3. The catchment has three major sub-catchments: the Chinchaga River, Upper Hay River and Lower Hay River basins.

The Chinchaga River basin is the upper, southern portion of the catchment and accounts for about 23% of its area. It is dominated by the Halverson Ridge which rises to an elevation of 1,200 m. Over 60% of this basin is above 610 m elevation (UMA, 1979). The vegetation is mostly white spruce and lodgepole pine (GNWT/IWD, 1984), indicating a relatively well-drained area.

The Upper Hay River basin represents about 42% of the Hay River catchment and lies to the west. It is dominated by lowlands, with only 15% of its area above 610 m. The major feature is Zama Lake, which is a low-lying swampy tract and is the only significant lake storage in the Hay River catchment. The majority of the Upper Hay River basin is covered with black spruce and aspen, indicating less well-drained conditions.

The Lower Hay River basin constitutes about 35% of the catchment. It is primarily a wide area of low-relief muskeg terrain that extends north-south between the Cameron Hills (elevation 750 m) to the west and the Caribou Mountains (elevation 900 m) to the east. Figure 4 shows portion of this basin with the Hay River at Meander River.

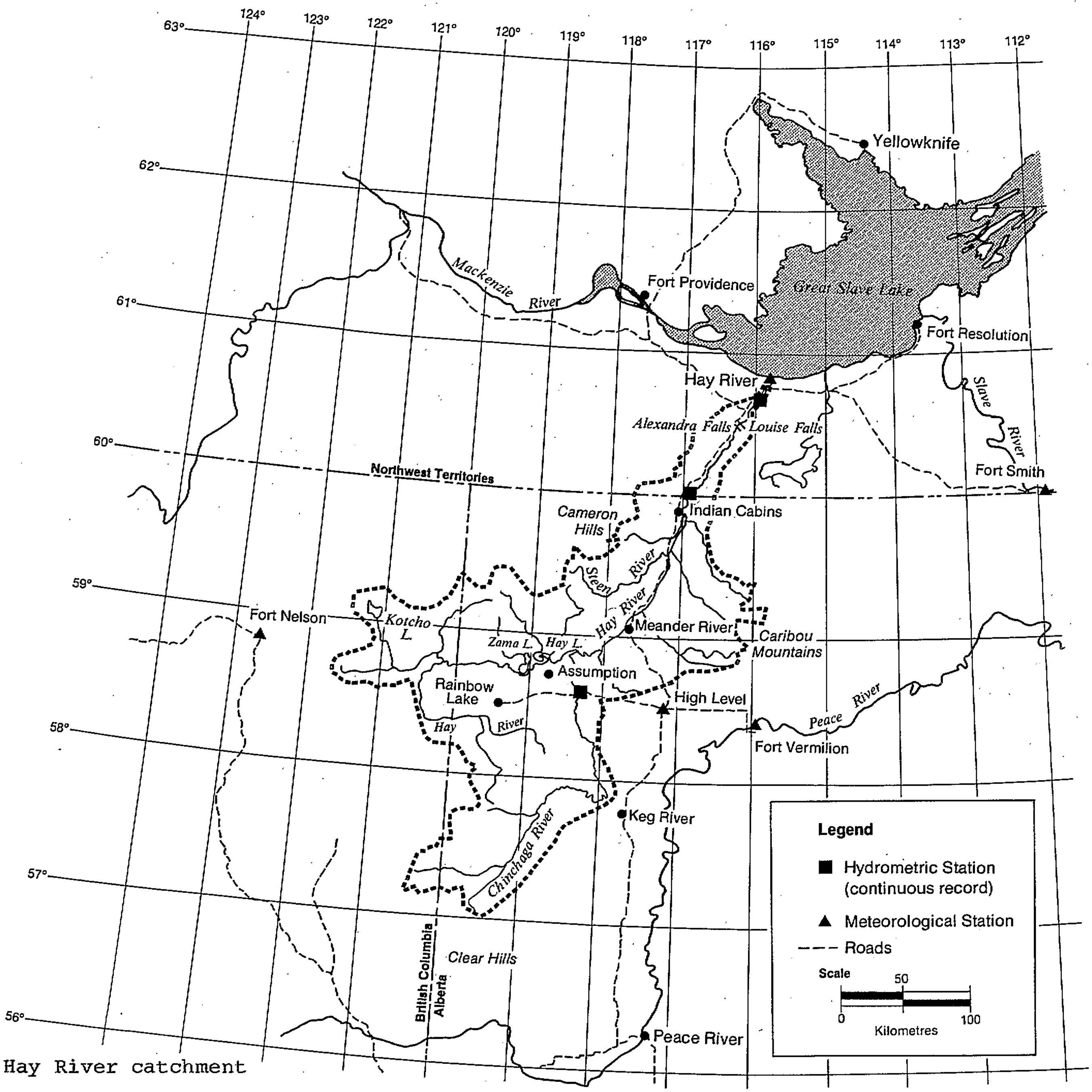

Figure 2 The Hay River catchment

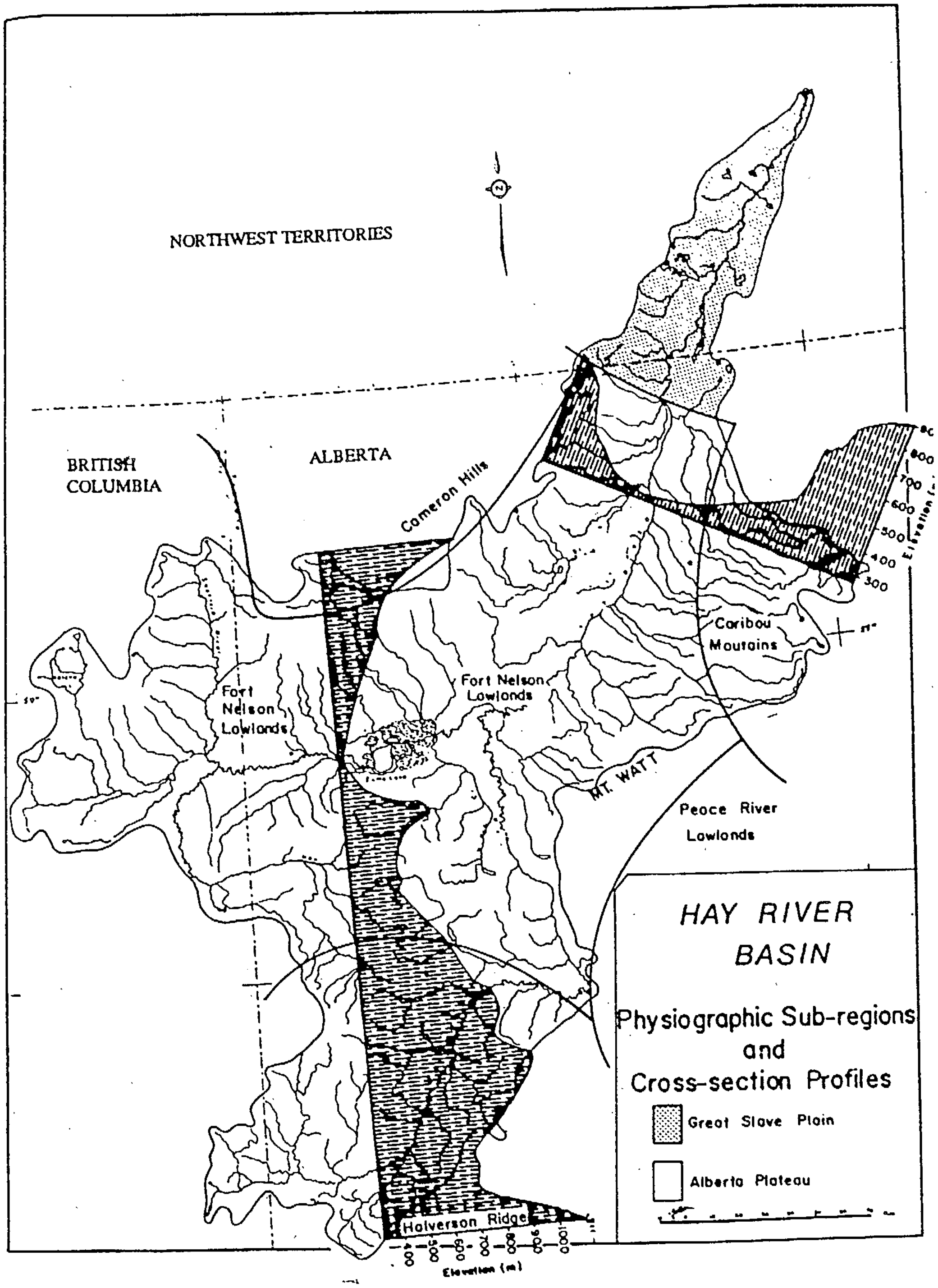

Figure 3. Physiography of the Hay River catchment (after GNWT/IWD, 1984).

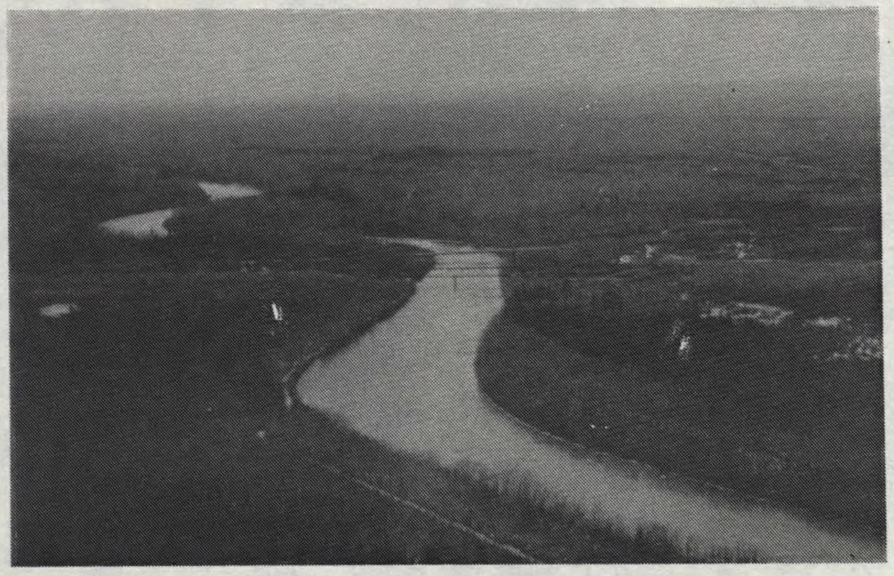

Figure 4 The Hay River looking upstream over the highway and railway crossing, and WSC gauge, near Meander River

The lowlands of the Lower Hay River basin slope gently northward to the escarpment at the edge of the Alberta Plateau just north of the Alberta - Northwest Territories border. Here the river plunges over two waterfalls. The first and largest is Alexandra Falls at km 1034.95*, shown in Figure 5(a), which is 33 m high. The second is Louise Falls, some 2 km downstream at km 1037.12, shown in Figure 5(b), which fall 15 m. To the north of the escarpment the river flows through a gorge, shown just downstream of Louise Falls in Figure 6, across the Great Slave Plain to Great Slave Lake at km 1114.24. As indicated earlier, the gorge walls gradually decrease in height towards the lake with the river remaining lightly entrenched just upstream of the mouth, as shown in Figure 7, with bank heights of 5-10 m. However within the delta the islands are as low as 1-2 m.

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* To provide unambiguous and convenient reference to position along the river, it is given as the distance from the river source at coordinates UTM 311280/6379670. The distances were calculated from a plan of the river digitized from 1:50,000 NTS maps as described in Appendix D.

Figure 5(a) Alexandra Falls, 33 m high (b) Louise Falls, 15 m high

Figure 6 Hay River gorge looking downstream from Louise Falls

Figure 7 The Hay River at Hay River, looking upstream

The general longitudinal profile of the river, plotted from 1:50000 NTS maps, is shown in Figure 8. The upper portion of the river (the Chinchaga River) is relatively steep with an average slope of 0.001. At about km 400 this has reduced to about 0.00045 and over the 200 km above the falls the slope is only 0.0001. Below the falls the river becomes very steep, with an average slope of 0.003 for the first 10 km. This reduces to about 0.0001 again at the delta.

At present there are four Water Survey of Canada (WSC) hydrometric stations usually operative during break-up in the Hay River catchment. Their locations are shown in Figure 2. The oldest is that on the Hay River at Hay River, with a drainage area of 47,900 km^2. This began operation in 1964. The newest is on the Hay River at the Alberta-Northwest Territories border, with a drainage area of 46,080 km^2. This was installed in 1986 to provide advance warning of high water levels approaching Hay River during break-up. It is equipped with a DCP that can be interrogated by satellite and has only recently been rated to allow estimates of discharge. The third station is near Meander River at the Highway 35 crossing, with a drainage area of 36,900 km^2. It was installed in 1974 and, although listed as a seasonal station, is made operational over break-up. The fourth station is on the Chinchaga River, with a drainage area of 10,400 km^2. This began operation in 1970.

The average annual hydrograph of the Hay River at Hay River is given in Figure 9. In common with other northern streams, it is dominated by the snowmelt peak. As mentioned earlier, an important feature in the present context is that the annual peak discharge occurs at about the time of break-up.

The exceedence probability distributions of the annual peak snowmelt and rainfall discharges of the Hay River at Hay River are given in Figure 10. These confirm the dominance of the snowmelt peak. (Note that the 'rainfall discharges' in Figure 10 represent the contribution from rainfall only; the estimated snowmelt contribution on the day of the rainfall peak was subtracted from the measured discharge.)

Meteorological stations that provide data relevant to break-up in the Hay River catchment are also shown in Figure 2. The average monthly temperature at the Town of Hay River is below 0°C in November, reaches a minimum of -26°C in January and does not return to above zero until May, giving an average of

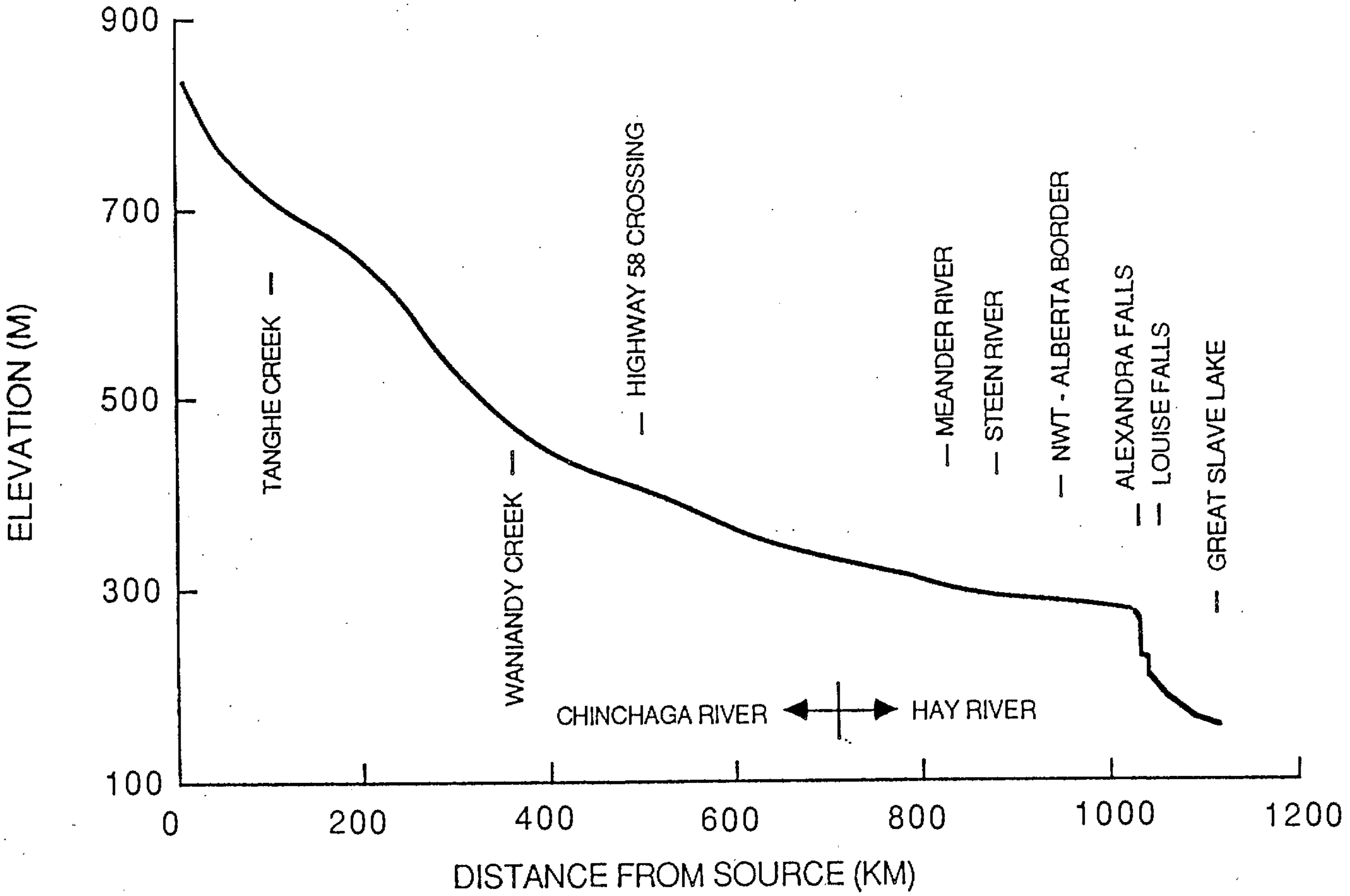

Figure 8 Longitudinal profile of the Chinchaga-Hay River

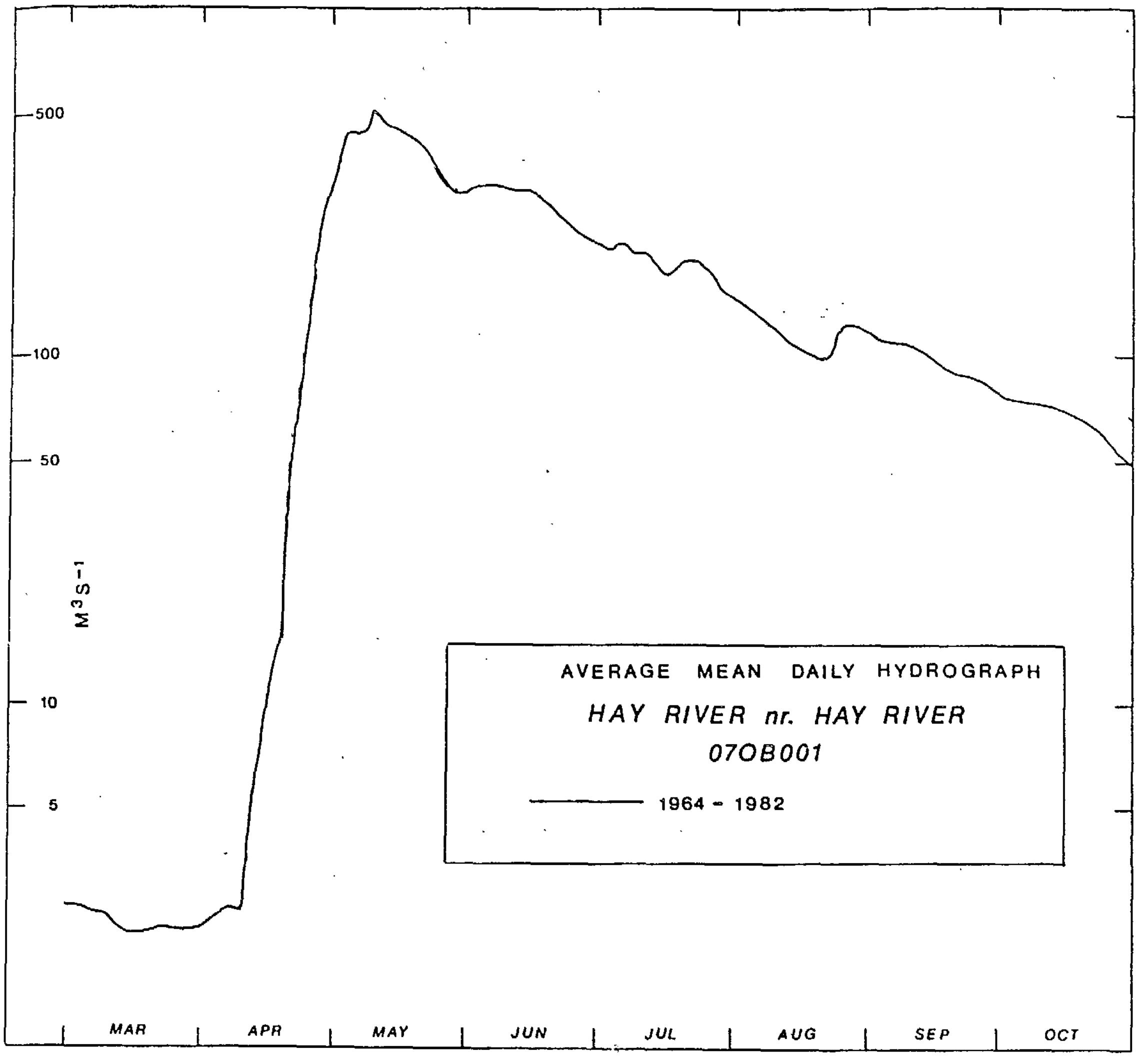

Figure 9 Average annual hydrograph, Hay River at Hay River (after GNWT/IWD 1984)

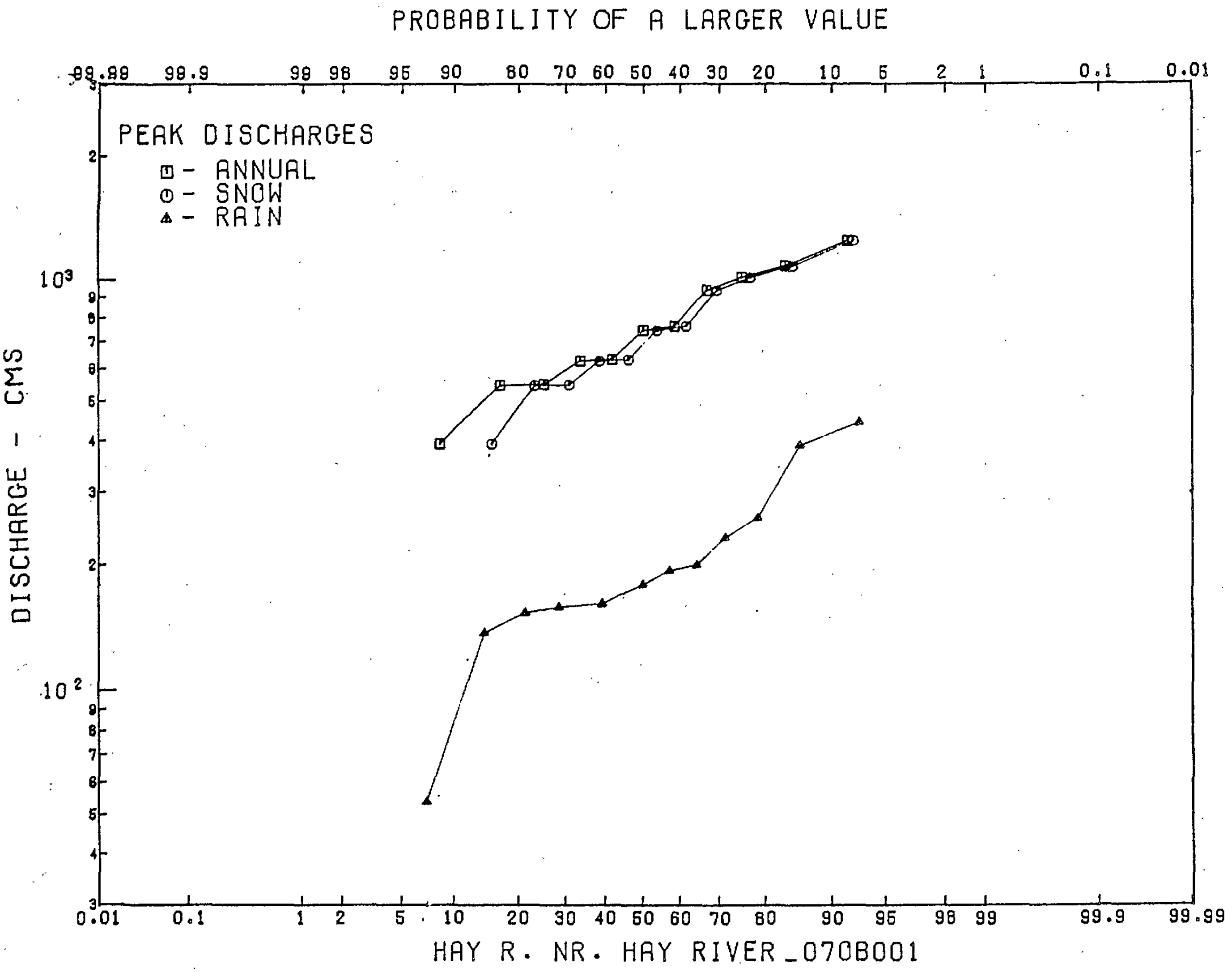

Figure 10 Exceedence probability distributions of annual,peak snowfall and rainfall discharges, Hay River at Hay River

about 3,147°C-days of frost over the winter (AES, 1982). It is 2,755°C-days at High Level. The average annual precipitation at Hay River is 340 mm. The approximate average for the basin is 400 mm, with the greatest precipitation occurring in the higher western region of the catchment. The portion of this precipitation of most interest is snowfall. The mean snowfall water-equivalent is about 165 mm at both Hay River and High Level, while it is 187 mm at Fort Nelson.

2.2 Delta channel and lakeshore characteristics

Figure 1 (d) is a detailed plan of the Hay River delta at Great Slave Lake. The river splits into the East and West Channels to form Vale Island, the largest of the delta islands. The delta is a relatively low flat area with both active and abandoned channels.

Figure 11 shows the thalwegs of the major channels in the delta. Typical cross sections of the East and West Channels are given in Figure 12. The East Channel is the main channel and normally carries about 65-75% of the flow passing through the delta. As is evident in Figure 11, the West Channel has the nature of a high-level by-pass, its bed being substantially higher than that of the East Channel. The West Channel becomes dry during low flows in the summer and freezes to the bed during winter. Near the lake the West Channel splits into two channels, with a high-level channel between them. The west arm is called the Rudd Channel.

There is a notable and sudden deepening of both the East and West Channels near the mouth. What seem to be bedrock or lag deposits almost form rapids at the upstream ends of the deep sections and, particularly in the East Channel, cause the channel to widen.

The nearshore lake bathymetry is shown in Figure 13. Because of its large expanse, the lake level varies little over the year, as indicated in Figure 14, particularly in late winter when the lake is not subject to storm surges. The most important feature of the bathymetry in Figure 13 is the shallow offshore bar, which is also evident in air photos of the area. The bar has been dredged off the East Channel and the east arm of the West Channel. While the location and details of the bar may change with storm activity on the lake, little maintenance dredging has been required at the East Channel mouth (DPW, personal communication). This suggests the bar is not too active.

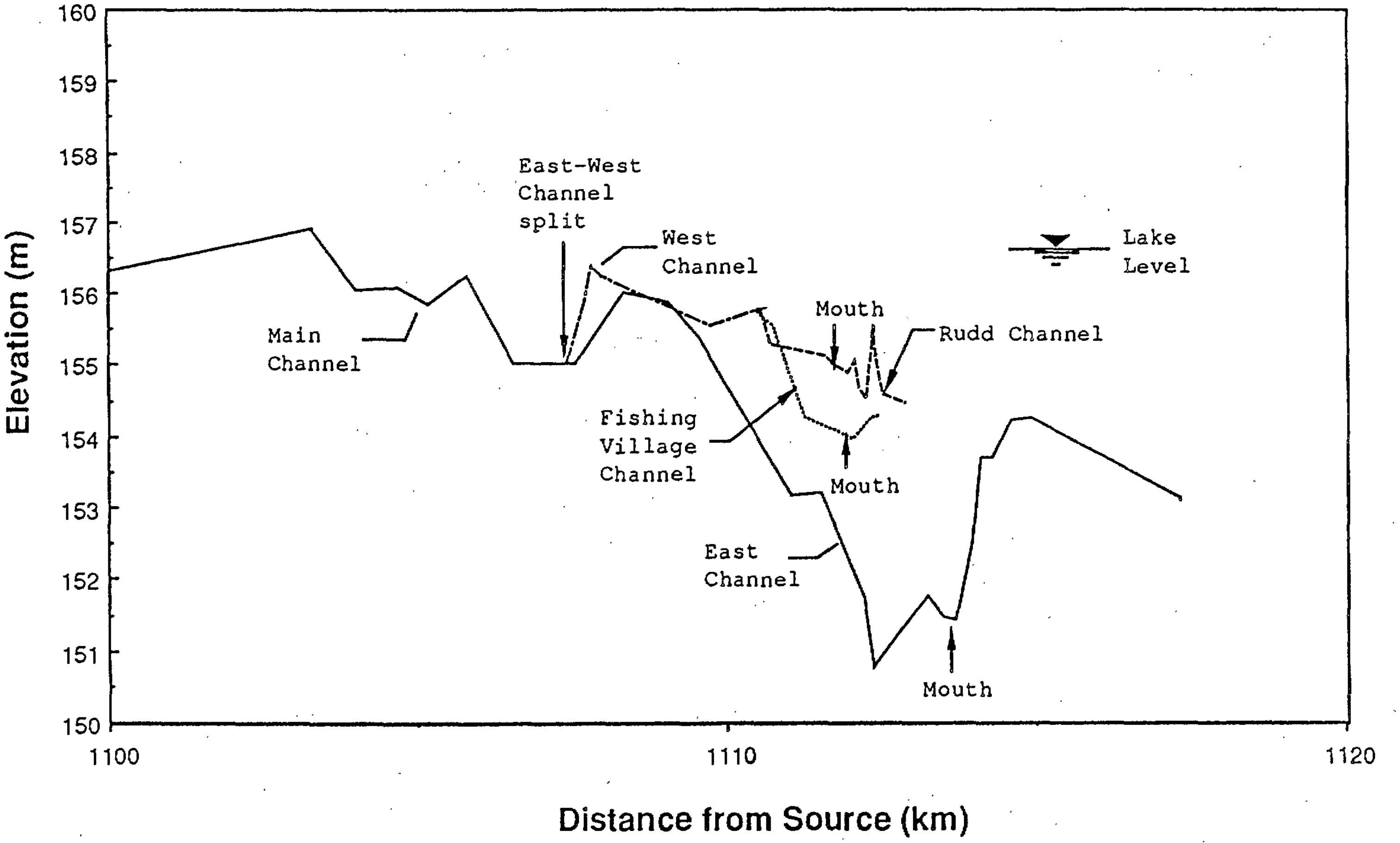

Figure 11 Thalweg profiles of the delta channels

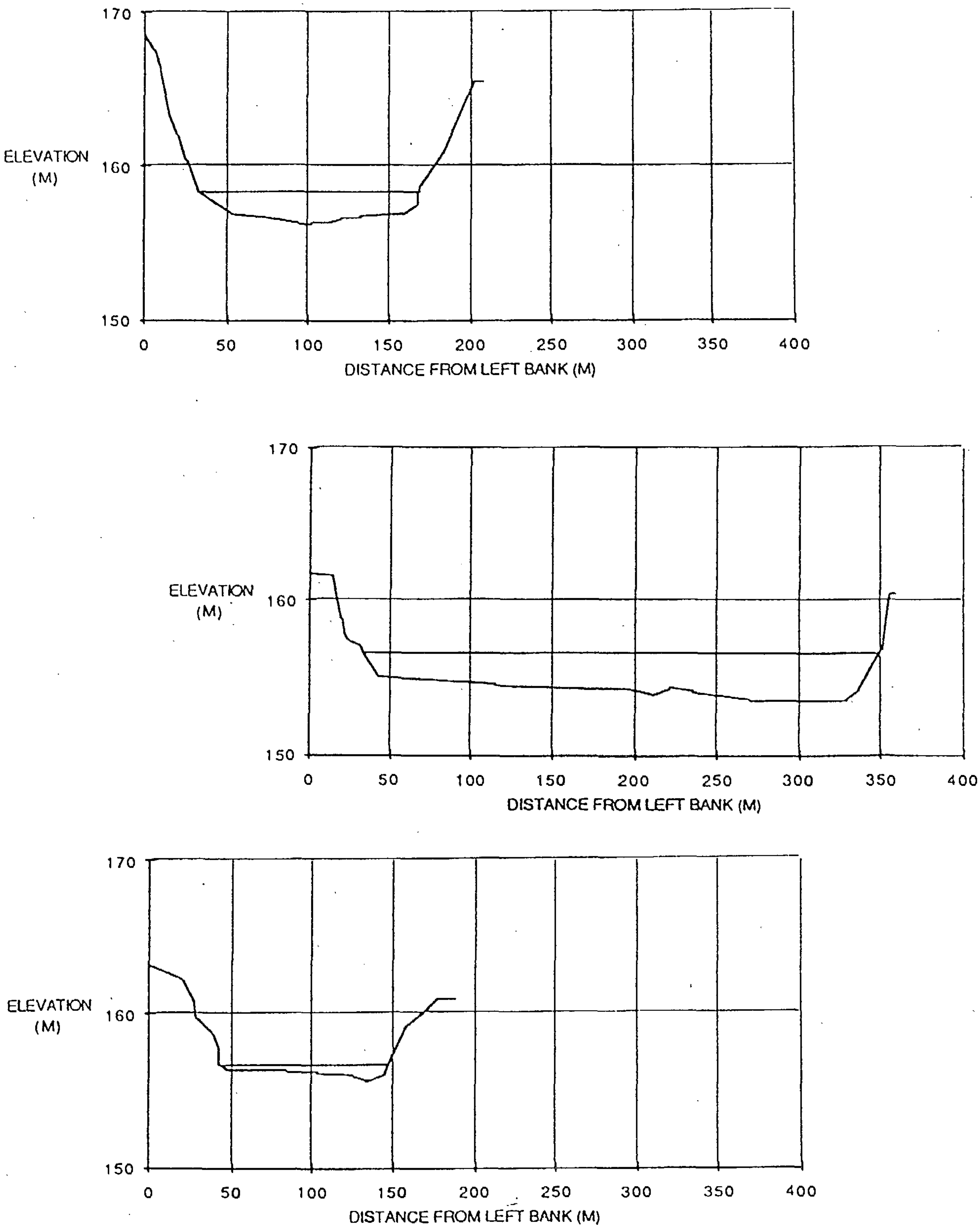

Figure 12 Typical cross-sections of the delta channels: (a) Hay River above the delta (km 1105.2); (b) East Channel (km 1111.0); (c) West Channel (km 1110.2).

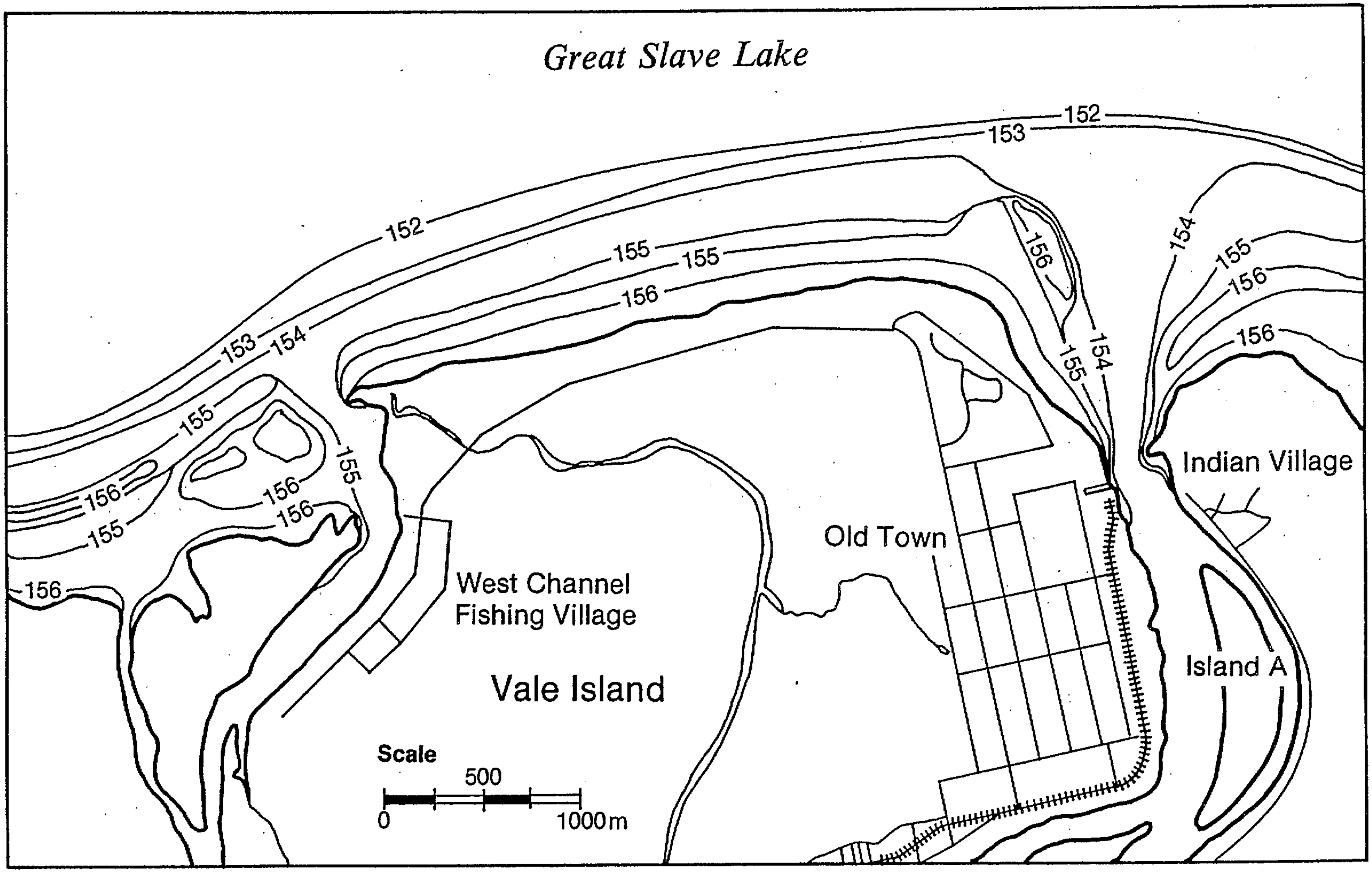

Figure 13 Nearshore lake bathymetry

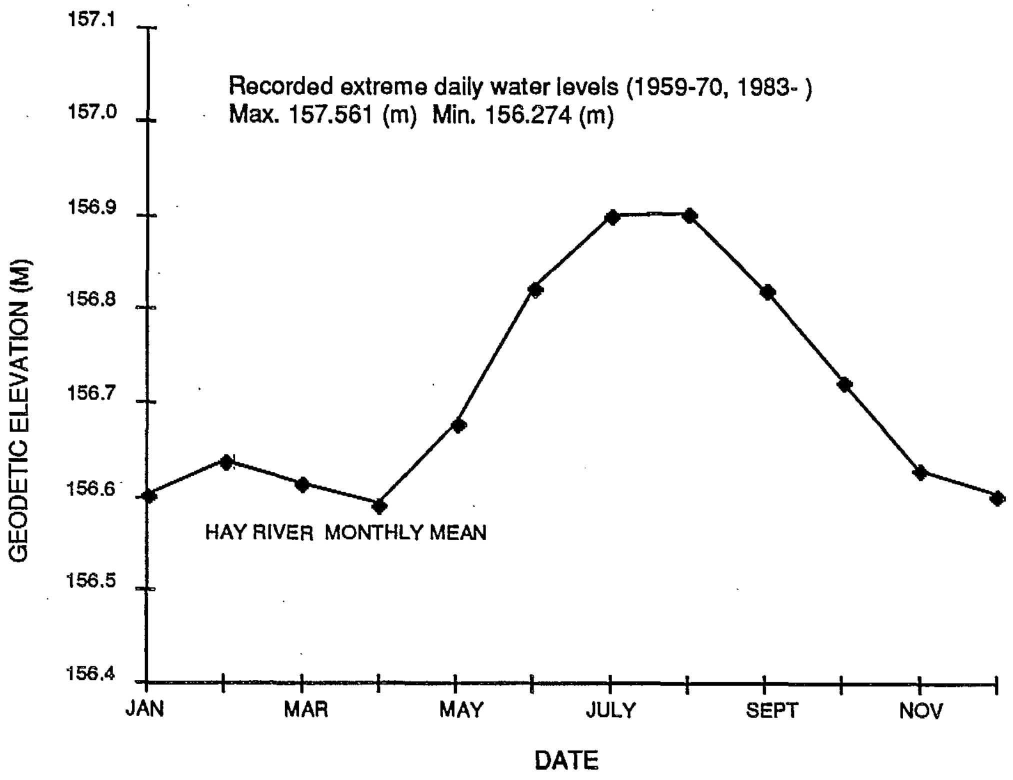

Figure 14 Typical annual variation of Great Slave Lake level at Hay River (from WSC data)

2.3 Ice regime

The major concern for the present study was the ice regime of the lower reaches of the river and the nearshore regions of the lake. Field observations of ice processes in this area were made during break-up in 1987 and 1988, during freeze-up in 1987 and in late winter, 1988. On the basis of these observations, the historical record review, and discussions with residents, it has been possible to assemble a reasonably firm understanding of the general ice regime.

2.3.1 Freeze-up

The lower reaches of the Hay River typically freeze over in early November (Allen, 1977). Within the delta the deep water at the channel mouths freezes over first. The initial lodgement of the frazil pans and slush moving down from upstream then typically occurs at the upstream ends of these deep sections forming quite rough ice. In the East Channel this lodgement occurs typically at Island CD, while in the West Channel it occurs in the vicinity of the split. The frazil slush and pans accumulate behind these lodgements and the freeze-up pack gradually builds back upstream, with the nature of the pack varying somewhat depending on the velocity at the head of the pack as it passes each section. For example, in 1987 a stretch of rough ice, possibly another lodgement, formed just downstream of the shallow reach opposite the Ptarmigan Hotel. While reaches between and below the falls remain open, frazil is generated and is carried downstream to form slush deposits under the solid ice at several locations in the delta, as indicated in Figure 15.

Except for the above lodgement locations, on November 16 the initial ice cover was smooth up to the golf course (km 1087.4), from where another pack of rough ice extended upstream for 21 km to open water just upstream of Paradise Gardens (km 1066.4). With 114°C days of frost accumulated to this date, this represents an average advance rate of about 0.4 km/°C day, a rate that would have been assisted by the 25 cm of snow that had fallen in the previous few days. The discharge at Hay River on November 16 was 63.0 m^3/s.

By late winter ice thickness reaches an average of 1.0 m on the river near the mouth and 1.3 m on the lake (Allen 1977), but only 0.64 m at the Hay River WSC station (May, 1971).

Discharge in the West Channel is largely controlled by the water level in the East Channel, and initially water depths in the West Channel are large enough to allow a regular ice cover to form. Eventually, though, as the water level in the East Channel falls due to decreasing discharge over the winter, the West Channel freezes to the bed except over the deep sections of the two arms near the mouth.

Freeze-up begins on the lake about the same time as on the river, but it is not until mid-December that the lake completely freezes over. Hence, initially, there is open water off the thin shorefast ice. At this time it is not unusual for a rubble ice ridge to form along the outer edge of the offshore bar due to the action of waves and the impact of large, but thin, floes moved by the wind. Although it was not possible to get access to it, this rubble ice was evident from shore during the freeze-up observations in November, 1987. In the March, 1988 survey the general location of this ridge was determined by resection to known targets on the shore and is shown in Figure 16. It was found to vary in height from about 0.8 to 1.5 m. Its position and appearance off the Rudd Channel are shown in Figure 17. Its location at the bar is evident.

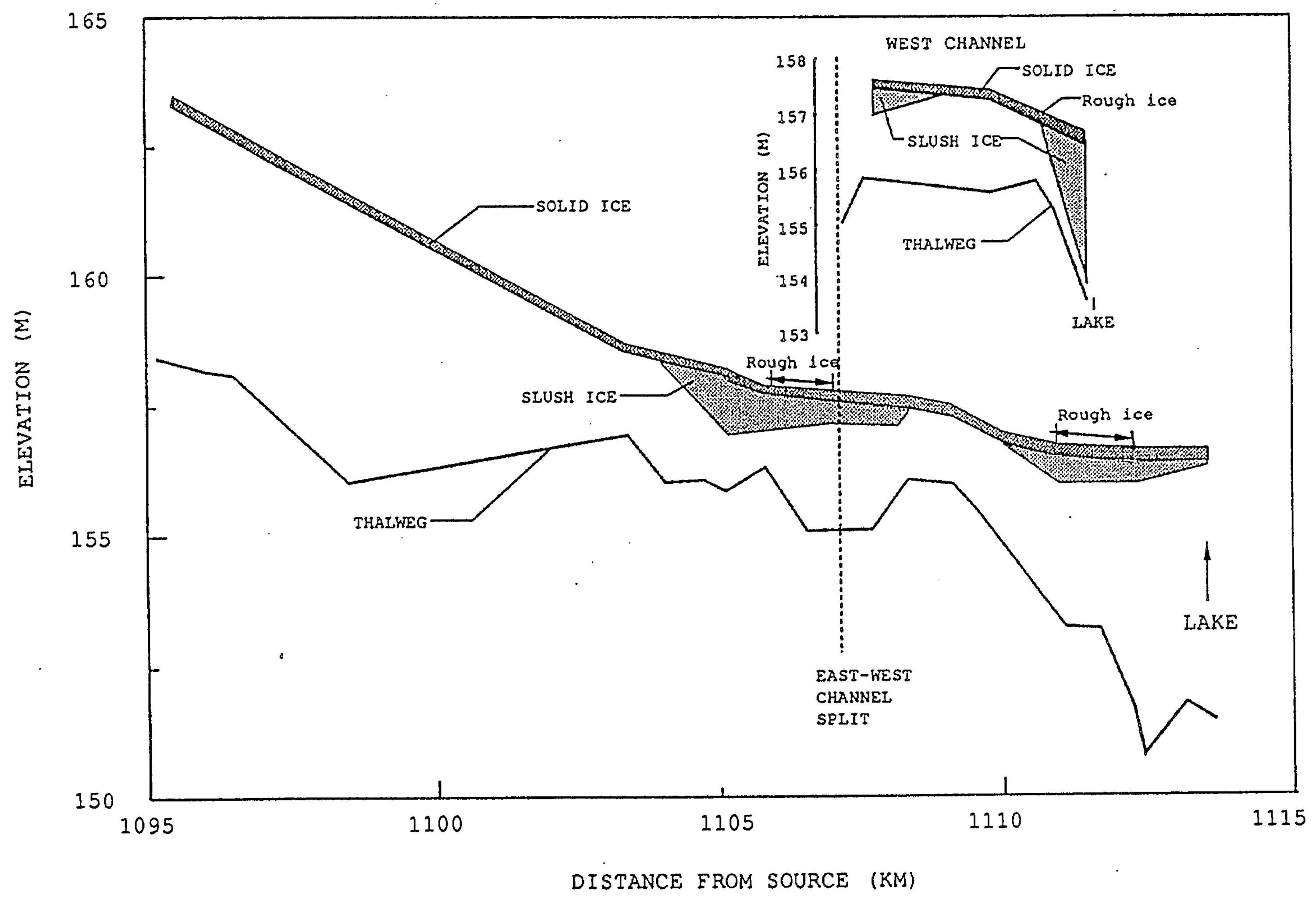

Figure 15 Ice thickness profile in the delta channels, 17 November, 1987

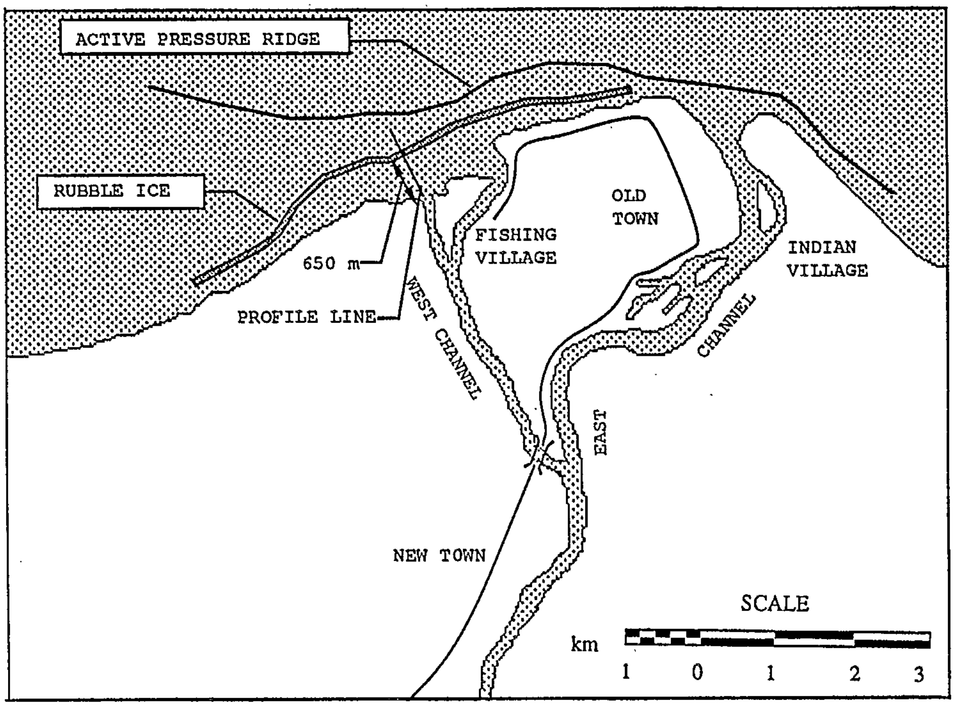

Figure 16 Locations of the rubble ice and pressure ridge off the West Channel, March 1988.

Further offshore a true pressure ridge usually forms. The position of this ridge in March, 1988 is also shown in Figure 16. At the time the ridge was active but still largely undeveloped at this location. One of the higher sections is shown in Figure 18. The nature of this ridge in other years is described by Arctec (1980).

2.3.2 Break-up

Break-up begins on the Hay River between mid-April and early May. The reach immediately below the falls typically breaks up first, presumably because of the fast water and thin ice there, and forms an ice jam.* More typically the accumulation is a regular floating ice jam. This jam gradually advances in irregular steps, increasing in size, until eventually its advance

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* The nature of this initial accumulation can apparently vary substantially. For example, Figure 19 shows the situation at Louise Falls during break-up in 1976. The water level has increased sufficiently to almost submerge Louise Falls! This suggests the formation of a large hanging dam or grounded ice jam downstream of the falls.

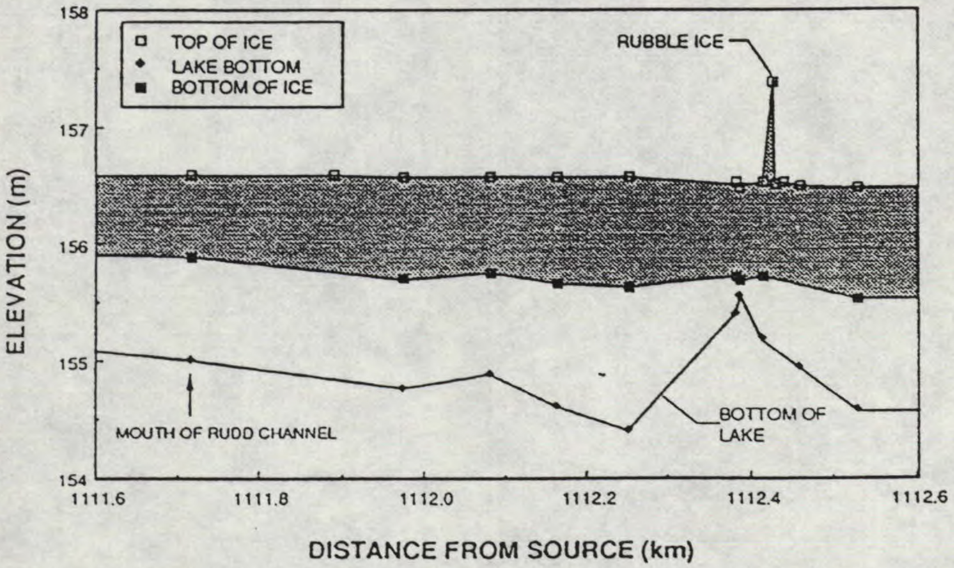

Figure 17 Rubble ice formed along the bar off the West Channel, March 1988.

Figure 18 Pressure ridge off the West Channel mouth, March 1988.

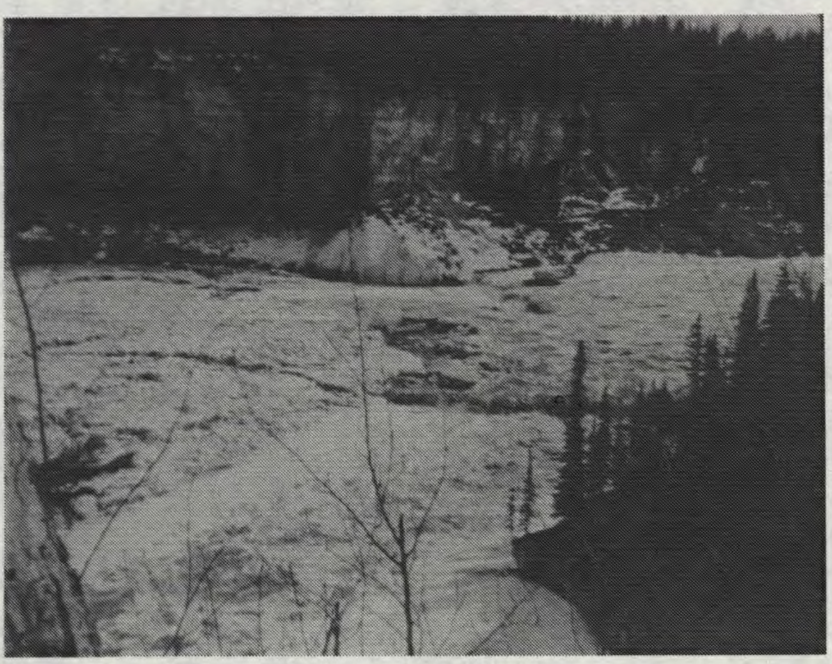

Figure 19 Backwater from ice accumulation in the gorge flooding out Louise Falls, spring 1976 (photo by L. Brunes)

releases a surge sufficient to generate an ice run that carries break-up to the delta. This run usually stalls and sets up a jam with its toe in or near the shallows of the East Channel opposite Island CD (km 1111), as shown in Figure 20, and a pack extending well upstream of the town. The average date of this ice run is April 30, with a standard deviation of about 5 days.

The increase in water level at the split as the break-up front passes diverts water and much of the ice down the West Channel, which thereby acts as a high-level by-pass. Generally the flow moves over the bottomfast ice in the West Channel, out onto the lake ice and then stalls just beyond the mouth, as shown in Figure 21, forming a jam that extends back up to the split where it merges with the pack on the main channel. While the offshore ice ridges no doubt contribute to the tendency of the run to stall at the mouth, it is likely the run would stall at about this location whether the ridges were present or not, because the water spreads out over the lake ice and the pack grounds. Furthermore, the weight of water and pack will depress the lake ice between shore and shoal, so adding further to the tendency for the run to stall.

As the run passes the West Channel split it can move into the east arm as shown in Figure 22. However field observations and historical data suggest this is not the norm: rather it seems a jam forms in the shallows at the upstream end of the east arm about 80% of the time (L. Brunes, Hay River, personal communication).

Although water levels may be quite high during the initial ice run in the delta, discharges are usually relatively low and no serious flooding takes place.

After this run, some 50 km of river can be open below the falls. With bright sunshine and warm air temperatures the water will warm as it passes through this reach and begin to melt the pack in the delta. It is this melt that eventually rids the delta of the ice jam pack. The average period between the initial ice run and the East Channel being free of ice is 6 days, with a standard deviation of about 3 days.

The discharge continues to increase if air temperatures remain warm enough and break-up begins on the river above the falls. This typically results in ice jam formation and failure, with surges of water and ice being released intermittently to move down to the pack in the delta. As mentioned earlier, the discharge often reaches its peak while the delta pack is still in place.

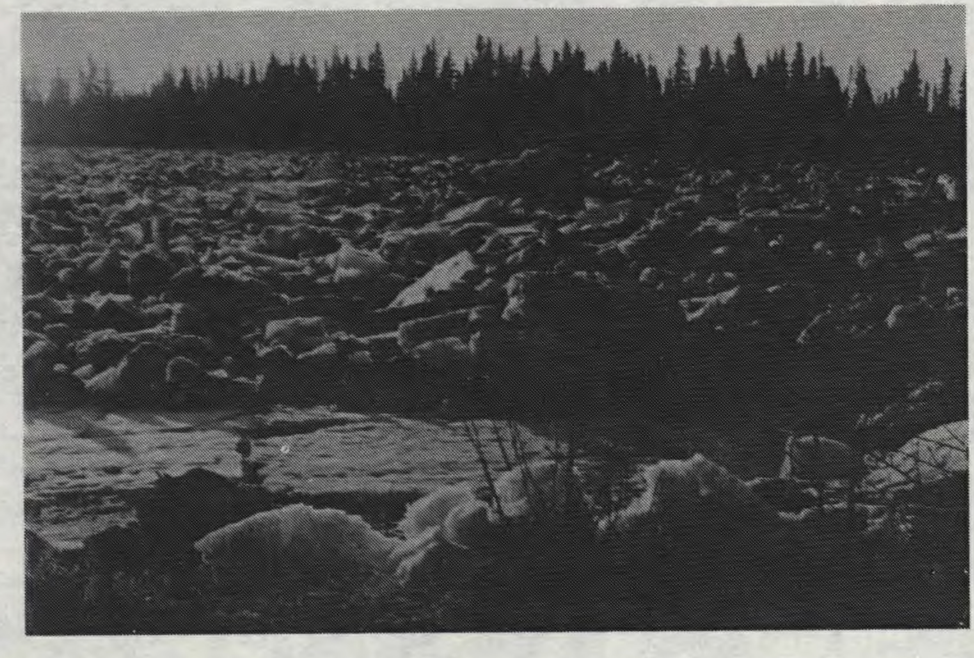

Figure 20 Toe of the ice jam at Island CD, 27 April 1987 looking (a) upstream over the toe and (b) from left to right bank across the pack near the toe.

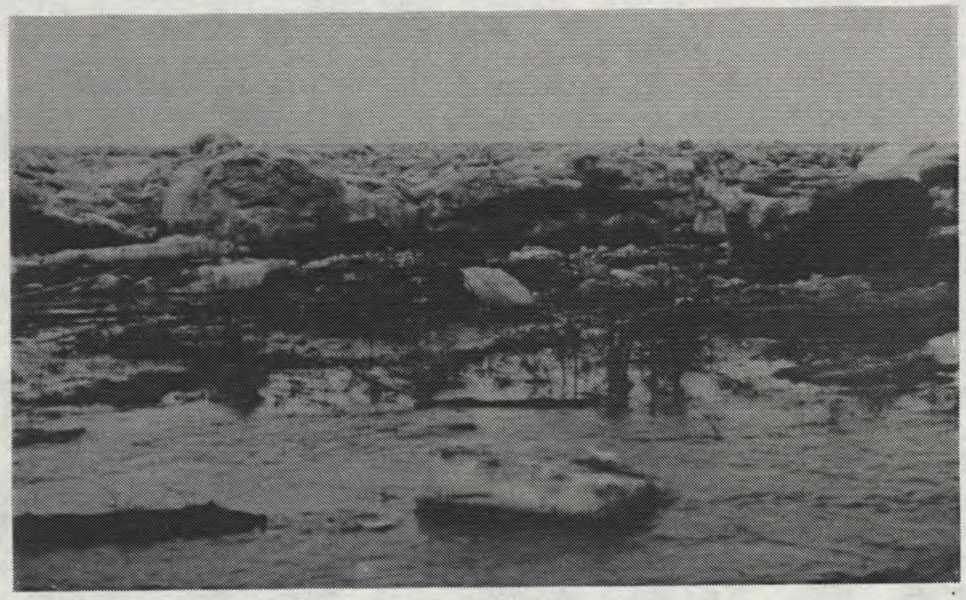

Figure 21 Ice run stalled at the West Channel mouth, 29 April 1988 (a) from the air looking upstream over the Rudd Channel and (b) from the lakeshore looking offshore just west of the Rudd Channel.

2.3.3 Flooding in the delta

Whether serious flooding occurs in the delta depends on the condition and configuration of the pack in the delta when the peak discharge arrives, and on the magnitude of this peak. It normally arrives 4-8 days after break-up in the town. If this peak discharge is high and arrives before significant melting has taken place, serious flooding in the delta can be expected. This can be made worse by surges released by ice jam failure upstream of the falls, and by rainfall.

In the East Channel the most severe flooding occurs when a high discharge arrives and moves the toe of the jam from Island CD to the mouth while the pack is still reasonably long. However the combination of circumstances required for this seems to occur only infrequently, with the only recorded instances being 1914 and 1963. Typically the toe will remain near Island CD, even with a high discharge, if the ice between it and the mouth is still competent. For example, in 1985 the peak discharge was near the 1% flood discharge yet the toe in the East Channel remained at Island CD.

Figure 22 Ice jam in the east arm of the West Channel looking downstream from the Fishing Village, 29 April 1988

The early movement of the toe of the jam to the mouth of the East Channel would require that the ice cover be quite weak. It seems the toe near

Island CD will not normally move until the head of the pack has progressed downstream enough due to melting that warm water reaches the ice below the toe of the jam and accelerates its deterioration. At this point the jam is normally quite short, as shown in Figure 23, but it still poses a flood threat if it moves to the mouth. The characteristic sharp increase in water level across the toe region of an ice jam (the water level variation through a jam is discussed in more detail in Appendix G) can be sufficient to flood low lying land near the mouth if the discharge is high enough, as happened in 1987. However, the levels will not be near those that would occur if the jam moves down suddenly while still fully developed, accompanied by a high discharge with the toe forming some distance out from the mouth, as happened in 1963.

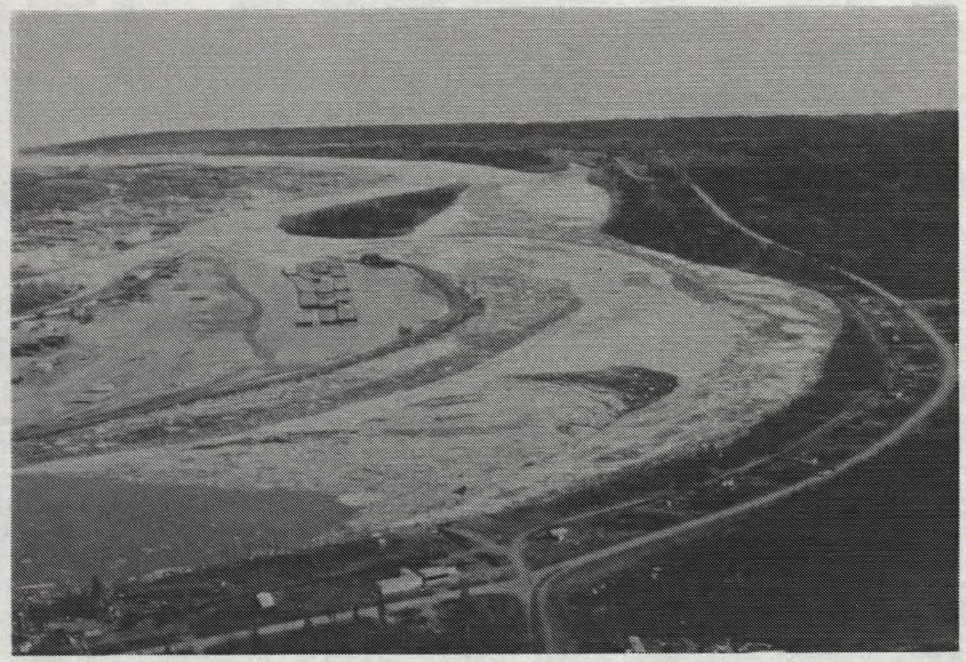

Figure 23 Ice jam in the East Channel, looking downstream, just prior to the toe moving to the mouth 30 April 1987

In the West Channel, flooding occurs if a high discharge arrives while the jams in both the East and West Channels are still in place. The ice jam in the East Channel causes high water at the East-West Channel split. This can then divert a significant portion of the flow down the West Channel. Then, if a pack is in place on at least the lower portion of the West Channel, water levels high enough to flood the delta near the mouth can occur. This occurred in 1985. The worst situation for flooding near the mouth of the West Channel would seem to be one in which the high discharge arrives when the head of the East Channel pack is just downstream of the East-West Channel split and the head of the West Channel pack is a little upstream of the West Channel split.*

In some years the jams, and the ice downstream of them, can be sufficiently deteriorated when the peak discharge arrives that they simply wash out into the lake and there is no flood threat.

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* Although a significant role in the 1985 flooding is attributed to the ice ridges off the West Channel mouth, the high water levels at the Fishing Village can be simply explained by the high discharge and the presence of a pack over the lower portion of the West Channel. Such a pack was present in the West Channel during the 1985 flood and the sequence of flooding and flow directions were compatible with flooding caused by high water levels above the Fishing Village, rather than by water backing up behind the ice ridges in the lake (J. Pollard, Hay River, personal communication. It is noted that the pressure ridge would have to be about 2 m above lake level over its whole length to simply back water up to the level of the Fishing Village dock.

3.0 THE TOWN OF HAY RIVER

Doubtless ice jam floods have occurred in the delta from time immemorial and, indeed, were likely the cause of some of the geomorphic features of the delta. However it is only relatively recently that these ice jam floods have had serious economic and social consequences. Although a minor fur trading post was established at Hay River in 1845, and two missions were established in the late 1800's, it was not until halfway through this century, with completion in 1948 of an all-weather road to Hay River from the Peace River area several hundred kilometres to the south, that sustained development began.

By 1964 the population was about 1,800, most of which was concentrated on Vale Island in the delta. At about this time there were two major events in the community: the occurrence of a disastrous ice jam flood in the spring of 1963, and completion of the Great Slave Lake Railway from the south at the end of 1964. Because of the flood, plans were made to relocate the town on high ground on the left bank upstream of the delta. With completion of the railway, the Town of Hay River became the head of navigation for the western Arctic.

The relocation and the arrival of the railway provided a fresh start and the town has continued to develop as a major freshwater fishing port and the trans-shipment and servicing centre for western Arctic shipping. By the 1980's the population was stable at about 3,000, making it the third largest community in the NWT.

As it now exists, the Town of Hay River has several distinct components, as shown in Figure 1. The Indian Village, shown in Figure 24(a), was the original settlement site and remains on the right bank at the East Channel mouth, with some relocation having taken place to higher ground on the right bank a few kilometres upstream. The considerable industrial activity related to shipping remains in 'Old Town', the area along the left bank of the East Channel near the mouth, shown in Figure 24(b), which was the town centre before the 1963 flood. Residences remain in this area, as well as on the right bank near the mouth of the east arm of the West Channel - the 'Fishing Village', shown in Figure 24(c) - and along the Vale Island shore of Great Slave Lake. The commercial centre of the town, and the majority of residential development today, is located in 'New Town', shown in Figure 24(d), on the high ground along the left bank of the river just upstream of the delta.

It is evident that, despite some relocation after the 1963 flood, industrial activity associated with the railway, shipping and fishing remains centred on Vale Island, and the planned relocation of all residential development to the new town site was not totally successful. Hence, a major portion of the town remains on the delta lowland and the ice jam flood threat remains.

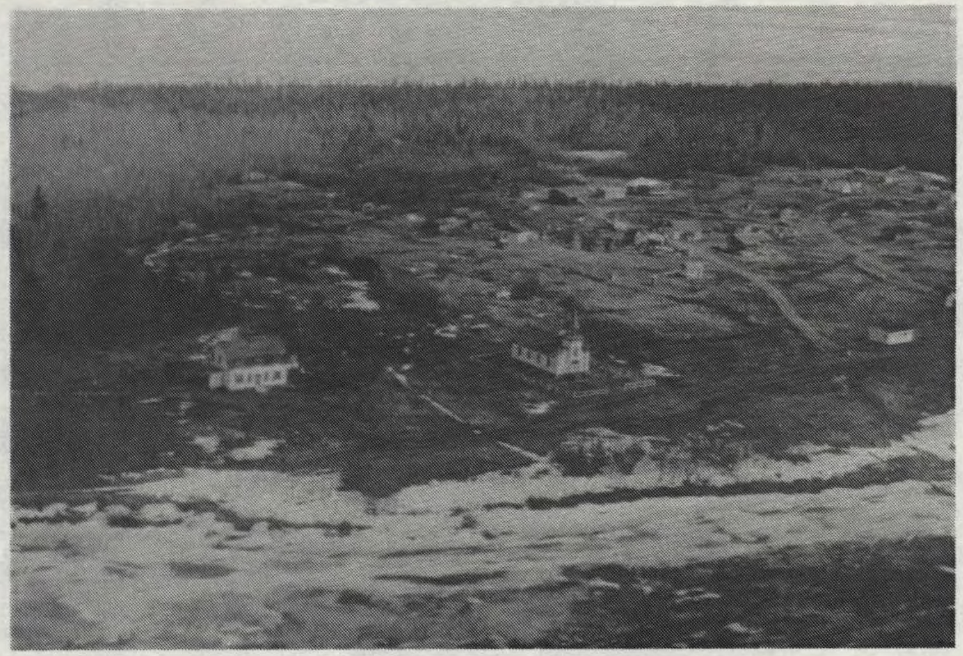

Figure 24 (a) The Indian Village on the right bank of the East Channel near the mouth.

Figure 24 (b) NTCL Docks and the 'Old Town' portion of Hay River on the left bank of the East Channel near the mouth.

Figure 24 (c) The Fishing Village along the right bank of the east arm of the West Channel.

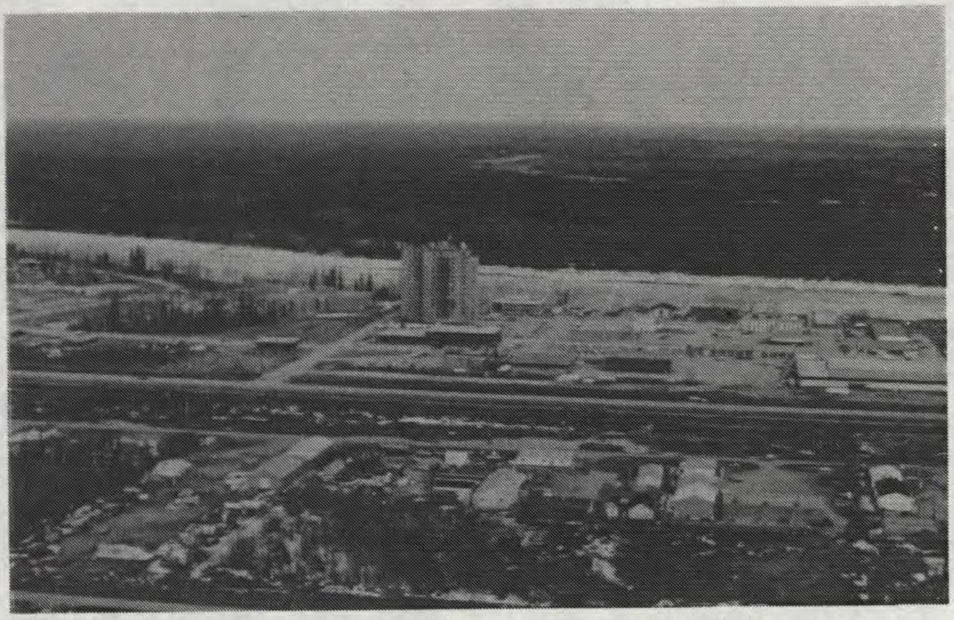

Figure 24 (d) The 'New Town' portion of Hay River on the left bank of the Hay River above the delta.

4.0 HISTORY OF FLOODING IN HAY RIVER

4.1 Previous flood studies and information sources

As indicated, the first task of the Phase 1 study was to review the available information on the history of ice jam flooding in Hay River with a view to assessing the current understanding of the ice regime in the delta and the range of possibilities.

Four major engineering studies have been concerned with ice jam flooding in the Town of Hay River. The first two were prepared by Stanley, Grimble, Roblin Ltd. (1959, 1963) for the then Department of Northern Affairs and Natural Resources. Both were a direct response to then-recent ice jam floods - those of the years around 1951 and the major flood of 1963.

The purpose of the 1959 report was to collate all available information related to the flooding problem in Hay River and to propose possible solutions. The suggested solutions can be broadly classed into four groups: altering the delta channel morphology; diking Vale Island; diverting or storing water far upstream to reduce peak flows; and weakening or otherwise modifying the ice cover in Hay River each spring in advance of break-up. The suggestions were intended to be preliminary only and it was emphasized that a much more detailed study would be required before any of them were implemented. Nevertheless, it is of interest to note that the estimate for diking Vale Island was $160,000, a figure much less than the damages caused by the major flood just four years later.

The main purpose of the 1963 report was to document, from aerial photographs, the flood levels that occurred in Hay River during the 1963 flood, and to 'update' the 1959 report.

As part of the Canada Flood Reduction Program, a report was prepared in 1979 by Underwood McLellan (1977) Ltd. (UMA, 1979), for the then Department of Fisheries and Environment, to serve as background for formal flood plain delineation in Hay River. The study area extended from Great Slave Lake to a point approximately 30 km south of the Town of Hay River. Both open water and ice jam floods were considered. Flood discharges in the reach were determined from records of the WSC station at Hay River. Flood levels along the reach were determined from these discharges using the HEC 2 varied-flow computer program and a limited number of cross-sections surveyed along the reach. To determine ice jam related flood levels, a fully-developed ice jam was assumed to exist at each section each year. The 1977 break-up was observed as part of this study to provide some information on the break-up ice regime for the analysis. Unfortunately this break-up was one of the mildest on record and 'the extended break-up period and resulting ice jams were not representative of historic ice jams and were therefore not too useful in the actual analysis of the ice jam regime'.

A report issued by Environment Canada (1983)* described the final basis for the flood risk zone designation shown on the Flood Risk Map published in 1984. The synthesized 1% flood levels presented in the UMA (1979) report were found to be lower than water levels caused by flood events in the past few decades in the Vale Island area. Therefore the flood risk area was delineated using the higher of the historic or the synthesized levels for each point over the reach of interest. Hence along the East Channel the flood level was set at that of the 1963 flood and along the West Channel at that of the 1974 flood.

However, the levels adopted for the West Channel were exceeded by about 1 m in the 1985 flood. A fifth report was therefore prepared by Underhill Engineering Ltd. (1985), for the Department of Indian and Northern Affairs, which documented the high water levels associated with the 1985 flood.

Various other informal reports and public agency memos were found that described aspects of flooding in Hay River. Two of the more fruitful sources were the GNWT Department of Highways and the Town of Hay River.

Most of the Department of Highways information was for the period 1947 to 1963, when a fill was in place across the West Channel. As indicated in Figure 1(d), to carry the road from Peace River onto the delta islands, embankments were constructed in 1948 at the upstream ends of the West Channel and the channels between the delta islands, effectively confining the flow to the East Channel. Because of its presumed role in exacerbating the flooding

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* Subsequent to the present study, an unpublished compilation of historical data (Jasper, 1983) was made available. The content of this report also formed part of the basis of the 1984 flood risk designation.

in 1951, the embankment over the West Channel was eventually replaced by the West Channel, or Vale Island, bridge. While it was in place, the embankment was washed out almost yearly during spring break-up, so in many years Department personnel monitored the fill and the water levels during break-up. The resulting reports provide a valuable source of information on water levels and other aspects of break-up in the delta.

The majority of information from the Town was in the records of the Town Flood Watch which is mounted each spring. This was set up after the severe flooding of 1963. Its purpose is to monitor break-up to provide some warning of impending high water. In most years a record was kept of the observations. However the quality of these records seems to depend on the time from the last significant high water, with detailed records only being available for a year or two afterwards.

Much information on the situation leading up to and during ice jam floods was obtained from residents. Of special note is Mr. 'Red' McBryan, a long-time resident, retired Superintendent of Highways for the GNWT, and former Mayor of Hay River. He has taken a special interest in the flooding in Hay River since 1950. He was the instigator of the Town Flood Watch and remains its chief organizer and supervisor. A notable feature of this flood watch is the extensive and periodic aerial and ground reconnaissances of the reach, from Hay River to as far upstream as the Chinchaga River confluence, undertaken each year by Mr. McBryan. From these observations he has developed a good understanding of the break-up ice regime of the river.

Another resident from whom much information was obtained is Dr. David Harrison, a teacher at the Diamond Jenness High School. He provided a copy of a high school class project in which he and the students had gathered remarkably detailed information on the history of ice jam flooding in Hay River (Harrison, 1978). His Ph.D. dissertation on the history of Hay River (Harrison, 1984) also provided information on the early years of Hay River that allowed better interpretation of archival descriptions of ice jam water levels.

Other information on past flooding was obtained from Hay River newspapers. The 'TAWPE' was published from 1961 to 1978 and the 'Hub' from 1977 to present.

4.2 Available historical data

The above historical data made it clear that all flood levels in Hay River have indeed been associated with ice jams. Unlike for open water floods, where discharges, and thereby water levels, can be transposed from other locations, ice jams can be very site specific, making it difficult to justify transposing water levels to even nearby sites. Hence, to assess the probability distribution for ice jam floods along a reach, a more-or-less independent probability analysis of available historical data must be carried out for each of several sites along the reach. However, the number of sites that can be considered will usually be severely constrained by the available historical data.

For Hay River it was felt that a reasonable compromise between the needed definition of flood limits and the available data would be provided by probability analyses of peak break-up water levels for three sites: the East-West Channel split (essentially the West Channel bridge); the East Channel near the mouth (Old Town and the Indian Village); and the West Channel near the mouth (the Fishing Village).*

The historical data was analyzed using the technique described by Gerard and Karpuk (1979). This requires that, as well as peak water levels for those years for which information exists, a 'perception level' be estimated above which each source would **not** have provided information on the break-up water levels. The water levels for each year of record are given in Table 1 and the justification for the water level in each case is given in Appendix B. The justification for the perception levels, and the general information available for each of the three sites, is as follows.

4.2.1 Near the East Channel mouth

This site has the longest record of the three. From 1894 to 1948 almost all information was obtained (through Harrison, 1984) from the diaries of the

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* An option exists to supplement the historical data with water levels developed from discharge estimates, ice jam mechanics, channel geometry and some knowledge of the frequency of ice jam formation and extent. This was not done in this preliminary study.

Table 1. Break-up flood levels, record lengths, and probability analysis results for three selected locations in the delta.

Year	High Water Elevation (m)	Stage Above Zero-Flow Stage* (m)	Years of Record	Rank	Exceedence Probability (%)	95 Percent Confidence Limits (%)	
						Lower Limit	Upper Limit
East Channel Near the Mouth							
1963	160.8	4.2	93	1	0.67	0.00	2.33
1914	159.8	3.2	93	2	1.74	0.00	4.40
1904	159.1	2.5	93	3	2.82	0.00	6.18
1947	158.9	2.3	93	4	3.89	0.00	7.82
1923	158.8	2.2	93	5	4.96	0.55	9.37
1934	158.8	2.2	93	6	6.03	1.19	10.9
1951	158.7	2.1	93	7	7.10	1.88	12.3
1957	158.7	2.1	93	8	8.18	2.61	13.8
1911	158.6	2.0	93	9	9.25	3.36	15.1
1952	158.6	2.0	93	10	10.3	4.14	16.5
1974	158.6	2.0	93	11	11.4	4.94	17.9
1932	158.5	1.9	93	12	12.5	5.75	19.2
1933	158.5	1.9	93	13	13.5	6.59	20.5
1950	158.5	1.9	93	14	14.6	7.43	22.8
1986	158.5	1.9	93	15	15.7	8.29	23.1
1985	158.5	1.9	93	16	16.8	9.17	24.4
1978	158.4	1.8	93	17	17.8	10.1	25.6
1987	158.2	1.6	20	5	22.8	8.70	49.0
1979	157.9	1.3	4	2	38.2	6.80	93.0
1977	156.9	0.3	3	2	50.0	1.30	98.7
1956	156.8	0.2	3	3	80.8	9.40	99.0

* Zero-flow elevation taken as 156.6 m at East and West channel mouths, and 156.7 m at East-West Channel split.

Table 1. (continued) Break-up flood levels, record lengths, and probability analysis results for three selected locations in the delta.

Year	High Water Elevation (m)	Stage Above Zero-Flow Stage (m)	Years of Record	Rank	Exceedence Probability (%)	95 Percent Confidence Limits (%)	
						Lower Limit	Upper Limit
East West Channel Split							
1951	164.0	7.3	41	1	1.52	0.00	5.3
1963	164.0	7.3	41	2	3.94	0.00	9.9
1985	163.5	6.8	39	3	6.90	0.00	13.8
1986	163.4	6.7	39	4	9.2	0.12	17.5
1952	162.8	6.1	21	3	12.4	0.00	26.4
1950	162.7	6.0	21	4	17.1	0.97	33.2
1974	162.2	5.5	21	5	21.8	4.1	39.4
1987	162.2	5.5	21	6	26.5	7.6	45.3
1981	161.9	5.2	21	7	31.2	11.4	51.0
1954	161.9	5.2	21	8	35.9	15.4	56.4
1979	161.7	5.0	21	9	40.6	19.6	61.6
1947	161.6	4.9	21	10	45.3	24.0	66.6
1977	161.1	4.4	21	11	50.0	28.6	71.4
1957	161.1	4.4	21	12	54.7	33.4	76.0
1956	161.0	4.3	21	13	59.4	38.4	80.4
1960	>160.5	>3.8	21				
1961	>160.5	>3.8	21				
1982	160.4	3.7	13	11	80.2	58.5	99.9
1955	>159.8	>3.1	13				
1953	158.2	1.5	13	13	95.3	83.8	99.9
West Channel Near the Mouth							
1985	159.9	3.3	24	1	2.58	0.00	8.9
1974	159.3	2.7	24	2	6.70	0.00	16.7
1986	159.0	2.4	24	3	10.8	0.00	23.3
1979	158.8	2.2	24	4	15.0	0.68	29.2
1972	158.6	2.0	24	5	19.1	3.4	34.8
1977	158.1	1.5	2	1	27.8	0.80	80.6
1987	158.1	1.5	2	2	72.2	1.30	98.0

Anglican and Catholic Missions that were located in the Indian Village on the right bank of the East Channel near the mouth. For this period the perception level was taken as that of the top of the bank at the Mission site, a geodetic elevation of 158.4 m.

In 1948 the settlement of Vale Island began and replaced the Missions as the centre of the community. Flood levels after this time were obtained from the Town Flood Watch reports, newspapers and Government records. For the period 1948-68 the perception level was again taken as 158.4, this also being the elevation of the road which borders the river on the left bank of the East Channel. After 1968 the perception level was lowered to 158.1 as development had occurred between the road and the river.

There were some exceptions to the above general perception stages. For the three years 1956, 77 and 87 the flood levels were measured as part of studies triggered by considerations independent of the flooding. Furthermore, the 1979 level was estimated from Town Flood Watch records, observations that are also independent of the water level reached during break-up. Hence for these four years a zero perception level could be allocated.

These perceptions levels and the known flood levels for this site are plotted in Figure 25. All levels were adjusted, to the extent possible with the available information, to apply opposite Island A (km 1113).

4.2.2 East-West Channel split

Records of flooding at this site begin with the development that started in 1947. In this year a fill was constructed to elevation 158.0 m across the West Channel to carry the new all-weather road onto Vale Island. The fill was located 100 m downstream of the East-West Channel split. It was raised to elevation 163.9 m in 1948 but, because of concerns about its role in the flooding of 1951, it was lowered to 161.0 m in 1953. On completion of the West Channel bridge in 1963 it was totally removed. As the fill was frequently overtopped during break-up, the water levels at the fill were routinely monitored during break-up by Department of Highways personnel. The fill elevations therefore provide a convenient reference elevation for the period to 1963 and are plotted in Figure 26. After 1963, flood levels were estimated from Town Flood Watch records, the water levels at the bridge being

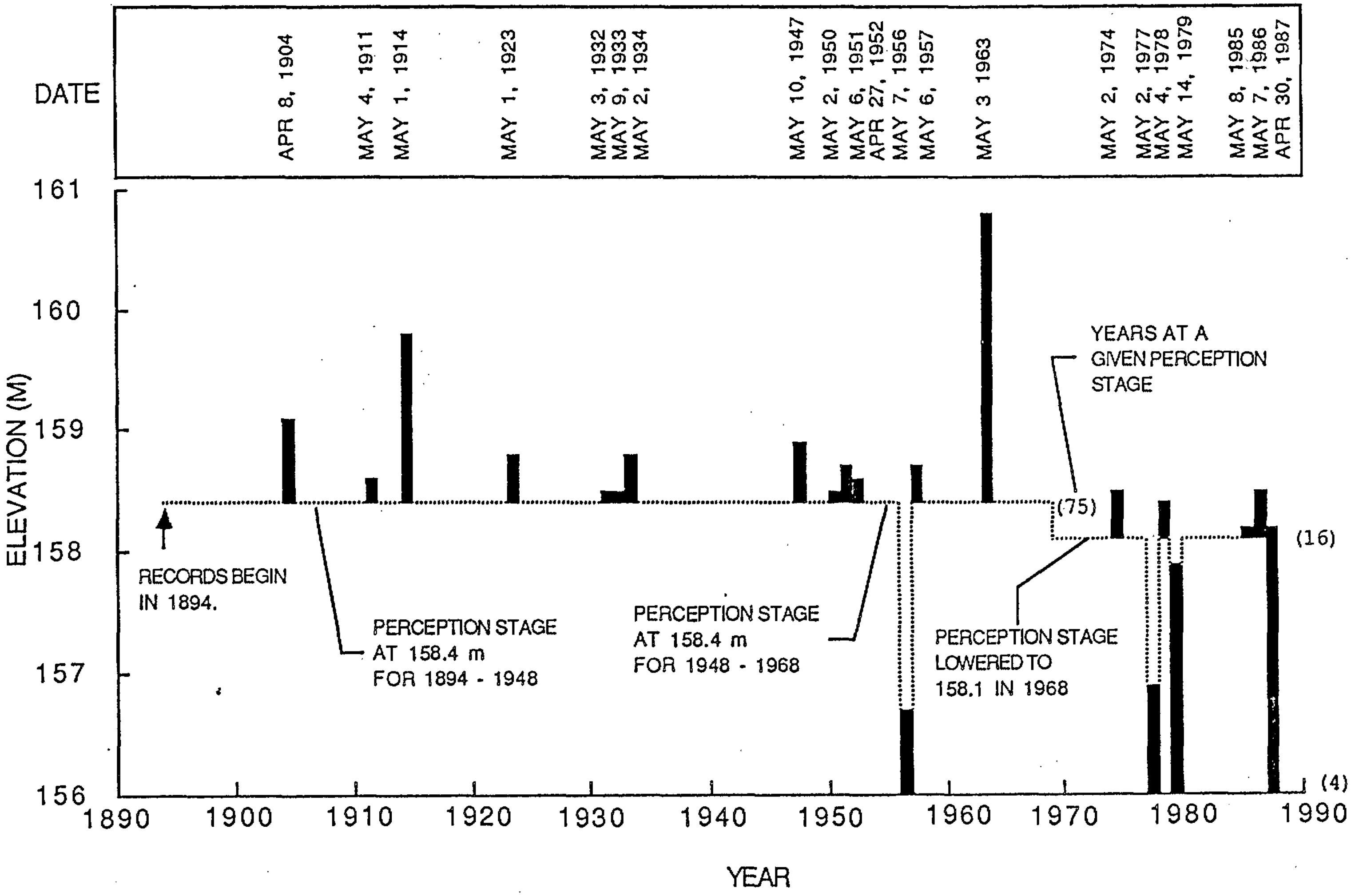


Figure 25 Flood and perception levels for the East Channel near the mouth (km 1113)

routinely monitored during the Watch. However, records for many of the years are missing and for other years the records are so vague that the peak level cannot be determined.

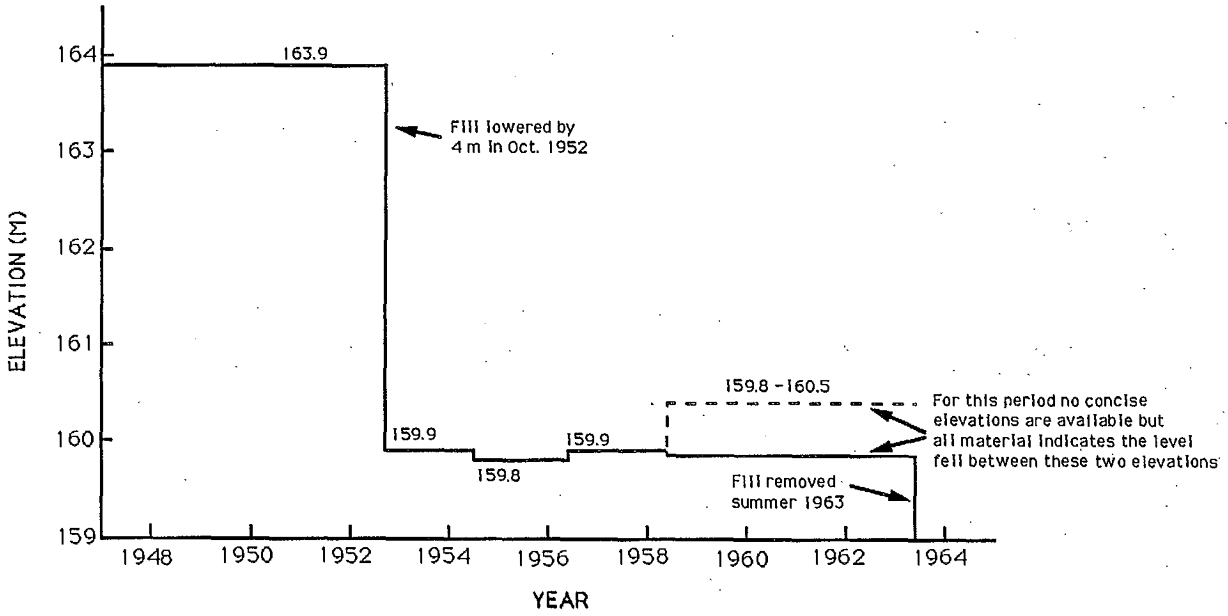


Figure 26 Variation in the crest elevation of the West Channel fill.

For the period 1947-63 the perception level was taken as about 1 m above the fill, this being estimated as about the depth for ice to move over the fill. From 1950-54 detailed reports on water levels during break-up were prepared by the Department of Highways. As these were more a matter of routine than a direct response to high water levels, a perception level of zero was allocated to these years. A zero perception level was also allocated to those years for which Flood Watch records were available.

The perception level for the years for which no records are available, or could not be interpreted, was more difficult to choose. The banks at this site are high, this being the highest ground in the whole area. Using the top of the bank as the perception level, as was done at the East Channel mouth site, would have been unrealistic because the whole island would be underwater if the level was this high. Instead a level was chosen that corresponded to significant flooding downstream because, if such flooding occurs, high water levels throughout the delta are then documented and reported by Government agencies. Analysis of the historical data indicated that any water levels over 163.0 m at the split caused flooding somewhere downstream, so this elevation was taken as the perception level for the years for which it was not defined otherwise.

The flood and perception levels for this site are plotted in Figure 27.

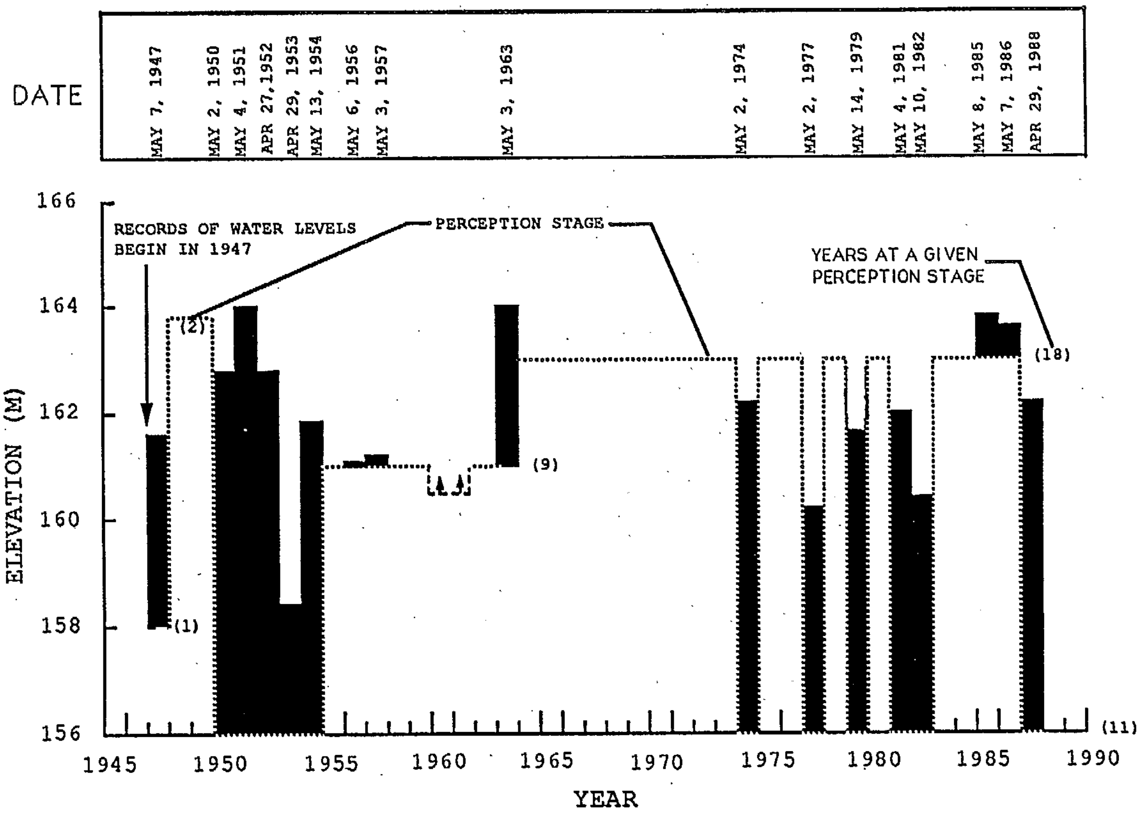


Figure 27 Flood and perception levels for the East-West Channel split.

4.2.3 Near the West Channel mouth

Although settlement of this area began in 1948, significant flow in the West Channel was prevented until 1963 by the fill at the upstream end of the channel. The major source of data used for levels after this date was the Town Flood Watch records. The perception stage for this period was taken as the bank level at the Fishing Village, elevation 158.5 m. As before, the years 1977 and 87 were allocated zero perception stages. The flood and perception levels are plotted in Figure 28.

4.3 Analysis of historical data

4.3.1 Probability analysis

Using the data displayed in Figures 25, 27, and 28, a rank and record length was allocated to each flood level following the procedure described by Gerard and Karpuk (1979). The results are given in Table 1.

The simplest probability distribution that can be expected to describe at least the below-bank levels adequately is the log-normal distribution, with the levels being referenced to the minimum water level possible at each site (i.e. the zero-discharge level at the East-West Channel split and lake level at the two channel mouths). Because of the expectation of an approximately log-normal distribution, the probability, Pr, of each level being equalled or exceeded in a given year was estimated using the Blom formula (Cunnane, 1978)

$$Pr = (m - 3/8)/(N + 1/4)$$

where m is the rank and N the record length. The resulting probability distributions are presented in Figure 29(a). Evidently the log-normal distribution does provide a reasonable description of the data.

The estimated 95% confidence limits for each probability estimate are given in Table 1 and shown in Figure 29(b). It is sufficient to note that most weight can be given to the probability estimates for the medium levels, these having the narrowest confidence bands, and that the real exceedence probability of the estimated 1% level can vary from about 5% to near-zero. Further details of the probability analysis and assessment of confidence limits are given by Stanley (1988).

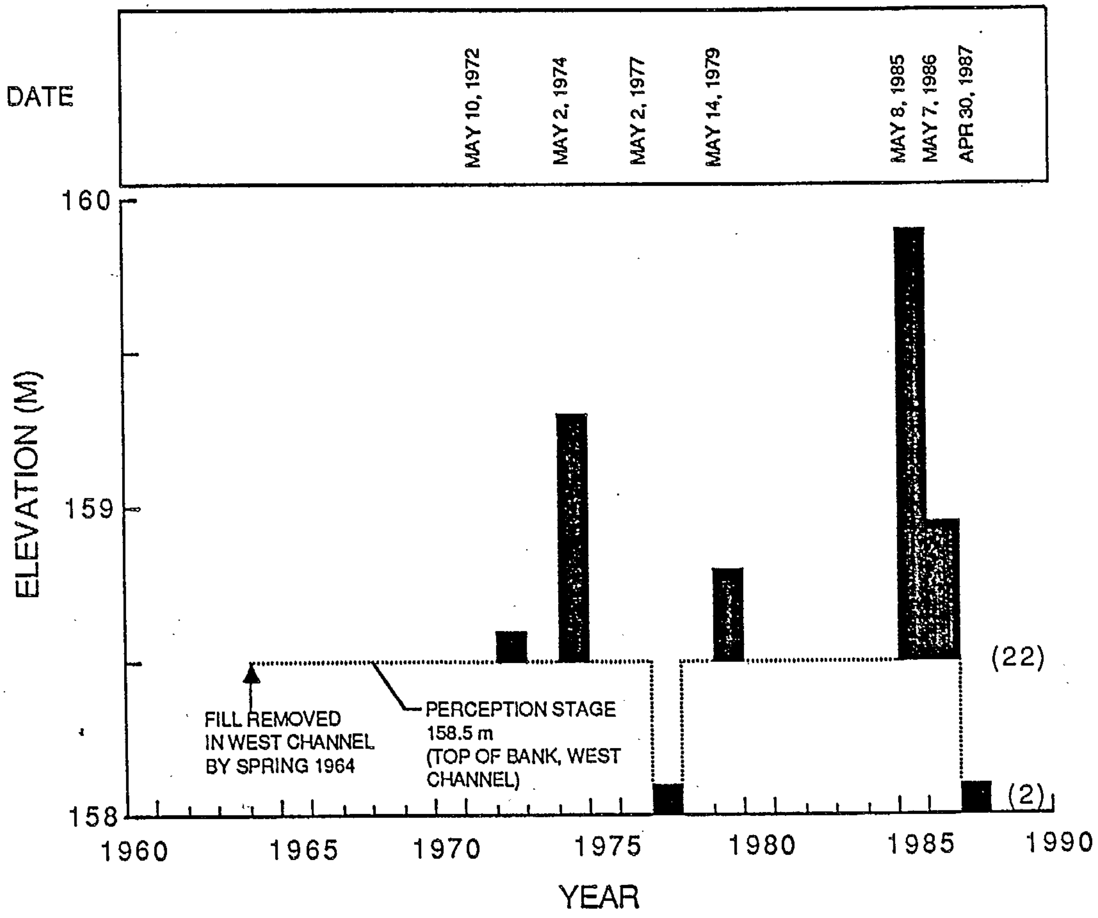


Figure 28 Flood and perception levels for the West Channel near the mouth

As is evident from Figure 29(a), the historical data analysis provided a reasonably well-defined probability distribution for each site. One item of note is the similarity of the water level variance for all three sites. This is likely because of the discharge being a common, and influential, factor at each site and the fact that, from the historical record, there seems to be an almost equal chance that a significant jam will form at one or the other of the channel mouths in a given year.

As indicated earlier, the 1985 high water level at the West Channel mouth

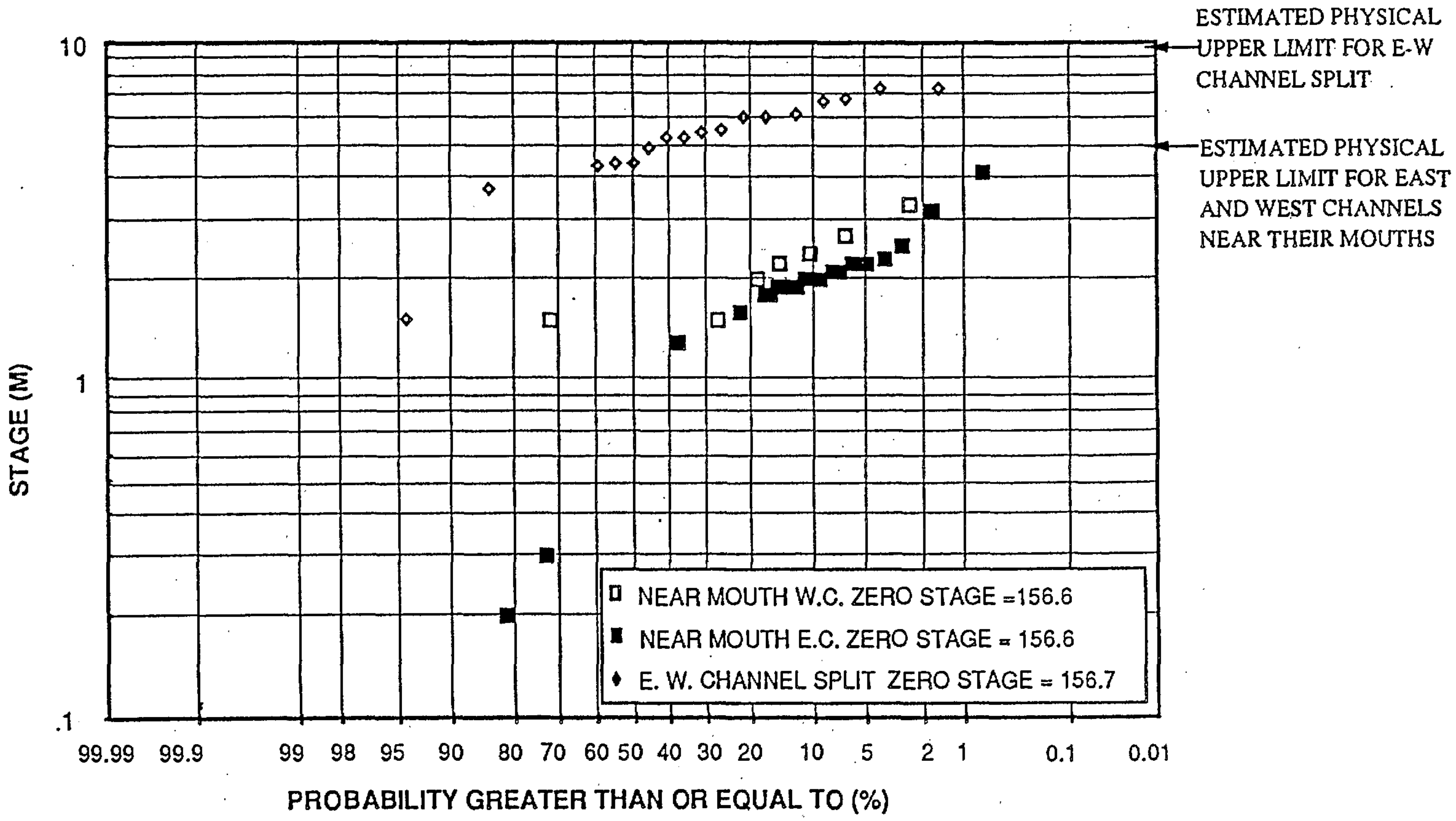


Figure 29(a) Water level exceedence probability distributions for the three reference locations in Hay River

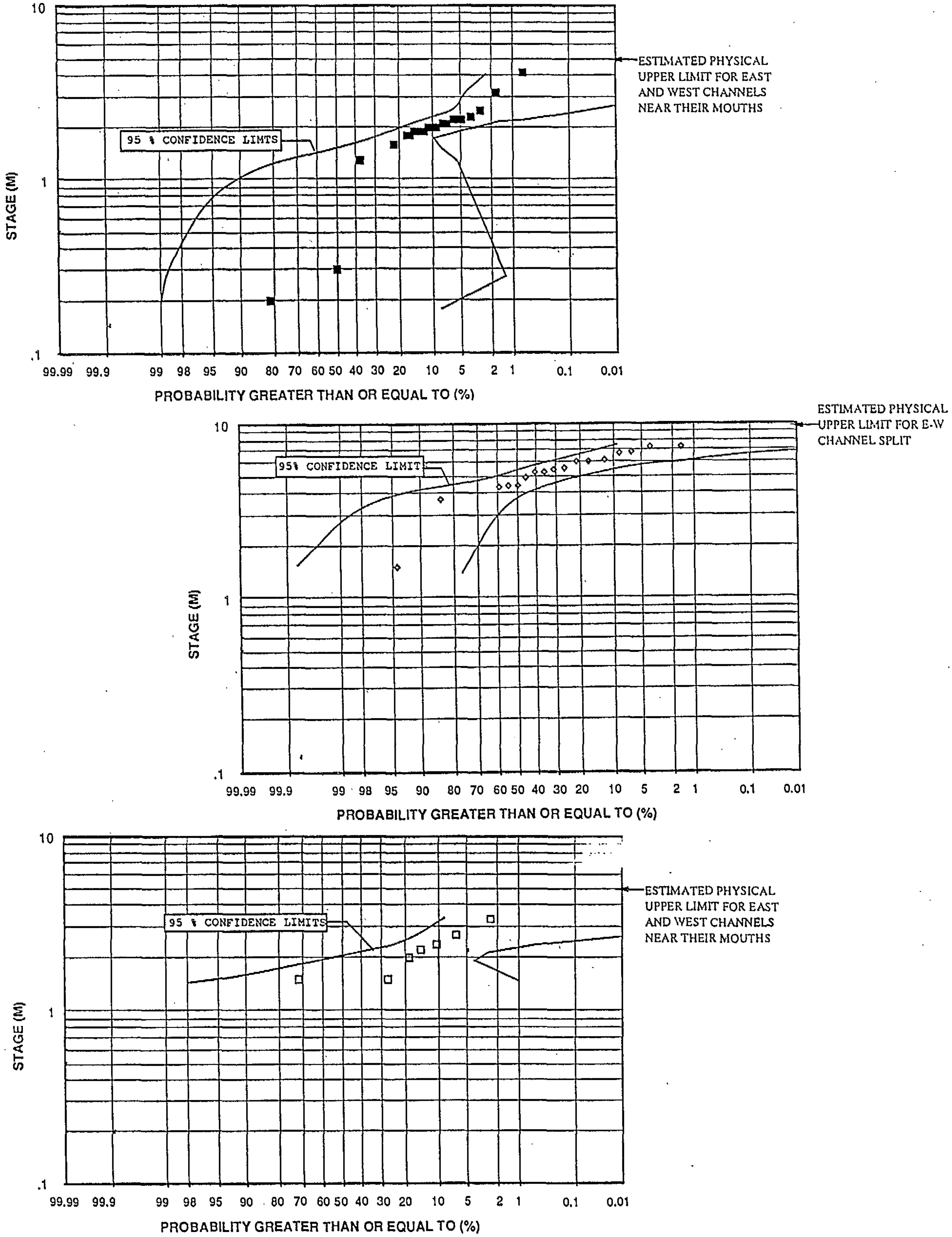


Figure 29(b) 95% Confidence limits for probability estimates (i) East Channel near the mouth (ii) East-West Channel split (iii) West Channel near the mouth exceeded, by about 1 m, the level established by Environment Canada for the purposes of flood risk delineation. Consequently the 1985 event is commonly viewed as a most unusual - even freak - event. However, inspection of the probability distribution for this site reveals that, even on the basis of data available up to 1983 (the year the flood risk zone was established), the 1985 event is not an outlier: it has an exceedence probability of about 1.8% and is therefore somewhat **below** the 1% event.

4.3.2 Upper limit to ice jam water levels

The possibility of a physical upper limit should be considered in any analysis of flood levels. At a site with a wide flood plain that is continuous along the length of the jam, water levels caused by an ice jam can only rise a little above the banks before water is free to flow around the ice accumulation in the river. This would be the case in Hay River and the levels at which significant flow would be free to move around a jam at the three sites of interest are shown in Figure 29(a). Evidently the water levels to date have been below that for which significant 'leakage' around the jam would be expected. Although there is some hint that the distribution levels off at 163.9 m at the East-West Channel split, at this elevation water would be just beginning to move overbank at and downstream of Fill B (km 1110; elevation 162.4 m) and so should not represent an upper limit at the East-West Channel split.

4.3.3 Influence of man-made changes to delta morphology

Another item of interest is the apparent lack of influence on flood levels of several man-made changes to the delta morphology. Since 1947 various subchannels of the East Channel have been cut off for road, railway and dock construction, and the West Channel was blocked by the road fill until 1963. It is commonly held by residents that flood levels have been higher and more frequent since these changes have been made. However, given that the major flooding along the East Channel is caused by ice jams that form at the mouth, where no channels have been modified, it is unlikely the changes to the channel would have had a large influence. In any event, despite 50 years of record before 1947 and close to 40 years afterwards, no such effect is evident in the East Channel probability distribution. Perhaps the community has simply become more aware of flood levels because of the extensive development that has taken place since 1947.

As well as imposing discipline on the review of the historical record, the probability analysis served to put the various historical flood events into perspective. This helped considerably when reviewing the data for clues as to the dominant processes governing ice jam flood levels in the delta, and the requirements of a flood forecasting procedure.

5.0 SALIENT FEATURES OF ICE JAM FLOODING IN HAY RIVER

The historical record review and field observations suggest the requirements for a useful first-generation flood forecast algorithm are predictions, as much in advance as possible, of the following:

1. The expected peak discharge during break-up;

2. The magnitude and timing of the peak water level to be expected at the East-West Channel split (i.e. approximately that at the West Channel bridge);

3. The portions of the peak discharge that could move down each of the East and West Channels;

4. The peak water level that could occur at the mouth of the East Channel if the toe of the East Channel jam moves to the mouth before there has been significant decay of the jam; and

5. The peak water level that could occur at the Fishing Village with the toe of the West Channel jam at the mouths of both the east arm and Rudd Channel.

Estimates of water levels to be expected in the delta in a given year, made using an algorithm built around these components, will likely be close to what will occur each year at the West Channel bridge. However the estimated levels near the East Channel mouth and the Fishing Village will be estimates of the maximum water levels that **could** occur. The actual water levels at these sites will usually be somewhat lower and will depend on the location of the jam toe in the east arm of the West Channel, and the movement of the toe and progression of melt in the East Channel.

5.1 Peak discharge

The main parameter that governs flooding in Hay River is the peak discharge following break-up. There are two discharge forecast requirements. The first is a very early estimate of the peak discharge that could occur.

This is required to provide as much warning as possible for planning and execution of flood mitigation activities which require long lead time. However, given the necessary lead time, this estimate can only be an approximate upper bound. The second requirement is for a more accurate day-to-day forecast, with as much lead time as is compatible with reasonable accuracy, for execution of short-term flood damage mitigation activities such as evacuation.

As mentioned earlier, spring runoff from the Hay River catchment is dominated by snowmelt. It should therefore be possible to estimate the maximum likely peak discharge during break-up from the snowpack depth near the end of winter. Measurements of snowpack depth are only available for a few years so, instead, accumulated winter snowfall could be used as an index of end-of-winter snowpack depth. In this study a weighted average snowfall for the basin was determined for each year of record from the three long-term meteorological stations that were reasonably representative of the different portions of the catchment. These were Hay River, High Level and Fort Nelson, shown in Figure 2. The weight for each station was determined using Theissen polygons, with the result that:

$$S_{av} = 0.10\ S_{HR} + 0.34\ S_{FN} + 0.56\ S_{HL} \tag{1}$$

where S_{av} is the weighted catchment-average accumulated winter snowfall, S_{HR} is the accumulated winter snowfall for Hay River, S_{FN} that for Fort Nelson and S_{HL} that for High Level. The weighted average snowfall in each year, and the related peak discharge at Hay River, are given in Table 2 and plotted in Figure 30 for the years for which data was available. Also given in Table 2, is the mean October discharge of the previous year. This was taken as an index of antecedent moisture in the catchment. As discussed in Appendix H, this parameter has no discernable influence on the peak spring discharge.

The upper envelope to the data of Figure 30 provides an indication of the possible maximum discharge during break-up in Hay River. Although this upper envelope will indicate some flooding potential in most years, there will be years when use of this approach will indicate little risk of flooding and therefore little need for extensive flood mitigation activities.

Table 2. Long-term discharge forecast: snowfall, and fall and spring discharges, for the Hay River catchment (from AES and WSC data)

Year	Accumulated snowfall (cm)				October mean discharge (m^3/s)	Spring peak mean daily discharge (m^3/s)
	Hay River	Fort Vermilion	Fort Nelson	Catchment Average		
1963	241	111	157	140	-	-
1964	221	106	111	119	127	725
1965	111	94	105	99	101	708
1966	185	111	105	117	26.3	521
1967	153	146	178	158	15.8	957
1968	141	112	101	111	28.3	518
1969	144	109	128	119	32.3	889
1970	178	98	111	110	66.6	374
1971	95	89	110	97	14.1	600
1972	133	184	130	161	16.0	1,020
1973	97	122	117	118	12.0	595
1974	139	157	175	161	75.5	1,180
1975	139	91	73	90	80.8	680
1976	149	205	94	162	56.3	685
1977	84	75	110	88	206	530
1978	67	118	104	108	142	818
1979	105	139	99	122	129	694
1980	52	44	81	57	107	120
1981	112	100	95	99	40.2	790
1982	128	72	188	117	6.1	657
1983	128	135	109	125	15.4	550
1984	86	84	56	75	72.2	172
1985	121	128	117	124	150	1,350
1986					188	900
1987					48.0	670

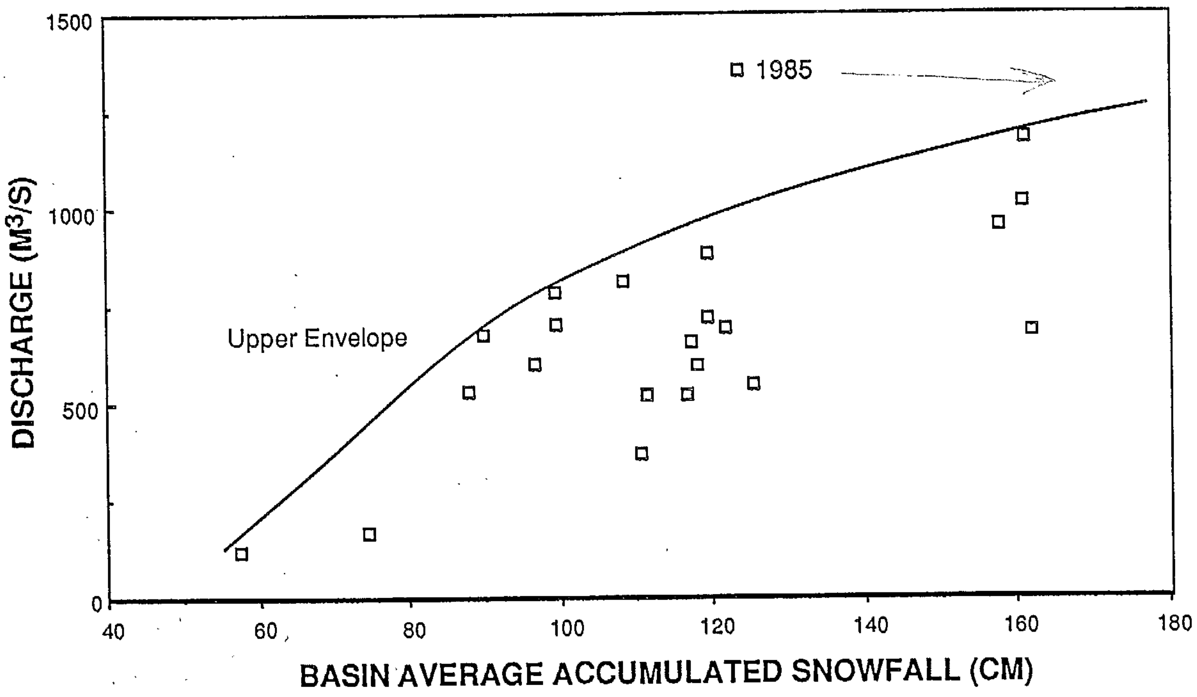


Figure 30 Variation of maximum discharge at Hay River with accumulated winter snowfall in the catchment

It is noted that the point representing the 1985 situation was ignored in drawing the envelope. This is because it is believed substantial rain fell during break-up in that year, so that the discharge was somewhat more than it would have been due to snowmelt runoff alone (Wedel, 1988). (This is a contentious point and is discussed in more detail in Appendix I).

Real-time forecasts of the discharge in Hay River during break-up can be made some two days in advance on the basis of discharges determined from the remotely-monitored WSC gauging station recently installed at the Alberta-NWT border. Only 6% of the Hay River catchment lies below this station, and most of this area is flat and covered with muskeg and so adds little runoff. Consequently discharge at the border station should be almost the same as the discharge in Hay River some two days later. However, to allow reasonable discharge estimates at the border station, periodic observations will have to be made of the nature of the ice cover at the station during break-up.

As discussed further in Appendix H, an extra 1-2 days lead time over that at the border may be possible if a precipitation-runoff algorithm for the catchment is calibrated and used and ,desirably, more meteorological stations are installed.

5.2 Timing of the peak water level

This is a function of the timing of break-up and of the arrival of the peak discharge. However, from the review of the historical data and field observations, it was evident that the onset of break-up is not of critical importance for flood forecasting in Hay River because break-up occurs first below the falls and it is not until 4 to 8 days later that the peak water level occurs. The timing of break-up was therefore only briefly considered in this study.

The variation in break-up date is given in Section 2.3. It was found that the principal factor indicating incipient break-up was a rapid increase in discharge, over a period of about a day, as illustrated in Figure 31. This can be determined by simply monitoring the WSC gauge at Hay River and by observing the progression of break-up below the falls. No simple relation with other hydrometeorological parameters could be found that would provide a longer lead time for estimating impending break-up.

As mentioned, it is the arrival of the peak discharge that is the most important parameter influencing the timing of the peak water level. This again can be determined with about 2 days lead time by monitoring the WSC gauge at the border and, for a longer lead time, by application of a precipitation-runoff algorithm.

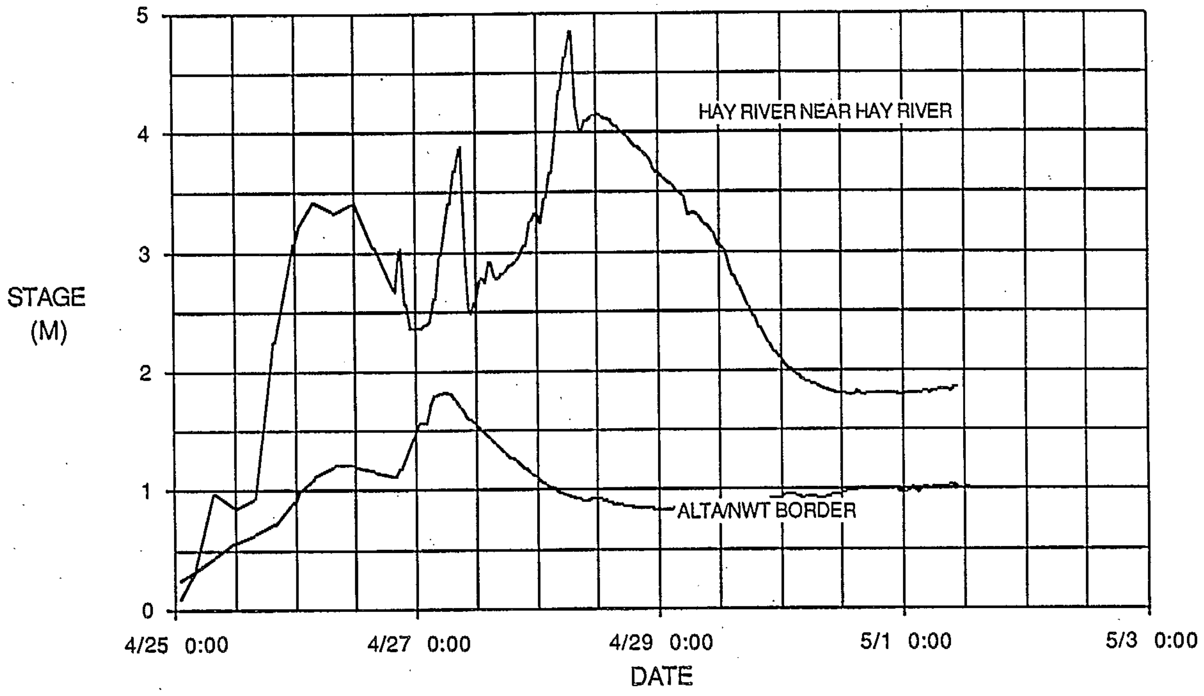


Figure 31 Water level variation at Hay River WSC station during break-up, 1987.

5.3 Peak water level at the West Channel bridge

An estimate of the peak mean daily discharge to be expected in the delta can be determined from the border WSC gauge and/or a precipitation-runoff algorithm. A first estimate of the peak water level caused by this discharge at the West Channel bridge can be determined by assuming the pack from the East and West Channel jams, established during the initial ice run, extend up past this site. For this circumstance the relation between the water level at the bridge (taken as approximately equal to that just upstream of the East-West Channel split) and the Hay River discharge is shown in Figure 32. (This is an ice jam 'rating curve'. The basis of this relation is described in Appendix G).

Also shown in Figure 32 are the available recorded **peak** water levels at the West Channel bridge, plotted against the corresponding **mean daily** discharges **on the day of the peak water level.** The fact that many of the points lie above the rating curve is likely due to the effect of surges that occur during the break-up period. These surges can be substantial and are

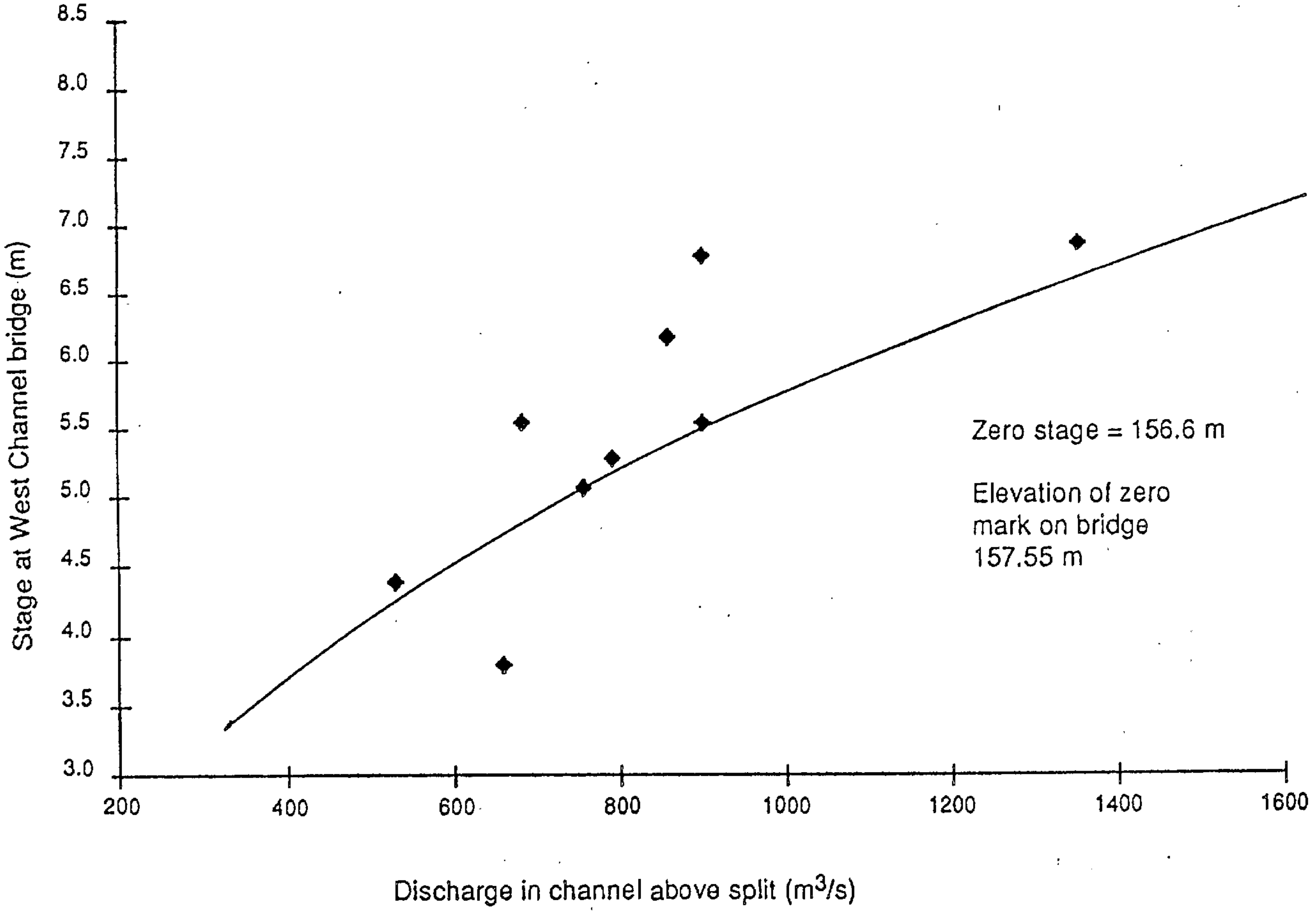


Figure 32 Relation between the water level at the West Channel bridge and the Hay River discharge

presumed to be released by ice jam failure in the reach upstream of the falls. The short-lived discharge increase that they cause is not represented by the mean daily discharge. This was substantiated by the break-up observations in 1987: water levels taken during steady flow conditions in the river were used to calibrate the ice jam rating curve of Figure 32, yet the surveyed **high water** marks for this year plot above the rating curve.

It is evident that using the rating curve of Figure 32 without an allowance for surges could underestimate the expected water level. As there is little direct data on these surges, an empirical approach was used to quantify the surge effect.

Because the surges are the result of the formation and failure of ice jams, the more conducive the situation is to ice jam formation, presumably the greater the chance surges will occur. Furthermore, other things being equal, the more competent the ice at break-up presumably the more likely is ice jam formation. Ice competence in a reach can depend on a number of factors, such as the manner of freeze-up, winter severity and energy input to the ice in spring prior to break-up. However, the latter is by far the most important for the reach of interest.

Energy input to the ice in spring is due to solar radiation, air temperature and water temperature. Of these, solar radiation has the largest influence on ice strength. However a snow cover on the ice can shield it from the effect of much of this radiation. It would seem, therefore, that the parameters with the most influence on ice competence variation from year to year at a given site are snow depth and incoming solar radiation. A relationship was therefore sought between these variables and the presumed surge effect on water level. In the absence of direct snow depth and solar radiation measurements, snow depth was represented by accumulated winter snowfall at Hay River, and solar radiation by the hours of bright sunshine at Fort Smith, this being the nearest station providing such data. Internal melt of the ice due to solar radiation absorption was assumed to begin when the mean daily air temperature reached about -5°C.

On the basis of these arguments it was taken that a suitable index, E, of energy input to the ice, and therefore of ice deterioration is:

$$E = B - aS_n \tag{2}$$

where B is the hours of bright sunshine accumulated at Fort Smith after the mean daily temperature at Hay River rises about -5°C, S_n is the accumulated snowfall at Hay River over the winter (cm) and a is an empirical coefficient.

An empirical relation was developed between this index and the increase in water level at the West Channel bridge estimated to have been caused by the surges (expressed as a ratio, R, of the actual peak stage to the stage predicted from the ice jam rating curve of Figure 32 using the mean daily discharge on the day of the peak water level). This relation was

$$R = b + cE^2 \quad (3)$$

where R is the water level ratio and b and c are empirical coefficients. The assumed form of this relation is the simplest that would satisfy the requirement that low values of E should have little influence on R, but that this influence should increase rapidly for high E. Using the data given in Table 3, the best fit values of the coefficients a, b and c were 1.20, 1.20 and 0.000024 respectively. This relation is compared with the available data in Figure 33. The agreement is reasonable. It is noteworthy that, because of snow on the ice, the relation does not indicate an influence of radiation until after about 100 hours of bright sunshine has accumulated. This is given some support by observations in 1988, when it was noted that most of the snow on the ice had disappeared after about 125 hours of bright sunshine. Further details of the above derivation are given by Stanley (1988).

Using Figures 32 and 33 it is possible to predict water levels at the West Channel bridge to within about 0.4 m if the discharge, accumulated bright sunshine and accumulated snowfall are known. A 2-3 day forecast is normally available for the meteorological variables and a 2 day forecast of mean daily discharges at Hay River can be determined from the border WSC station. Hence at least a 2 day warning of high water at the West Channel bridge is possible.

Water levels can be transferred upstream and downstream (East Channel) of the split at a slope of 0.5 m/km **over a fully-developed** pack. Along the upper half of the West Channel a 0.4 m/km slope seems appropriate.

With high water at the West Channel bridge, flooding of Vale Island is usually caused by one of two events. Either there is a high discharge down the West Channel with a jam in place at the mouth, particularly in the east

Table 3. Surge effect data for the East-West Channel split

Year	High water elevation at split (m)	Mean daily discharge (m^3/s)	Estimated mean daily elevation (m)	Ratio of high water to mean daily stages	Hours bright sunshine Fort Smith	Accumulated snowfall Hay River (cm)
1974	162.2	680	161.4	1.16	200	139
1979	161.7	620	161.2	1.11	191	105
1981	161.9	790	161.8	1.03	219	112
1982	160.4	657	161.3	0.80	282	128
1985	163.5	1,350	163.2	1.04	237	121
1986	163.4	900	162.1	1.24	223	171
1987	162.2	670	161.4	1.17	190	141

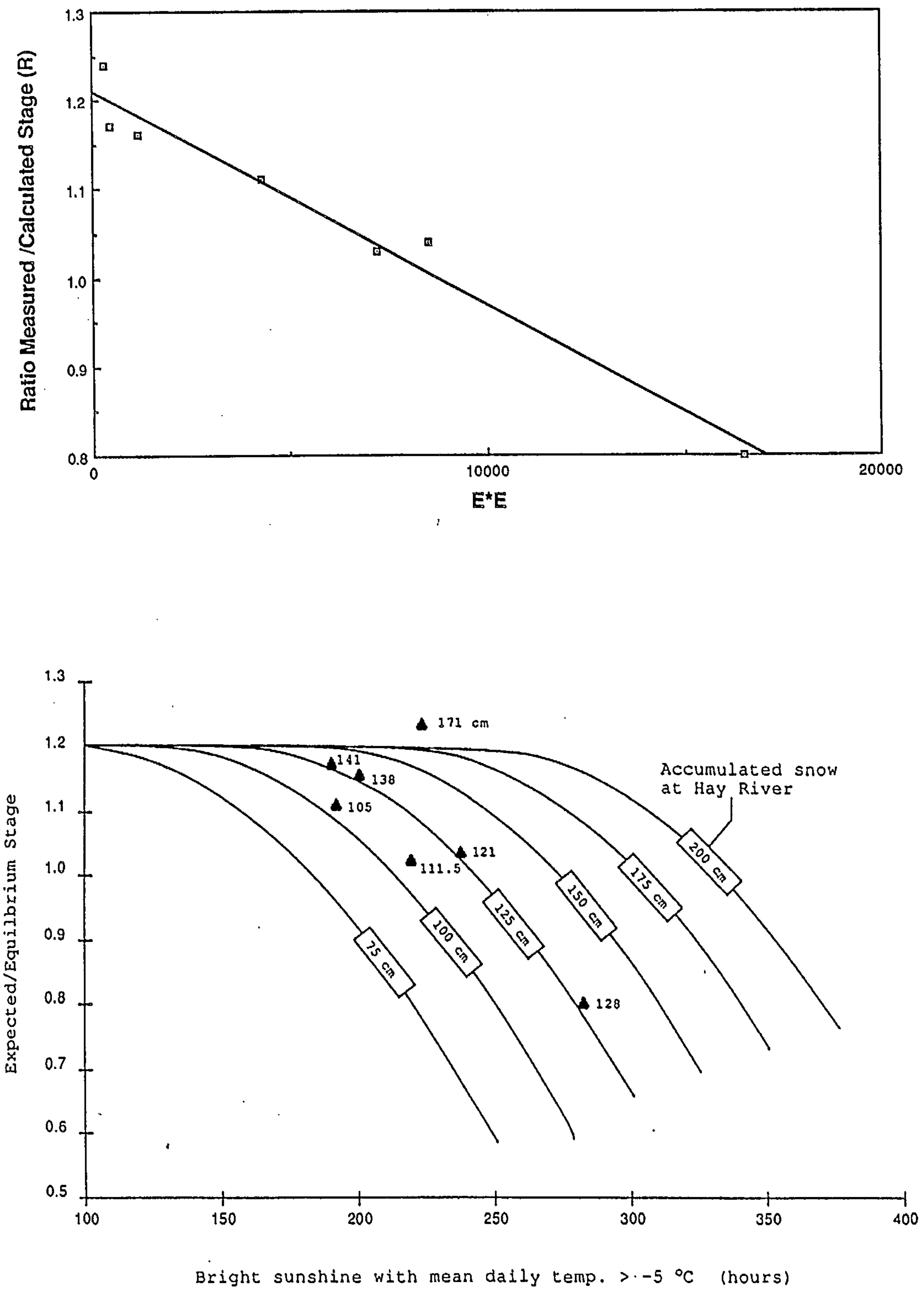


Figure 33 Variation of the water level increase at the West Channel bridge with the index of energy input to the ice (a) in the form of Equation 3 and (b) with the influence of each parameter shown explicitly.

arm (e.g. 1985), or the jam that is nearly always present at Island CD in the East Channel moves down early to the mouth of the East Channel while the discharge is high (e.g. 1963). To estimate the likely high water levels that would occur for each of these cases it is first necessary to estimate the apportionment of flow between the two channels.

5.4 Apportionment of flow at the East-West Channel split

Field observations suggest there are two extremes of concern: a fully-developed pack through the split on both channels; and a pack up to the split on the East Channel and open water downstream of the split on the West Channel. Estimates of discharge down the West Channel as a function of the water level at the West Channel bridge were determined for both circumstances using standard hydraulics and the fully-developed ice jam thickness equation. Details are provided by Stanley (1988). The resulting 'rating curves' for the West Channel are shown in Figure 34.

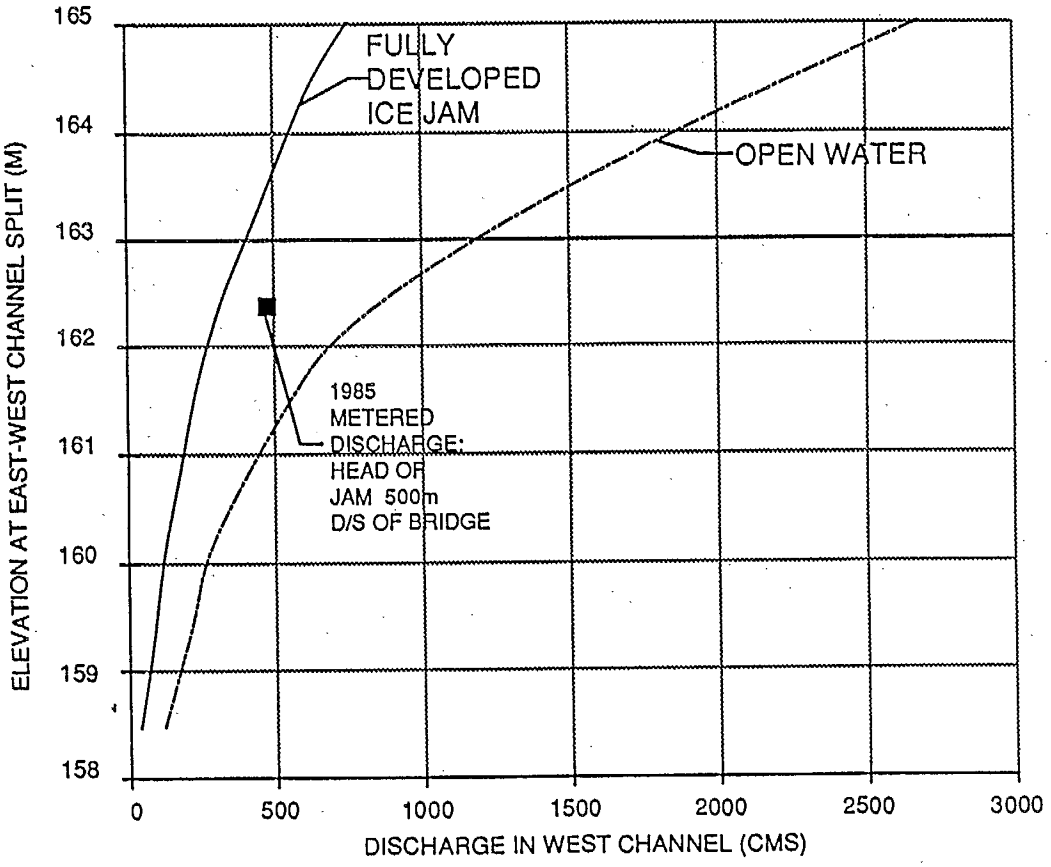


Figure 34 Relation between the discharge down the West Channel and the water level at the West Channel bridge

Only two measurements of discharge down the West Channel at break-up were available. Both were taken by WSC during the 1985 flood. A measurement was taken on two different days, but the measured discharge was almost the same in each case. At the time the head of the West Channel jam was about 500 m downstream of the bridge. Because of the backwater influence from this jam the measured discharge should plot between the two curves in Figure 34, as it does.

With the discharge down the West Channel estimated from Figure 34, the discharge down the East Channel can be determined from the forecast Hay River discharge. From these estimated discharges in the East and West Channels an estimate can be made of the maximum likely levels that will occur near the channel mouths.

5.5 Maximum water level near the East Channel mouth

Serious flooding of Vale Island occurs when the toe of the East Channel jam sets up at the mouth of the East Channel while the pack is still reasonably long. A rating curve was therefore developed for this situation for a point opposite Island A (km 1112) and is given in Figure 35. The algorithm used was calibrated with the measurements obtained during the 1987 and 1988 break-up observations as described in Appendix G. A typical calculated water level and ice thickness profile through a jam at this site for a discharge of 1,000 m^3/s is shown in Figure 36.

The flood of 1963 was caused by such an ice jam. Water levels for this flood are known but no discharge measurements are available. However UMA (1979) estimated the discharge in the East Channel was about 900 m^3/s during this event. This is in reasonable agreement with the rating curve of Figure 35.

Some allowance for the effect of surges from upstream on water levels at the mouth can be made by directly transposing the estimate of the surge height at the East-West Channel split, determined from Figures 32 and 33, down to Island A. Another possibility for increased water levels is a surging action, and momentarily increased water levels, that can occur as the pack movement is halted. No allowance has been made for this.

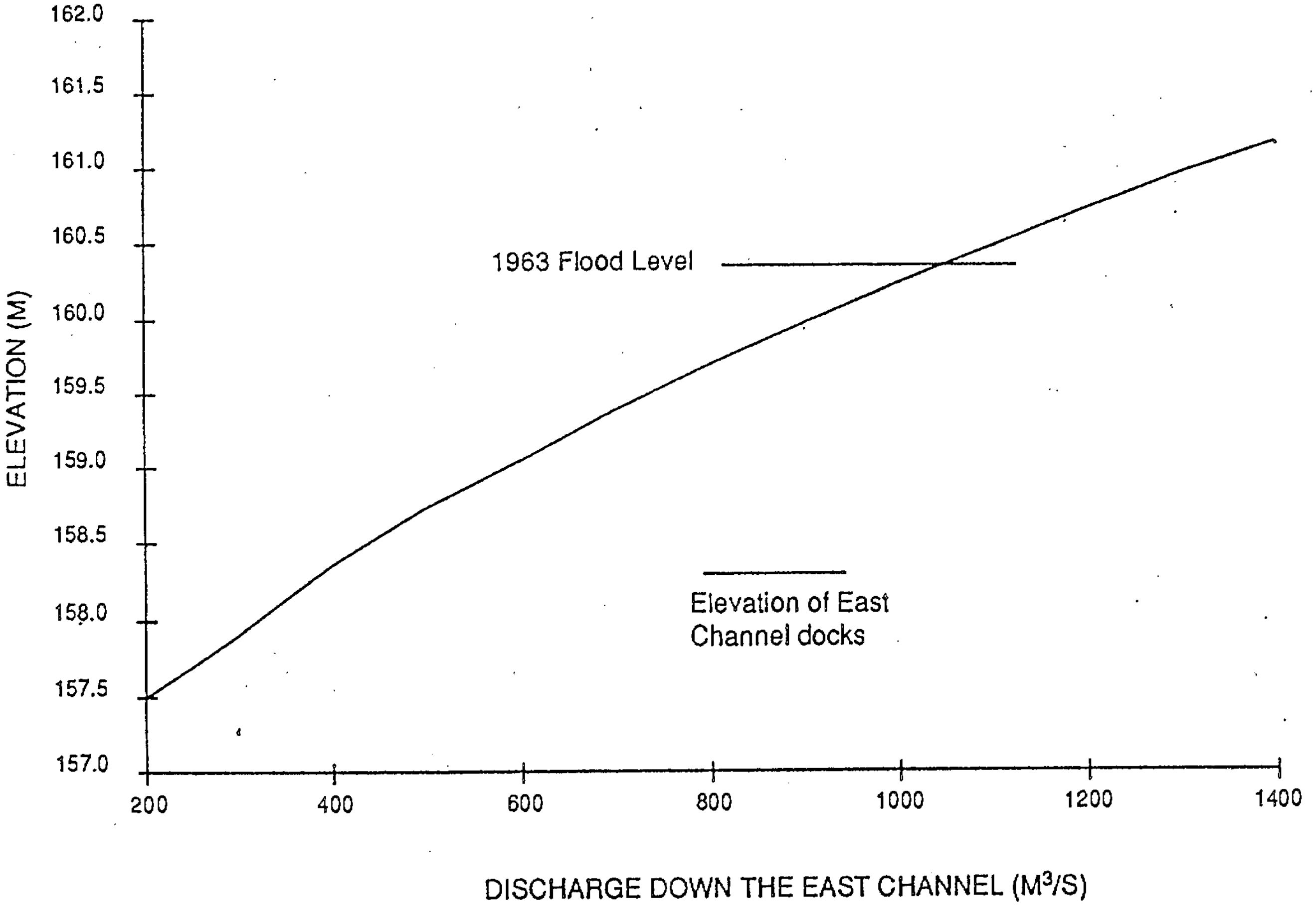


Figure 35 Variation in water level at Island A (km 1113) with discharge in the East Channel, for an ice jam at the mouth of the East Channel

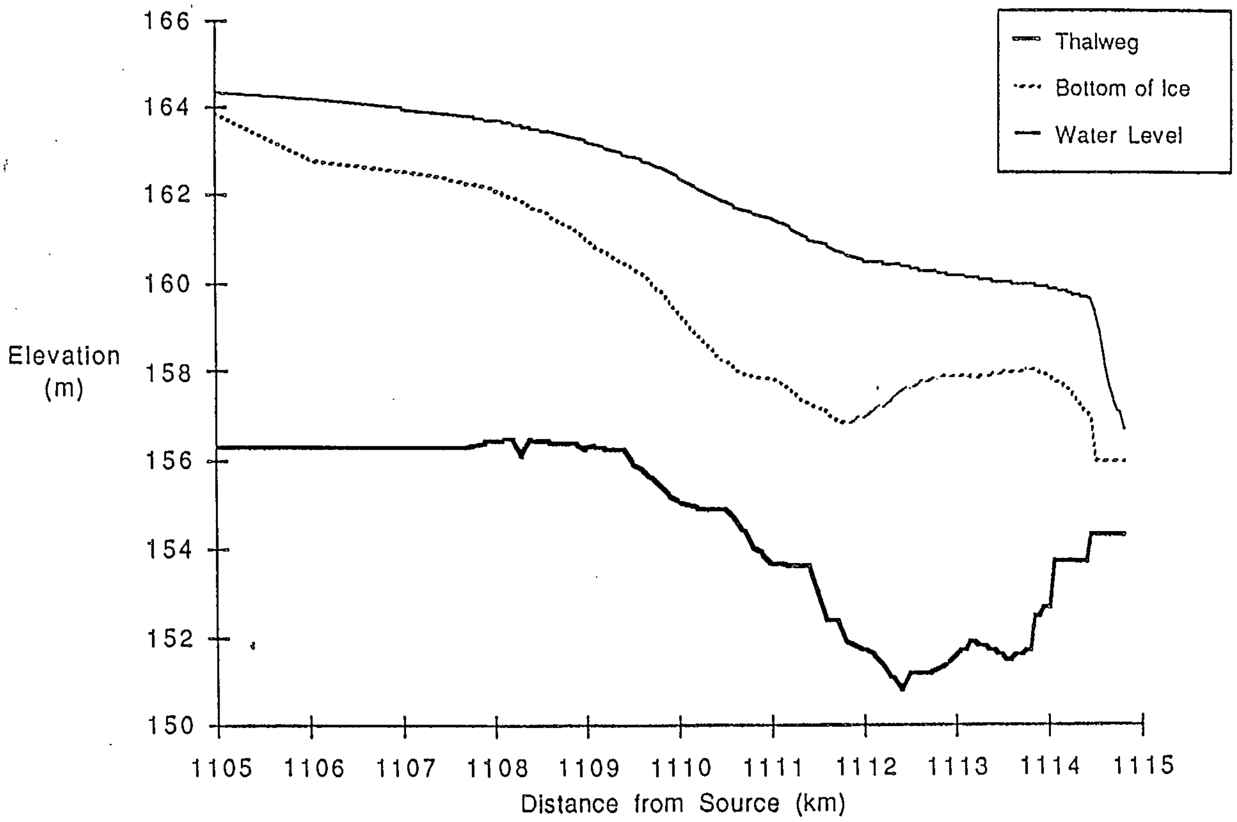


Figure 36 Calculated water level and pack thickness variation through an ice jam at the East Channel mouth for a discharge of 1,000 m^3/s.

Because of the short pack remnant that seems to usually exist when the toe of the East Channel jam moves to the mouth, water levels estimated from Figure 35 will likely be upper bounds. Further refinement of this estimate may be possible if account is taken of the pack melt. Detailed consideration of this was considered beyond the bounds of this study. However a rough allowance for the position and length of the jam might be made from field observations of the pack length and toe position, and the ice jam profile given in Figure 36.

5.6 Maximum water level near the West Channel mouth

The flow down the West Channel tends to move over the bottomfast ice and out onto the lake ice. There is therefore no well-defined toe position.

However water level profiles taken along the jam at this location in 1988 indicated that when the pack has moved out onto the lake ice there is a constant water surface slope in the vicinity of the West Channel split. This suggests the pack in this area might be treated as fully-developed and an ice jam rating curve determined on this basis. The result is shown as the upper curve in Figure 37, based on calibration with the 1987 and 1988 field observations as described in Appendix G.

The upper curve in Figure 37 does not allow for overbank flow. However overbank flow can be expected when the water level at this location exceeds about 160 m elevation. To estimate the overbank flow, use was made of data for the 1985 flood at this location. The peak water level reached in 1985 was 160.9 m (Underhill, 1985). From the description of the surge event in the historical record, and the WSC measurement of a discharge of 480 m^3/s in the West Channel just prior to the surge, it is estimated the peak discharge was between 600 and 670 m^3/s. Using this information the lower curve shown in Figure 37 was drawn as an estimate of a rating curve that allows for overbank flow.

The level given by Figure 37 is for the upstream end of the Fishing Village (km 1111.1) The 1988 field surveys suggest it is reasonable to transfer this level along the east arm past the Fishing Village at a slope of 0.9 m/km. It is noted that this implies flooding of the Fishing Village can occur without the jam moving into the east arm if the water levels above the split are sufficiently high to flow overbank there, as apparently happened in 1985. However movement of the jam toe to the mouth of the east arm would likely cause at least minor flooding to occur under less extreme circumstances, and exacerbate the problem in years of high discharge.

Again some account of surges moving down from upstream can be taken by simply transposing the estimate of surge height at the East-West Channel split, as was suggested for the East Channel mouth. And again some allowance should be made for surging action as pack movement is halted. Although no specific recommendations can be made for the latter, it is noted the high water at the Fishing Village in the 1988 break-up was due to a momentary surge of about a metre associated with the initial ice run.

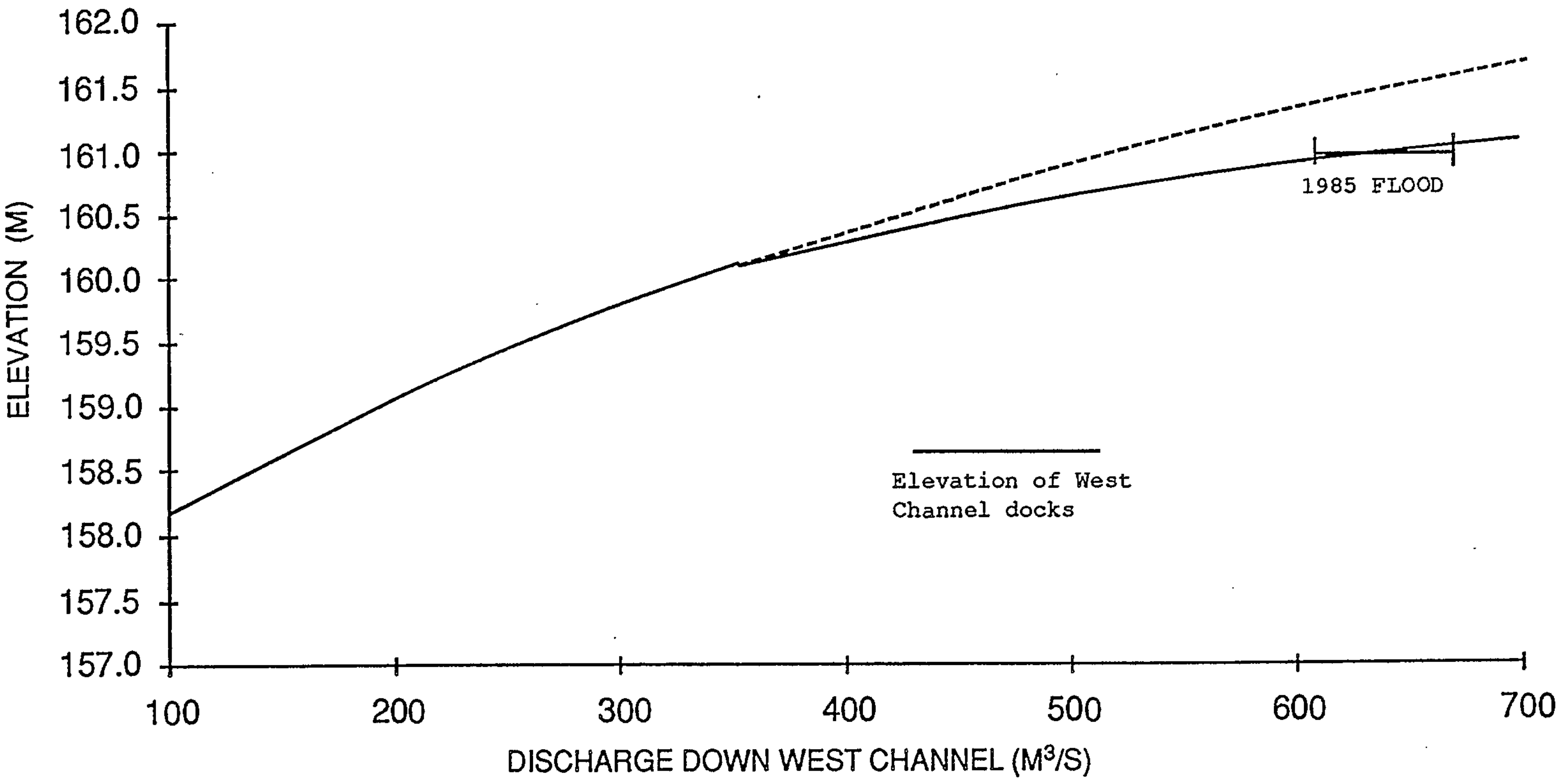


Figure 37 Water level-discharge relation just upstream of the West Channel split (km 1111.1) for an ice jam at the mouth of the West Channel

6.0 PROPOSED FLOOD FORECAST PROCEDURE

6.1 Description of the flood forecast procedure and its proposed implementation

Using the above relations it is possible to put together at least a first-generation ice jam flood forecasting procedure for Hay River. A flow chart for such a procedure is given in Figure 38. Details of each step are as follows:

Step 1: A first-level flood watch should be mobilized in mid-March to assess the flood potential for the coming spring. This initial flood watch would presumably just involve the head of the Town Flood Watch and appropriate Town and Government officials. The reported snowfall accumulations for Hay River, Fort Nelson and High Level would be used with Equation 1 and Figure 30 to estimate the maximum likely discharge that would reach the delta in the coming spring. Then, from Figure 32, an estimate of the maximum likely water elevation at the West Channel bridge would be made. Based on this, and ice conditions in the delta, it could then be decided whether flood mitigation activities should be initiated. At this time WSC should be requested to ensure their gauges at the Chinchaga, border and Hay River stations be made, and kept, operational for break-up.

Representatives of this first-level flood watch should then continue to monitor water levels at the Chinchaga, border and Hay River WSC stations, and meteorological developments in the catchment, and modify actions accordingly.

Step 2: At the first sign of significant water level increase at the Hay River WSC station, a second-level flood watch should be mobilized because break-up can then occur at any time within the next few days (the actual time of break-up will depend on developments in the ice cover upstream, particularly downstream of the falls). The second-level watch would include all members of the Town Flood Watch and, if significant flooding is anticipated, it might also include Emergency Measures Operations personnel.

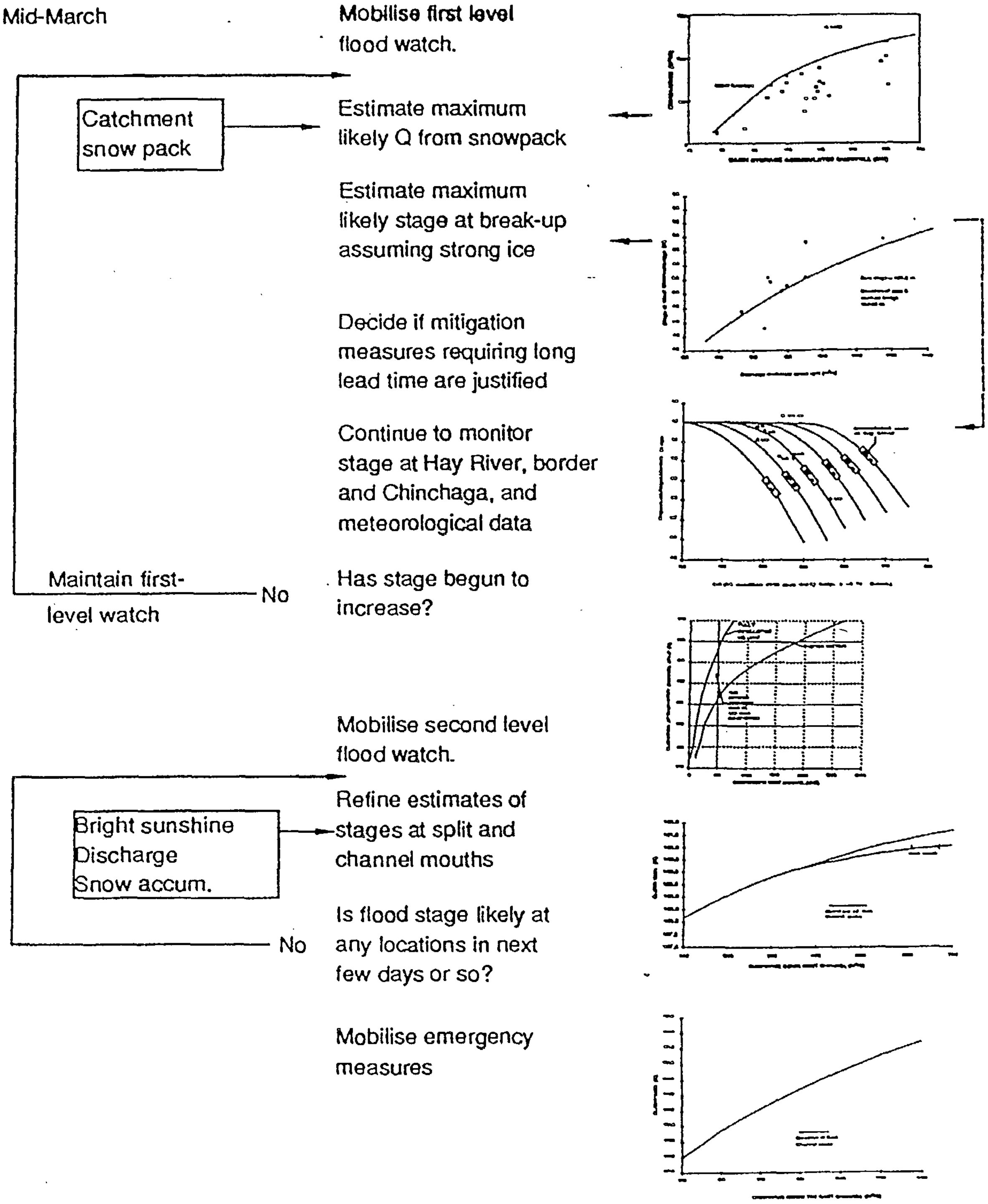


Figure 38 Flow chart for the ice jam flood forecast algorithm, Hay River at Hay River

Aerial reconnaissance over a long reach upstream should now be undertaken periodically as appropriate, together with at least daily ground observation of developments in the ice cover between the falls and the lake. Based on these observations, meteorological forecasts and developments with regard to precipitation, temperature and bright sunshine, and discharges at the border and Hay River WSC stations, forecasts of the maximum likely water levels to be expected at the three reference sites in the delta can be provided using Figures 32, 34, 35 and 37. The estimates for the mouths of the East and West Channels can be modified as break-up develops, based on judgement and the observed pack configuration.

6.2 Evaluation of the proposed procedure

As the 1988 break-up observations were not used in calibration of the above procedure, they can be used to provide at least a preliminary evaluation of the above procedure's utility.

In mid-March, 1988, the weighted accumulated snowfall for the catchment was 114 cm. From Figure 30 the maximum likely discharge the following spring would then be 950 m^3/s (the actual peak discharge at the Hay River gauge was approximately 750 m^3/s). For this discharge Figure 32 indicates the water level at the West Channel bridge would be 162.3 m, or a reading of 15.5 ft using the Town Flood Watch marks on the pier (the actual peak water level was 161.7 m). This is more than sufficient to cause concern and a decision would be made about flood mitigation activities that require long lead time (e.g. snow clearing, snow bank construction, blasting). At this time the WSC would be asked to ensure their stations on the Chinchaga and on the Hay River at the border and at Hay River are made operational. Members of the first level flood watch should begin more-or-less daily monitoring of the water levels at these stations, as well as of the measurements and forecasts of precipitation at Hay River, High Level and Fort Nelson, the temperature at Hay River and bright sunshine at Fort Smith.

....

April 22: A significant water level increase was noted at the Hay River WSC station. Break-up should therefore occur within the next few days if warm weather continues. A start should be made on mobilizing the Town Flood Watch. A reconnaissance flight should be undertaken to the Chinchaga confluence to determine the upstream ice conditions, the progress of break-up, and the location and extent of major ice jams, if any, in the upstream reach. A ground reconnaissance of the river between the falls and the lake should also be undertaken to establish ice conditions at access sites. The ground reconnaissance should be repeated at least daily and the aerial reconnaissance as often as conditions and experience indicate is appropriate.

....

April 24: Ground reconnaissance revealed that break-up had begun below the falls. Another aerial reconnaissance at this stage would likely be worthwhile.

....

April 26: Break-up in the town appears imminent. At this time discharge at the border WSC station would have been about 700 m^3/s (as no rating for the border station was available in 1988, this discharge was estimated from that at the Hay River station, allowing for a travel time of 26 h). Using a two day forecast, the accumulated bright sunshine at Fort Smith, after the mean daily temperature at Hay River had risen above -5°C was expected to be 190 h. The accumulated snowfall at Hay River was 114 cm and no rainfall was expected. From Figure 32 the likely mean water level at the West Channel bridge in two days, if break-up occurs, would be 161.5 m. Allowing for surges, using Figure 33 (b), the peak water level would be 162.1 m, or a Town Flood Watch reading of 14.9 ft.

From Figure 34 the expected discharge down the West Channel under these conditions would be 240 m^3/s so that, from Figure 37, the expected mean water level in two days at the West Channel split would be 159.4 m, or 0.8 m above the West Channel docks (about elevation 158.6 m), in the absence of surges. If the surge expected at the East-West Channel split was simply transposed to the West Channel split, the water level could reach 160.0 m, or 1.4 m above the dock.

The expected discharge down the East Channel would be 700-240 = 460 m^3/s. Hence, from Figure 35, if the toe of the East Channel jam moved to the mouth, the mean water level near Island A in two days, if break-up occurs, would be 158.6 m, or 0.3 m above the East Channel docks (about elevation 158.3 m). If the surges at the split are again simply transposed to this site, the peak water level would be 159.2 m or 0.9 m above the docks.

....

April 27: Break-up occurred in the town. Ground reconnaissance through the delta showed that the toe of the jam in the East Channel was at Island CD as usual. In the West Channel the situation was somewhat unusual. The toe was at the mouth of the east arm, and ice had broken out into the lake at the mouth of the Rudd Channel and caused the lake ice to break up for about 1 km along the lakeshore to the west.

.... and so on.

Using the above procedure it would have been forecast in late afternoon on April 26th that the highest levels for the spring would occur at about late afternoon on April 28th and would be as follows:

At the West Channel bridge: 161.8 m. The actual peak at this location was 161.7 m and occurred at 16:00 h on April 28th.

At the West Channel split: 159.5 m. The actual peak was 159.3 and occurred at 10:00 h on April 27th. It was caused by a surge associated with the initial ice run.

At Island A on the East Channel: 158.4 m. The actual peak was 156.7 m and occurred at 12:00 h on April 28th, at which time the toe of the jam was still at Island CD.

It is evident from the above example that the algorithm and the associated relations can work quite well and provide about a 2 day warning of potential high water at the three reference locations in the delta. Despite this success there are several limitations.

6.3 Limitations of the proposed procedure

Probably the major limitation is the inability to predict if and when the jam will move to the East Channel mouth, or into the east arm of the West Channel. This will mean that in most years the water level estimates at these two locations will be unreasonably high (as occurred for 1988 at the East Channel mouth).

In the proposed algorithm the only means of assessing the time of arrival of a surge is by tracking its passage past the Hay River WSC station (which will require concurrent ice observations in this reach to interpret the water level record). Furthermore, the estimate of the surge magnitude is not very rigorous, particularly for the channel mouths.

Another limitation is the present reliance on the WSC border station for discharge forecasts. This provides about a 2 day forecast of discharges in Hay River. However, if a suitable precipitation-runoff model could be developed, or an existing model calibrated, for the Hay River catchment, use could be made of 2-3 day meteorological forecasts to extend at least the mean daily discharge forecast for Hay River to 3 or 4 days.

As well as possibly providing some indication of when the jam in the East Channel will move to the mouth, consideration of pack melt should allow more effective utilization of the longer discharge forecast afforded by a precipitation-runoff algorithm when predicting water levels throughout the delta. At present the procedure does not take account of the mitigating influence of pack melt, although likely an approximate allowance could be made using real-time water temperature measurements upstream and observations of the rate of pack retreat.

6.4 Possible future development

It is presumed the annual Flood Watch will continue. In the absence of other flood mitigation activities, this is required to remove the risk to life associated with the sudden onset of ice jam floods, and to reduce flood damages. Even if other mitigation works are undertaken, a Flood Watch will likely still be required to remove the risk to life.

6.4.1 Evaluation of the present algorithm

To evaluate the efficacy and limitations of the above algorithm, and to collect further data with a view to possible improvement of the algorithm, systematic observation of break-up in the delta should be continued as part of the Flood Watch, along the lines of the 87 and 88 observations. In these observations particular attention should be paid to the ice jam toe configurations and their development over the break-up period. Useful supplements to these observations would be time-lapse photography from vantage points overlooking the three locations of most concern in the delta; discharge measurements within the delta channels during break-up, together with documentation of the associated ice conditions; and temperature measurements throughout the delta, particularly across the toe in the East Channel. Ice thicknesses, ice types, snow depths on the ice, and rubble and pressure ridge configurations just prior to the ice run should also be documented. Meteorological measurements in Hay River should be supplemented as soon as possible by bright sunshine or radiation measurements, at least over the break-up period.

These observations are intended to provide confirmation and possible refinement of the rating curves used in the first-generation model, to allow calculation of pack melt, to begin to gather information that may reveal the circumstances that control the ice jam locations, particularly in the East Channel, and better documentation of surge effects in the delta.

6.4.2 Discharge estimates

A rating curve has recently been established for the WSC station at the border. However, even with a rating curve, during break-up it is hard to estimate discharge from a water level reading because of the constantly changing ice conditions. Hence, although the periodic aerial reconnaissance recommended in the flood forecast procedure will allow observation of ice conditions at the border station, and will therefore mitigate the problem to some degree, a precipitation-runoff model for the Hay River catchment is desirable. This should allow some refinement of the border discharge estimates and also allow advantage to be taken of meteorological forecasts to provide a discharge forecast more than two days in advance. However, as discussed in Appendix H, such a model will have significant limitations because meteorological data for the lower Hay River catchment is not presently available. Even if it becomes available, calibration of the model will have to await the collection of a year or two of appropriate data.

Acquisition of the needed data will require establishment in the Cameron Hills and Caribou Mountains of remotely-monitored meteorological stations that are operational over the break-up period. It is emphasized that the required data relates to rainfall as much as snowpack and temperature.

An alternate to this meteorological instrumentation is the installation of more elaborate hydrometric instrumentation in the lower catchment. This would provide information of direct use and be less susceptible to access problems. For example, the Steen River WSC gauge could be upgraded to be operational and reasonably reliable during break-up and capable of being monitored remotely. This would provide an indication of runoff from the Cameron Hills. To this might be added a similar station on the east side of the Hay River on a stream draining the Caribou Mountains, although access to such a station during break-up will likely be difficult. Possibly the existing WSC gauge on the Ponton River at Rocky Lane might serve if upgraded.

The reliability over break-up of WSC gauge installations would be enhanced by development of a technique to measure water level from **above** the water, rather than from below as is done at present, and a means to get an approximate indication of ice conditions at the site. It is understood that the technology is readily available for the former and, for inaccessible sites, the latter can be accomplished to some degree by aerial reconnaissance. It may eventually be possible to develop remote monitoring by video camera. Deployment of instrumentation to measure water levels from above the water would also be of considerable value at other locations in the delta (such as the Pine Point and West Channel bridges) and at other locations along the river upstream to document the progression of surges.

6.4.3 Explicit allowance for surges

As mentioned, a limitation of the above procedure is that it is based on mean daily discharges, with only indirect account taken of surges through the use of Figure 33. If an estimate of the discharge increase caused by a surge can be determined, explicit account of the surge can be taken through the use of Figure 32 with the actual surge discharge. Information on such surges might be obtained with a little warning by close monitoring of the WSC gauge at Hay River and the aerial reconnaissance. However, ultimately it would be useful to develop an unsteady flow model that would allow the routing of surges to and through the delta, based on upstream ice jam configurations and their time of release, and observed ice conditions over the intervening reach.

To allow calibration of such an algorithm, data is required on channel characteristics and surge propogation through the lower reaches of the Hay River. It is expected initial information on this must come from reliable operation of the WSC gauges along the main stem of the Hay River, and perceptive aerial reconnaissance of the variation of ice conditions along the river during break-up. The additional item needed is documentation of the hydraulic geometry of the main stem at several locations. It is recommended that this be obtained by standard documentation of the hydraulic characteristics of the reaches through the WSC gauges on the main stem that have not been so documented, these being the Chinchaga River at Highway 58, and the Hay River at the Highway 35 and at the border. Such documentation should also be carried out for reaches prone to significant ice jam formation, such as that at Indian Cabins.

6.4.4 Assessment of pack melt

At present crude allowance for pack melt can be made by simply tracking the pack retreat, with some judgmental allowances for measured changes in water temperature upstream. However it should be possible to develop a simple algorithm that would allow direct estimates of pack melt and water temperature variation under the pack, and under the ice downstream of the pack, based on water temperature measurements upstream. As well as allowing account to be taken of the mitigating influence of pack melt, it would allow a start to be made on investigating the possible role of water temperature increases, and the attendant ice deterioration downstream, on the timing of the movement of the pack to the mouth of the East Channel.

Eventually it may prove worthwhile to extend this model to be able to forecast water temperature changes, as is done with discharge. To begin to gather the data on which to base such a procedure, it would be worthwhile if the WSC gauges in the lower Hay River catchment, especially those on the main stem, could be modified to monitor water temperatures.

In addition, further attention should be paid to the development of open water during the aerial reconnaissance associated with the Flood Watch, both because it is vital input to any thermal model of the river, and it is required to develop a better understanding of the ice regime above the falls and the circumstances that lead to break-up and the formation and failure of major ice jams in the reach.

6.4.5 Flood damage relation

It seems flood mitigation activities of one form or another will be required in Hay River for some time to come. Planning, and assessment of the worth of such flood mitigation activities would be aided by development of a flood damage-water level relationship for the Town.

7.0 CONCLUSION

From a review of the available historical data, resident interviews and field observations and measurements, it has been possible to put together a first-generation ice jam flood forecast algorithm that provides about a two day forecast of the likely maximum water level at the West Channel bridge and of the maximum likely water levels at the Fishing Village in the West Channel and near Island A in the East Channel. Comparison of predictions using this algorithm with events during the 1988 break-up supported the utility of the algorithm, but further evaluation during future break-ups is essential. Suggestions were made about additional developments that would likely be worthwhile.

From the historical data it was possible to derive quite well-defined ice jam flood probability distributions for three reference locations in the delta. These allow rational definition of 1% flood limits and suggest that this flood would cover more area than is currently designated. Furthermore, they showed that the 1985 flood was well within the range of expectations, being below the 1% event.

It was evident that ice jams can be expected to form in the Hay River delta every year, and that the important parameter with regard to flooding at break-up was the peak discharge that occurred while these ice jams were in place. However, as well as the usual snowmelt and rain contributions to this discharge, it was also apparent that surges released by ice jam failure upstream can have a significant influence on the peak discharge.

An important consideration for flooding in the Old Town area along the East Channel was the timing of the movement of the jam toe to the mouth of the East Channel. It seems that if the toe of the jam could be held in its usual location near Island CD until the pack had been shortened substantially by melt, the flood risk in Old Town would be significantly reduced.

In the West Channel the indications were that the rubble ice and pressure ridges in the lake ice offshore are only incidental to flooding at the Fishing Village. The governing consideration seems to be the discharge in the West Channel and the presence of an ice jam pack through the West Channel split.

8.0 REFERENCES

AES, 1982. Canadian Climate Normals 1951-80. Atmospheric Environment Service, Environment Canada.

Allen, W.R. 1977. Freeze-up, break-up and ice thickness in Canada. Atmospheric Environment Service, Environment Canada.

Arctec, 1980. Hay River water intake line damage. Report prepared by Arctec Canada Ltd. for Department of Sanitation, Government of the Northwest Territories, Yellowknife, N.W.T.

Cunnane, C. 1978. Unbiased plotting positions - a review. Journal of Hydrology, Vol. 37: pp. 205-222.

Environment Canada, 1983. Hay River flood risk study. Report prepared by Inland Waters Directorate, Western and Northern Region, Yellowknife, N.W.T. 27p.

Flato, G. and Gerard, R. 1986. Calculation of ice jam thickness profiles. Proceedings of Workshop on the Hydraulics of Ice-covered Rivers, Montreal, Quebec.

Gerard, R. and Karpuk, E.W. 1979. Probability analysis of historical flood data. ASCE Journal of the Hydraulics Division, Vol. 105, No. HY9, pp. 1153-1165.

Gerard, R. and Stanley, S. 1988. Ice jams at a lake: the situation at Hay River, Northwest Territories, Canada. Proceedings of the International Association of Hydraulic Research Ice Symposium, Sapporo, Japan.

GNWT/IWD 1984. Hay River basin overview. Report prepared by Environmental Planning and Assessment Division, Government of the Northwest Territories, and Inland Waters Directorate, Department of the Environment, Yellowknife, N.W.T.: 59p.

Harrison, D.A. 1978. Informal compilation of historical records on ice jam floods at Hay River. Available from Dr. D.A. Harrison, Box 1484, Hay River, NWT, X0E 0R0.

Harrison, D.A. 1984. Hay River, N.W.T., 1800-1950: a geographical study of site and situation. Doctoral dissertation presented to the Department of Geography, University of Alberta, Edmonton: 283p.

Jasper, J.N. 1983. Hay River: historical flood review. Draft report prepared by the Water Resources Division, Northern Affairs Program, Indian and Northern Affairs Canada, for the Northwest Territories Technical Committee, Flood Damage Reduction Program, Yellowknife, N.W.T.

May, R.D. 1971. Ice thickness of selected streams in Alberta, Saskatchewan and the Northwest Territories. Water Survey of Canada, Calgary.

Stanley, S.J. 1988. Ice jam analysis in a complex reach: a case study. M.Sc. thesis presented to the Department of Civil Engineering, University of Alberta, Edmonton: 248p.

Stanley, Grimble, Roblin Ltd. 1959. Civil engineering report on flooding of Hay River townsite. Report prepared for the Canadian Department of Northern Affairs and Natural Resources: 96p.

Stanley, Grimble, Roblin Ltd. 1963. Engineering report on flood protection at Hay River, N.W.T Report prepared for the Canadian Department of Northern Affairs and Natural Resources: 73p.

Underhill Engineering Ltd. 1985. Flood levels 1985, Hay River, N.W.T. Report prepared for Indian and Northern Affairs Canada: 29p.

Underhill and Underhill. 1983. Establishment of bench marks, Hay River, N.W.T. Informal report obtained from Underhill and Underhill, Hay River, NWT.

UMA, 1979. Flood risk mapping for Hay River, Northwest Territories. Report prepared for the Canadian Department of Fisheries and the Environment, by Underwood McLellan (1977) Ltd: 128p.

Viessman, W., Knapp, J.W., Lewis, G.L. and Harbaugh, T.E. 1977. Introduction to hydrology. Harper and Row, New York: 704p.

Wedel, J. 1988. Internal report on 1985 discharge at Hay River, prepared for Water Survey of Canada, Yellowknife, NWT.

APPENDIX A

TERMS OF REFERENCE

APPENDIX A

TERMS OF REFERENCE

A.1 STATEMENT OF WORK

(a) Title

Hay River Ice Jam Flood Study - Phase I

(b) Background

The severity and unpredictability of flooding in the Hay River Estuary, especially on the deltaic structure known as Vale Island in the community of Hay River, N.W.T. is a cause of great concern to the residents, to the Government of the Northwest Territories (GNWT) and to the federal government departments of Indian Affairs and Northern Development (INAC) and Environment Canada (DOE).

Previous studies have indicated that Hay River flooding problems are caused by a combination of high river flows and riverine ice jams. Major flood events in 1963, 1974, 1985 and in 1986 point to a third factor in Vale Island flooding: the location of the annual ice pressure ridge offshore from the estuary in Great Slave Lake.

Development of a flood prediction system at Hay River must include a scientific investigation of each of the three processes and of the factors that determine when these processes will act in combination to generate significant floods in the community.

The study described in this contract proposal is Phase I of a two-phase program. Phase I is designed to identify and assess the processes that precede flooding in the community and to propose a prototype flood prediction model. Phase II, not a part of this contract, will develop the model and make it operational.

A further, separate contract with the GNWT, to assess current and proposed mitigative works, will likely be undertaken by the contractor concurrently with the Phase I study proposed in this document.

(c) Objectives

The objective of this study is to select, to assemble, to interpret the background data and information, and to propose a scientifically sound method of flood forecasting relevant to the town of Hay River and to those government departments involved in the Flood Damage Reduction Program, DOE and INAC.

Tasks

1. Review and evaluate historic information and data for floods at Hay River.
2. Conduct field programs in the lower Hay River Basin during freeze-up and break-up in each year of the study.
3. Investigate the factors which determine the location of offshore ice-pressure ridges and their magnitude in the Hay River vicinity.
4. Investigate factors which determine the location and strength of ice jams in the Hay River vicinity.
5. Establish linkages between break-up timing, discharge magnitude and antecedent hydrometeorological conditions.
6. Investigate models or techniques of combining the effects of river ice jams, discharge, and flow blockage by offshore pressure ridges with significant hydrometeorological factors to predict flood stages in Hay River.
7. Provide first estimates of the predictive capabilities of a prototype model.

(d) Expected Results

Since the purpose of the Phase I contract is a study of the factors causing major floods in Hay River and identification of potential models for flood prediction in a complex hydrologic environment, a final study report should contain the following items:

1. A description of the methods and data lists used to investigate historical and current flood events in Hay River.

2. Documentation and analysis of the linkage between antecedent hydrometeorological conditions or other factors and the severity and timing of break-up events in the past and during the study.

3. Recommendations on new data collection programs to improve estimates for magnitude of river ice jams and for flood impacts.

4. Recommendations on data collection programs to enhance early-warning capabilities which can be incorporated into subsequent flood forecasting models.

5. Clear, scientific direction for development of flood prediction methods for the town of Hay River in Phase II of the study.

(e) Required Reporting

1. Concise progress reports to support invoices.

2. A preliminary report outlining sufficient details and recommendations to assist in contract development for Phase II.

3. A final, summary report in sufficient detail to use as starting point in the subsequent Phase II contract. It must also contain results from data collection programs undertaken in the course of this contract and suitable documentation of new scientific knowledge or techniques.

APPENDIX B

SUMMARY OF
HISTORICAL RECORD OF EVENTS DURING
BREAK-UP IN HAY RIVER

APPENDIX B

SUMMARY OF HISTORICAL RECORD OF EVENTS DURING BREAK-UP IN HAY RIVER

B.1 Available data

Although the recorded history of Hay River dates back to 1868, there is no informaton on flooding in the period 1868 to 1878. From 1894, when St. Peter's Anglican Mission began, a relatively continuous record of at least the dates of break-up exists for the East Channel in the St. Peter's and St. Anne's Roman Catholic Mission diaries. Only in years of significant flooding is there mention of more than the break-up date, and then it is descriptive in nature. After 1950, spring break-up data is much more detailed, with a number of years having a complete description of break-up. The available historical data indicates that significant flooding has occurred in 1904, 11, 14, 34, 47, 51, 63, 74 and 1985.

Information on break-up in all years for which records exist is given in the following. For any given year the information was put together from as many sources as possible. The general references used are given in the main body of the report; only particular references are noted in this appendix. The emphasis of the review was on assessing the manner of break-up, ice jam locations, and on allocating a maximum water level for each year at each of the three selected locations in the delta: near the East Channel mouth, the East-West Channel split and the Fishing Village.

B.2 Chronological summary of break-up occurences

1894 - 1903

Records mention the dates of break-up but no significant flooding was recorded.

1904

On April 27 the ice began to break-up in front of St. Peter's Mission. On April 28 "By a.m. both banks and a great part of the mission clearing were under water and most of the village...But by two o'clock in God's Goodness the water began to subside". At St. Anne's Mission "Break-up 27th - 28th May, great flood, broke fence, covered field to a few steps from house, but some water in cellar. The point flooded to cemetery".

High water elevation was taken as that of the ground in front of the house steps at St. Anne's Mission: 159.1 m.

1905 - 1910

Records only contain break-up dates.

1911

At St. Peter's Anglican Mission on May 3 "At 10:30 p.m. the ice in the river began to show signs of going out. Later, it broke up and caused us a good deal of anxiety at it overflowed the bank in some places causing some of our skiffs to float..."

High water elevation was taken as that just over the banks at the Mission: 158.6 m.

1912 - 1913

Both of these years were recorded as especially mild, with descriptions indicating a thermal break-up.

1914

Ice began to push on April 30th, with break-up starting early May 1st. At the Anglican Mission on May 1 "It came into the Mission house, the floors of the dining room, kitchen and girls play room were flooded halfway across... Water reached the stable and then receded. Water in a menacing condition all day". On May 2 "Ice moved out this p.m. and all danger is now past".

At the Catholic Mission: "Church full of water to above floor, water and ice round house".

The high water was estimated as 159.8 m, based on the floor elevation of the Catholic Mission and the ground elevation of the stable area at the Anglican Mission.

1915 - 1922

No flooding was recorded in this period. In 1918, there is mention in the Catholic Mission diary of ice going out on the West Channel: "Ice block upstream of the island, May 7th and ice went out from West Channel... Ice went out peacefully at Mission on 9th May".

1923

In the Anglican Mission diary on April 29 "Hunters report ice gone out of other branch of river". On May 1 "About 4 p.m. ice broke up in the river and water overflowed the banks... Water remains over the banks on potato grounds". On May 4 "River still up even on the banks" and by May 7 "River has dropped this p.m. and all danger of the flood is past".

The high water elevation was taken as 158.8 m, based on the ground elevation at the potato field.

1924 - 1931

No flooding was recorded in this period.

1932

At the Anglican Mission on May 2 "The ice began to move in the river. It blocked just above barracks". On May 3 "The water rose to the top of our banks here today due to a jam at the mouth... The main river is nearly cleared now by 10 p.m."

High water elevation was taken as the top of the banks at the Mission: 158.5 m.

1933

At the Anglican Mission on May 9 "The ice in this river began to move from above Mission Island sometime before 4 p.m.... The river rose over two feet so that Mission Island and Vale Island were partly covered".

High water elevation was estimated as 158.5 m, the elevation that would cause Mission Island to be partly covered.

1934

At the Anglican Mission on May 2 "The main river began to move after midnight...the water was rushing like a rapid over the bank into the field. The water at the corral division was knee high".

The elevation of the high water was estimated as 158.8 m. This would correspond with knee-high water at the corral.

1935 - 1946

No flooding was recorded.

1947

In 1946 fills "A" (km 1110.2), "B" (km 1109.9), "C" (km 1109.4) and "D" (across the West Channel) were placed across the channels between islands to carry the road from the mainland onto Island C as shown in Figure 1(d). It was not until the summer of 1947 that they were raised to their design heights: "It will be understood that these fills were merely built to a height and width sufficient to allow machinery and motor vehicles to cross and were in all cases much lower than they were finally built" (Douglas, 1952 from Harrison, 1978).

Water levels over-topped these fills early in the break-up. Water levels were high during break-up but no significant flooding took place as no permanent building was damaged.

At the Catholic Mission there was a "Moderate scare at Mission, with water halfway to house... No noteworthy damage at Mission however, and the break-up was relatively uneventful".

A profile of high water levels from Stanley Grimble and Roblin (1959) is given in Figure B.1. Peak levels were 161.6 m at the East-West Channel split and 158.9 m at the mouth of the East Channel.

1948 - 1949

No flooding was experienced in these periods. Fill "D" (across the West Channel) was at an elevation of 163.9 m and was not overtopped at any time in these years. In this period blasting of the ice was done to minimize

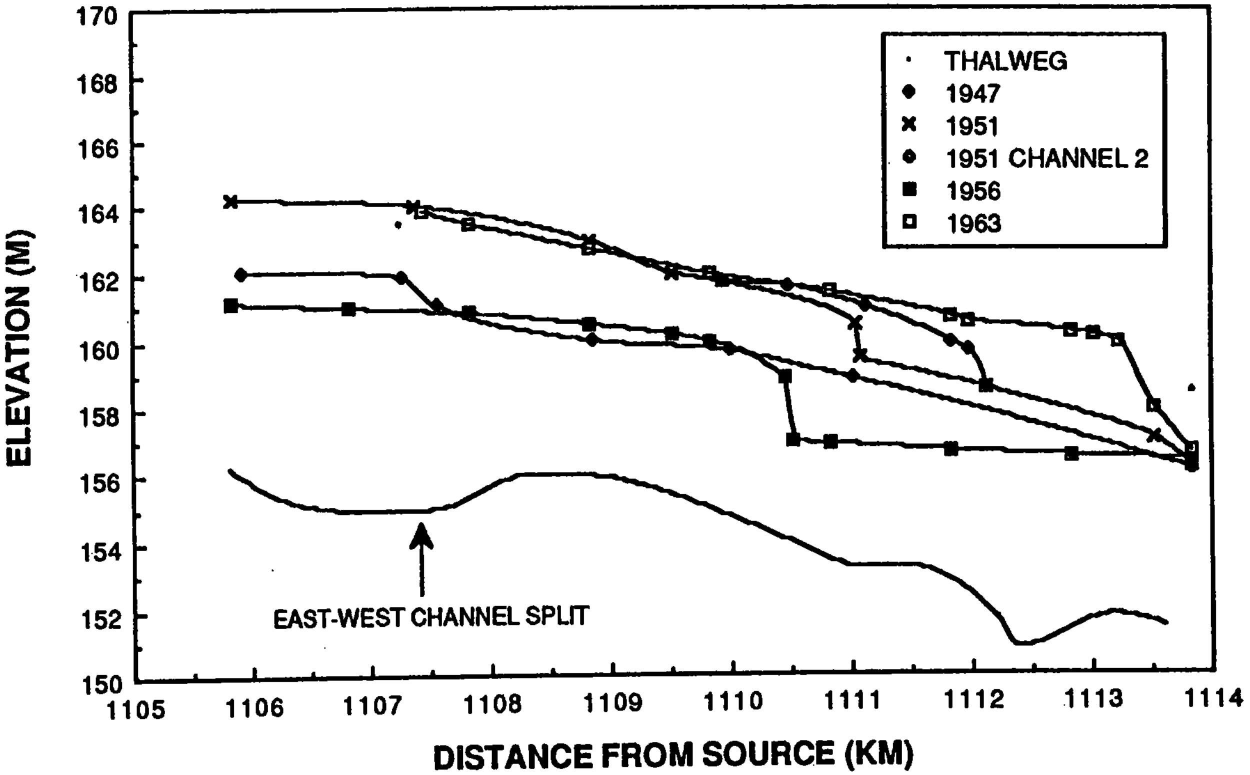


Figure B.1 Water level profiles for various past break-up events in the East Channel (after Stanley, Grimble, and Roblin Ltd., 1959, 1963).

flooding. The exact location of blasting in 1948 was not recorded, but in 1949 the ice was blasted from km 1108.8 to km 1111.0 in the East Channel (Douglas, 1952 from Harrison, 1978).

1950

No significant flooding took place in this year but a detailed account of break-up was recorded in a "Memorandum for the Chief" by Douglas (1951) (in Harrison, 1978). Blasting operations began on April 21 and continued to April 25 when flow increased considerably. Two rows of blast holes were completed from km 1108.8 to km 1111.0 (close to the downstream end of Island CD).

At midnight May 2 the first rush of ice came, breaking ice to km 1111.0, where the toe of the jam formed. Fill "D" had a 4 ft (1.22 m) free board (water elevation 162.68 m), and at Fill 'B' the water level was 160.99 m. The jam remained in place until early May 7 when the river opened right through to the lake, where the ice jammed again for about one hour causing the water to rise and flood that section of the town between the main street and the river (water elevation 158.5 m).

The report also states that runoff was probably more than that of 1947.

1951

In 1951 no blasting was done prior to break-up. Break-up commenced on May 3rd, with the ice breaking down to km 1110.7 (Island D). Water began to flow over the West Channel Fill "D" late on May 4th. This was about the peak flood level in the airport vicinity. Water was flowing to a depth of 1.22 m over the runway.

By early morning on May 5th water was flowing over both river banks along the whole East Channel, from the East-West Channel split to the mouth of the East Channel. One man was drowned. Water going over the airport was flowing over the West Channel road over a length of some 3 km. Then, at about 3:30 a.m. May 6th, a new rush of ice and water came down the river and the East Channel jam broke through to the lake. The river cleared on May 7th.

Figure B.1 shows the profile of the high water levels given by Stanley et al. (1959). It is evident that these were generated by a jam with the toe located some distance upstream of the mouth. As pointed out by Douglas (1951) (in Harrison, 1978), this probably limited the flooding that could have occurred in the town: "This last move was the feared one as in other years the ice has always jammed at the lake. This was the jam which we wished the R.C.A.F. to stand by for and very lucky it did not happen. I believe every building in the settlement would have been flooded".

Peak water levels were taken as 164.0 m at the East-West Channel split and 158.7 m at the East Channel mouth.

1952

Because of the flooding in 1951, an extensive blasting program was undertaken in the spring of 1952. The East Channel was blasted from km 1108.8 to the mouth, almost 5 km. Five pound charges were placed in 3 lines across the channel, with 75 feet from line to line and the holes 60 feet apart on each line. It was found as work progressed upstream that only 2.5 pound charges were needed. In total some 700 holes were blasted.

The river began to break-up on April 25th. On April 27 the toe of the jam was just upstream of Island A (km 1112.3). At the East-West Channel split the water reached a level of 162.8 m and at Fill "C" it reached 161.6 m.

On April 28th this jam broke and the toe moved to the mouth of the East Channel. This caused minor flooding at the Hay River Hotel and Menzies Fish Company (near the mouth of the East Channel). By the afternoon of the 28th the ice was out of the East Channel.

It is estimated that a water level of 158.6 m near the East Channel mouth would cause minor flooding at the Menzies Fish Company.

1953

Break-up in 1953 was very quiet. From the descriptions available it was probably a thermal break-up: "April 29: River very low and rotted out clearing through this late evening" (EMO File).

The West Channel Fill "D" was lowered in the fall of 1952 as shown in Figure 26. Even at this low level water did not flow over it. The peak water level at the East-West Channel split was noted to be 5.5 ft (1.7 m) below the fill (MacQuarrie, 1954 in Harrison, 1978). This is an elevation of 158.2 m.

1954

Prior to break-up the East Channel was blasted from the upstream end of Island B (km 1111.5) to the mouth. Break-up began on the night of May 11-12, when the stage at the West Channel fill increased by 2.75 m (Ross, 1954 in Harrison, 1978). This increase in stage broke the ice up to the upstream end of Island B (km 1111.5), where the toe of a jam formed. During the night of May 12-13 the river rose another 2.4 m at Fill "D" and reached a peak of 161.9 m, at which point 2.1 m of water was flowing over the fill. This water level remained relatively constant until May 15. During this period the toe of the jam in the East Channel remained in place. On the 16th the river began to clear and "the ice was reduced in volume by breaking and melting to about a quarter mile in length at the mouth of the river" (Ross, 1954 in Harrison, 1978).

The West Channel fill was completely washed out. The first rush of water after the fill was over-topped fanned ice and water over the lake ice at the mouth of the West Channel, due to the latter being frozen to the bottom. A cross section was taken on the West Channel approximately 400 m downstream of the fill on May 14. Surface floats were placed on the water and were observed travelling at 1.9 m/s. From this Ross estimated a discharge of 453 m^3/s in the West Channel by assuming actual velocity was 80% of the surface velocity, allowing for dead water and using the measured area of the channel. He also estimated the discharge in the East Channel to be at least 700 m^3/s and perhaps as high as 1,400 m^3/s. No actual measurements were done in the East Channel. No flooding occurred at the mouth of the East Channel.

1955

Little information could be found on break-up for this year. The only account was a letter by Miss E. Ramsey, a school teacher at St. Peter's Mission: "The water went over the fill on May 1st and washed the highway out taking most of the ice out the West Channel. The ice broke at the mouth in front of the Mission May 5th and was all clear by the next morning. There was no flood water at all on the Island".

Water levels at the fill must have been higher than 159.8 m, the height of the fill at this time.

1956

In 1956 a blasting program was started in late April. The East Channel was blasted from the downstream tip of Island B (km 1112.2) to the DPW docks (km 1113.3). Because of warm weather blasting of the rest of the channel to the mouth could not be completed but the lake ice was blasted in a fan shape at the mouth (Harriot, 1956 in Harrison, 1978).

During the night of May 2-3 river ice broke up to km 1108.9. It was observed that on May 3 no ice was left on the river from Alexandra Falls to the jam in the town. On the 4th and 5th little change occurred in the conditions. On May 6 the jam pushed and a new toe was formed at the middle of Island D (km 1111.0). The West Channel Fill "D" was overtopped and the water level reached a maximum of 161.0 m. The toe of the jam remained at km 1111.0 with the pack slowly melting in place. It was not until May 13 that the river was completely free of ice. A profile of peak flood levels in this year is given in Figure B.1.

From this profile peak levels were obtained for the East-West Channel split and near the mouth of the East Channel. They were 161.0 m and 156.8 m respectively.

1957

Water began to flow over Fill "D" early April 29. In the East Channel ice broke down to the downstream end of Island D where the toe of a jam formed. On May 3 blasting was done on the solid ice below the toe, from km 1112.4 to the mouth of the channel. Water levels at Fill "D" reached a peak on May 3 with a level of 161.1 m. This elevation was obtained from the description that water was flowing over the fill at a depth of approximately 8 ft (2.4 m) (Anonymous, 1957 in Harrison, 1978).

On May 5 some minor flooding occurred in the West Channel. Late on May 6 the jam in the East Channel began to move downstream. Water just reached the road at Royal Canadian Corps of Signals corner (km 1112.4), an elevation of 158.7 m. By May 7 the river was clear.

1958

Much work was done in 1958 prior to break-up. A pressure ridge had formed 800 m to 1,200 m offshore opposite the West Channel. This ridge was about 3.7 m high and ran parallel to the shore (Harriot, 1958 in Harrison, 1978). It was blasted along with the East Channel. In the East Channel a 9 m wide strip was blasted from km 1111.0 to the mouth.

On April 22 water began to rise and by midnight a jam had formed at the mouth of the West Channel, but no flooding occurred in that area. Early on the 23rd the discharge dropped, probably because of an upstream jam. In the afternoon a large surge of ice and water arrived in Hay River, breaking the jam in the West Channel and moving the ice out into the lake. This surge also broke up the East Channel to the downstream end of Island D, where a jam formed. The toe stayed in this location until April 30 when the ice moved out into the lake. No flooding occurred in East Channel.

1959

Break-up was very mild, with no water going over the West Channel fill (EMO Files). The blasting program was apparently quite extensive but little specific information could be found (Stanley Grimble Roblin Ltd, 1959).

1960

Break-up started on April 24 with the water and ice going over Fill "D". To be conservative this was taken as having an elevation greater than 160.5. The river was completely clear by May 1 (EMO File). No mention of significant flooding could be found.

1961

Ice and water began to spill over Fill "D" on May 8. By May 12 the river was clear of ice (EMO File). As for 1960, the peak water level was taken as greater than 160.5.

1962

Little information available on break-up. River clear of ice between May 16-18 (EMO File).

1963

Little information could be found on the progression of break-up; most records concentrated on the effects of the flooding of the Town. On April 27 water levels began to increase with water running over Fill "D" at 1930 hours. A jam had formed in the East Channel in the area of Island D. Flooding in the Old Town area started early on April 30 when the jam moved downstream and the toe lodged at the mouth of the East Channel. At 4:00 p.m. on April 30 a jam 35 km upstream broke sending a surge downstream. This surge hit Hay River about 7:40 a.m. on May 1 creating the peak levels. The high water level profile from Stanley Grimble Roblin Ltd. (1963) is shown in Figure B.1. Peak levels for the East-West Channel split and near the mouth of the East Channel were 164.0 m and 160.8 m respectively.

Although Fill "D" was washed out, little flooding occurred in the West Channel.

1964

Break-up was relatively quiet in 1964. Flood control measures were taken prior to break-up and included plowing snow off the river ice and blasting. The West Channel fill had been removed as the bridge across the channel was now complete. Break-up began on April 28 and by April 30 ice had pushed out the West Channel and into the lake. It was not until May 10 that the river was completely clear of ice (EMO Files). Most accounts attribute the lack of problems to lower than normal run-off.

1965

Blasting was done prior to break-up along the river and for 500 m out into the lake. A reconnaissance flight on April 24 revealed that the river ice was still solid south of the border but north of the border the river was beginning to break-up (Town Flood Watch, 1965). On April 23 the river began to break-up and push down the West Channel, where it stalled at the mouth. In the East Channel a jam formed at km 1111.15 (downstream end of Island D). This jam moved downstream on May 2, forming a toe at approximately km 1112.2. The river was clear of ice by the evening of May 4. No significant flooding was reported.

1966

Break-up was extremely quiet. "Warm spring weather, with temperatures in the mid seventies helped to disintegrate the thin, rotten ice that remained on the surface of the river" (TAWPE, 1966).

Discharge was reported to be very low and ice was completely clear of the river by May 12.

1967

Early indications were that flooding was a good possibility (TAWPE, 1967). Above average snow depths existed in the basin, and the river and lake ice was thick, with a heavy snow cover. Flood control measures included plowing the snow off the river and for a distance out into the lake. Blasting of the ice was done in the East Channel from km 1110.0 out into the lake for a distance of 500 m.

By May 8 levels at Indian Cabins were reported to be up to the 1963 levels (TAWPE, 1967). Although the peak discharge was very high in Hay River, the ice had deteriorated greatly by the time it arrived and no flooding occurred. The river was completely clear by May 13.

1968

The East Channel was blasted prior to break-up (TAWPE, 1968). By April 20 it was reported that the river was open for a distance below Louise Falls. It was not until May 4 that the river was completely out. No 'push' of water and ice came from upstream. The ice that did come was so slushy it simply ran under the intact ice at the mouth (TAWPE, 1968).

1969

The ice was very rotten by the time discharges started to increase. A jam formed in the East Channel on April 26-27, but the discharge was low so no high water occurred (TAWPE, 1969). No blasting was done prior to break-up, but blasting was done in front of the jam that formed in the East Channel because high water was reported to the far south of the basin. The river went out on April 29 before any dramatic increase in discharge was experienced.

1970

No blasting was carried out. Instead the ice was perforated with 20 inch diameter holes put down on 20 foot centres (Town Flood Watch, 1970). From the description it seems this was just done in the middle section of the East Channel. Break-up was very mild with levels below normal. The river was clear by May 7 (TAWPE, 1970).

1971

McBryan reported levels were the lowest since 1959 (TAWPE, 1971). Some sections of the East Channel simply rotted in place. The river was clear of ice by April 30 (TAWPE, 1971).

1972

Discharge was reported to be above normal at break-up (TAWPE, 1972). On May 5-6 both channels broke with some jamming occurring. This created some concern because a greater than normal discharge was reported in the south. By May 7 most of the jammed ice had moved out into the lake, so little flooding was experienced when the flood crest arrived on May 10. This crest carried some ice but as the ice was very deteriorated it did not jam. Some minor flooding took place as water went over the bank in the West Channel, an elevation of 158.6 m.

1973

No information could be found on the 1973 break-up, neither in the Town flood reports nor in the newspapers.

1974

In 1974 a number of flood reduction measures were undertaken. These included plowing and perforating the East and West Channels. A pressure ridge was present off the West Channel mouth and was closer to shore than normal, with about 600 m of rough ice in front of it (Town Flood Watch, 1974). Sections were cleared through the pressure ridge to allow water to flow through it.

On April 27 ice started to move through the West Channel and jammed at the mouth. In the East Channel ice broke up to Island D where the toe of the jam formed. A large jam was reported at Indian Cabins (km 920.6) on the 28th. This jam broke on April 29 at 3:00 p.m. and a surge was sent downstream. On April 30 the surge hit Hay River, sending water over the banks at the new Indian Village on the East Channel (km 1110.8) and reaching a peak water level of 162.2 m at the East-West Channel split (UMA, 1979). This surge moved the toe of the jam downstream in the East Channel to about km 1112.25, with water flowing over the Government Docks (km 1112.1) and reaching the highway. Ice started to move in the West Channel on May 1 and flooding started to occur there. Despite the cleared sections, ice and water could not get past the rough ice and the pressure ridge. On May 2 it was decided to blast the pressure ridge on the West Channel as water levels reached a peak of 159.3 m (this level was a surveyed high water level obtained from the 1:2000 flood risk map for Hay River). Water levels receded after the blasting (TAWPE, 1974). In the East Channel the toe of the jam began to move downstream on May 3. As it moved water levels rose to the railroad track at Carter's Float Plane Base (km 1112.5) reaching an elevation of 158.6 m (Town Flood Watch, 1974). By May 4 at 7:00 a.m. both channels were clear of ice.

1975

Break-up for this year was one of the quietest on record (TAWPE, 1975). The ice was completely out on May 1.

1976

The ice in both channels was perforated prior to break-up. With above normal temperatures, flooding was feared and so the ice was also blasted at the mouth of the West Channel (Town Flood Watch, 1976). Break-up was complete by April 27 with no flooding occurring.

1977

Break-up in 1977 was very mild with the river all clear by May 4 (Hub, 1977). This break-up was monitored by UMA (1979). Break-up progression was unusual in that the ice of the lower reach was the last to break-up. The ice run moved into the delta on April 27, with a jam toe forming upstream of Island CD (km 1110), upstream of the mouth in the Rudd Channel (km 1111.5) and at the upstream end of the Fishing Village in the east arm (km 1112). The ice run down the West Channel moved out onto the lake ice through the mid 'high-level' channel at the mouth. The jam toe in the East Channel remained in place until the jam melted out on May 3.

Water levels were recorded as part of the UMA study. Water levels near the mouth of the East and West Channel were 156.9 m and 158.1 m respectively. At the East-West Channel split the peak level was 161.1 m.

1978

The first push occurred on May 3 in both the East and West Channels. By May 4 the toe of the jam in the East Channel was at the upstream end of Island B (km 1111.5) (Town Flood Watch, 1978). This caused water levels in the new Indian Village (km 1110.8) to go over the road. Later on the 4th the toe moved downstream to km 1112.2, sending water over the Government docks (km 1112.1) up to the railroad tracks (Hub, 1978), an elevation of 158.4 m. The river was completely clear of ice by May 7.

1979

Prior to break-up the ice on both channels was perforated (Town Flood Watch, 1979). By May 10 the river had broken up to the NWT-Alberta border (Hub, 1979). On May 11 the West Channel broke and 'plugged' at the mouth and, on May 12, the East Channel broke to the upstream end of Island B (km 1111.5). A jam that had formed at Indian Cabins broke on May 13. The surge from the Indian Cabins jam cleared the West Channel on the 14th but not until water went over the banks at an elevation of 158.8 m. No flooding occurred in the East Channel, although water levels reached to within 0.15 m of the docks (Town Flood Watch, 1979) (elevation 157.9 m). The peak flood level of 162.7 m at the East-West Channel split was estimated from a report in the TAWPE (1979) that water levels peaked at the West Channel bridge 16 ft (4.9 m) above the original ice level. The river was completely clear by the 15th.

where

1980

Break-up was mild, with the river being clear by April 29 (Hub, 1980).

1981

Prior to break-up ice was reported to be thinner than normal (Hub, 1981). For the most part water levels were low during break-up, with some minor flooding taking place at the new Indian Village (km 1110.8), an elevation of 160.0 m. A peak level of 161.9 m was estimated at the East-West Channel split from a photo in the Hub (1981). Ice was out by May 6.

1982

No flooding occurred in 1982 as flows were very low. Ice was out by May 11. Again the peak water level of 160.4 m was estimated from a photo in the Hub (1982).

where?

1983

The river broke up at the East-West Channel split on April 28. Water levels were very low, with the ice going out May 3-5 (Hub, 1983).

1984

Break-up was very mild with ice being thinner than normal (Hub, 1984). Channels were clear of ice by April 24.

1985

Over the 1984-85 winter the pressure ridge formed on the lake off the West Channel mouth was closer to the mouth than normal, being about 400 m off-shore, and was reported to be 2 to 4 m high (Wedel, 1988). No blasting or grading was done on this pressure ridge as had been done in past years.

Break-up began on April 28 at the WSC gauge site. On April 29, ice began to move down the West Channel. During the period to May 4 it was reported that ice and water was flowing over the bottom-fast ice at the mouth of the West Channel and was ponding at the base of the pressure ridge.

A large jam that had formed at Indian Cabins was reported to have broken on May 5. The next day the ice on the East Channel began to move and a jam was formed at the downstream end of Island CD. This jam caused extensive flooding of Island CD. Early on May 7 a huge surge of water and ice was reported moving down the West Channel. This surge was thought to be the result of the Indian Cabins jam. Within 15 minutes the Fishing Village was flooded, with water reaching a depth of over 1 m on the roadway (an elevation of 159.9 m) (Underhill Engineering Ltd., 1985). At this time there was a pack over the lower reaches of the West Channel and the water appeared to move into the Fishing Village over the north end of the airport, from the West Channel upstream of the West Channel split. At the lakeshore east of the east arm of the West Channel the water was coming off Vale Island and running along the shore to the west (J. Pollard, Hay River, personal communication). During this flooding it was also reported that ice and water was accumulating against the pressure ridge at the mouth of the West Channel.

By early May 8, water levels had lowered in the West Channel. Later on the 8th ice moved through the East Channel to the mouth, but water levels downstream of Island CD did not reach flood level.

Underhill Engineering Ltd. was contracted to document high water marks in Hay River. From this work peak flood levels were obtained for the mouth of the East Channel and the East-West Channel split. These were 158.5 m and 163.5 m respectively.

Ice was completely out by 4:00 a.m., May 9.

1986

Prior to break-up it was reported that lake and river ice was thicker than normal. Because of the thick ice, blasting was done on the West Channel.

Ice began to move in the West Channel on May 2. In the East Channel the ice broke to the downstream end of Island CD on the 4th. Later in the day the toe moved downstream a few hundred metres, stopping behind the Hay River Hotel (km 1111.7).

On May 5 a jam that had formed at Indian Cabins broke. On May 6 some flooding was reported at the new Indian Village (km 1111) as water reached the road. On May 7 water levels reached a peak of 163.4 m at the West Channel Bridge and water went over the banks at the Fishing Village (elevation 159.0 m). In the East Channel some minor flooding occurred below Island B as water went over the docks to reach an elevation of 158.5 m (Town Flood Watch, 1986).

McBryan summarized the 1986 break-up as a smaller version of 1985, the difference being a lower discharge. The river was completely clear by May 8.

1987

Prior to break-up considerable flood mitigation work had been done on the river. This included clearing the snow from the lower portions of the East and West Channels and using a ditch witch to make long narrow longitudinal cuts in the ice in the East Channel. In the West Channel snow dykes were built out onto the lake to constrain the flow as it moved onto the lake, in the hope that it would carry ice and water out away from the mouth.

Ice began to break-up at the townsite on April 26. A jam was formed in the West Channel just upstream of the mouth in the Rudd Channel, and in the East Channel ice jammed at the downstream end of Island CD.

A large jam at Indian Cabins gave way on the 27th. Over the next few days little movement occurred in the delta. Ice from the jam at Indian Cabins arrived on the 28th. This caused the head of the jam to grow upstream with little movement occurring at the toes. On the 29th and 30th the jam began to melt in place due to warm water coming from upstream. Ice began to move out into the lake on the 30th and by May 1st the river was free of ice.

Peak water levels at the mouths of the East and West Channels and the East-West Channel split were 158.2 m, 158.1 m and 162.2 m respectively.

1988

See description in Appendix C and high water levels in Section 6.2.

APPENDIX C

ICE REGIME OBSERVATIONS

1987-88

APPENDIX C

ICE REGIME OBSERVATIONS

C.1 Introduction

The nature of the ice regime of the Hay River was determined from the historical record, resident interviews and from field observations during the 1987 break-up and freeze-up, and late winter and break-up observations in 1988. Details of the observations taken during the field studies are presented below.

C.2 Freeze-up observations, 1987

Because freeze-up events often have significant implications for ice behaviour at break-up, freeze-up observations were made from November 16 to 18, 1987. The work included ground and aerial observations of ice conditions, and measurement of water level and ice thickness profiles on the river to determine if any unusual ice thicknesses or types were established at freeze-up, and to provide data for calibration of a varied-flow algorithm for the delta reaches. Another item of particular interest was to see whether a pressure ridge had been formed on the lake near the mouth at this time and, if so, to determine its nature and position.

As shown in Figure C1, prior to November 16 Hay River had experienced 114°C days of frost. The accumulated snowfall up to the 16th was 45 cm, with much of it falling just prior to the field observations as shown in Figure C2. October 1987 had had above average precipitation, with that in Hay River being 127% of normal, while in High Level it was 424% of normal. The discharge at Hay River on November 16 was 63.0 m^3/s (WSC).

At the time of the first flight on November 16, freeze-up had occurred from the lake up to about km 1066. The recent 23 cm snowfall likely hastened freeze-up progression. It also obscured details of the freeze-up process that would have been evident with a snow-free ice cover. Nevertheless, lodgement points during freeze-up were indicated by the rough ice which was evident through the snow.

Ice had apparently lodged at Island CD in the East Channel (km 1111.0), as shown in Figure C3, with a 1.0 km pack of rough ice above this location. In the West Channel the ice lodged just downstream of the split of the Rudd

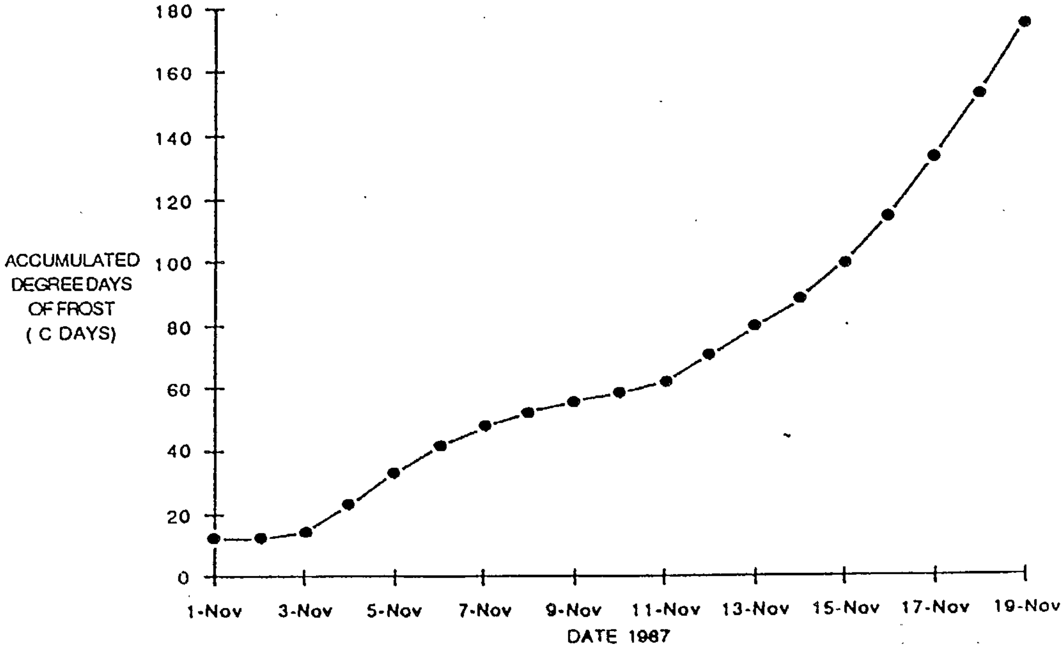


Figure C1. Accumulated degree-days of frost prior to freeze-up, Hay River, November 1987 (based on AES data).

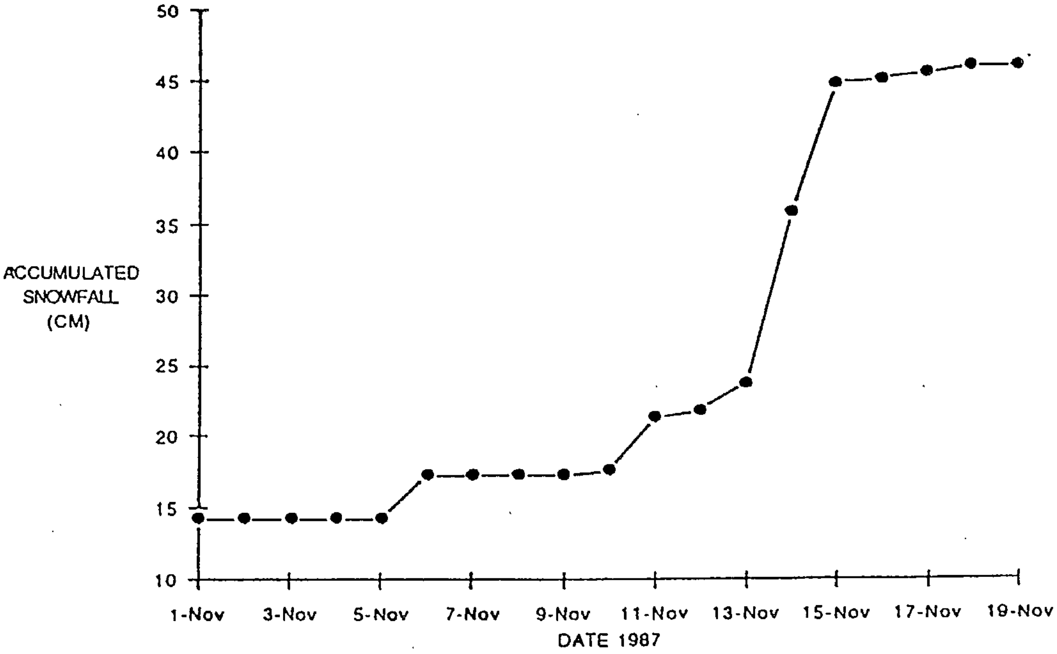


Figure C2. Accumulated snowfall prior to freeze-up, Hay River, November 1987 (based on AES data).

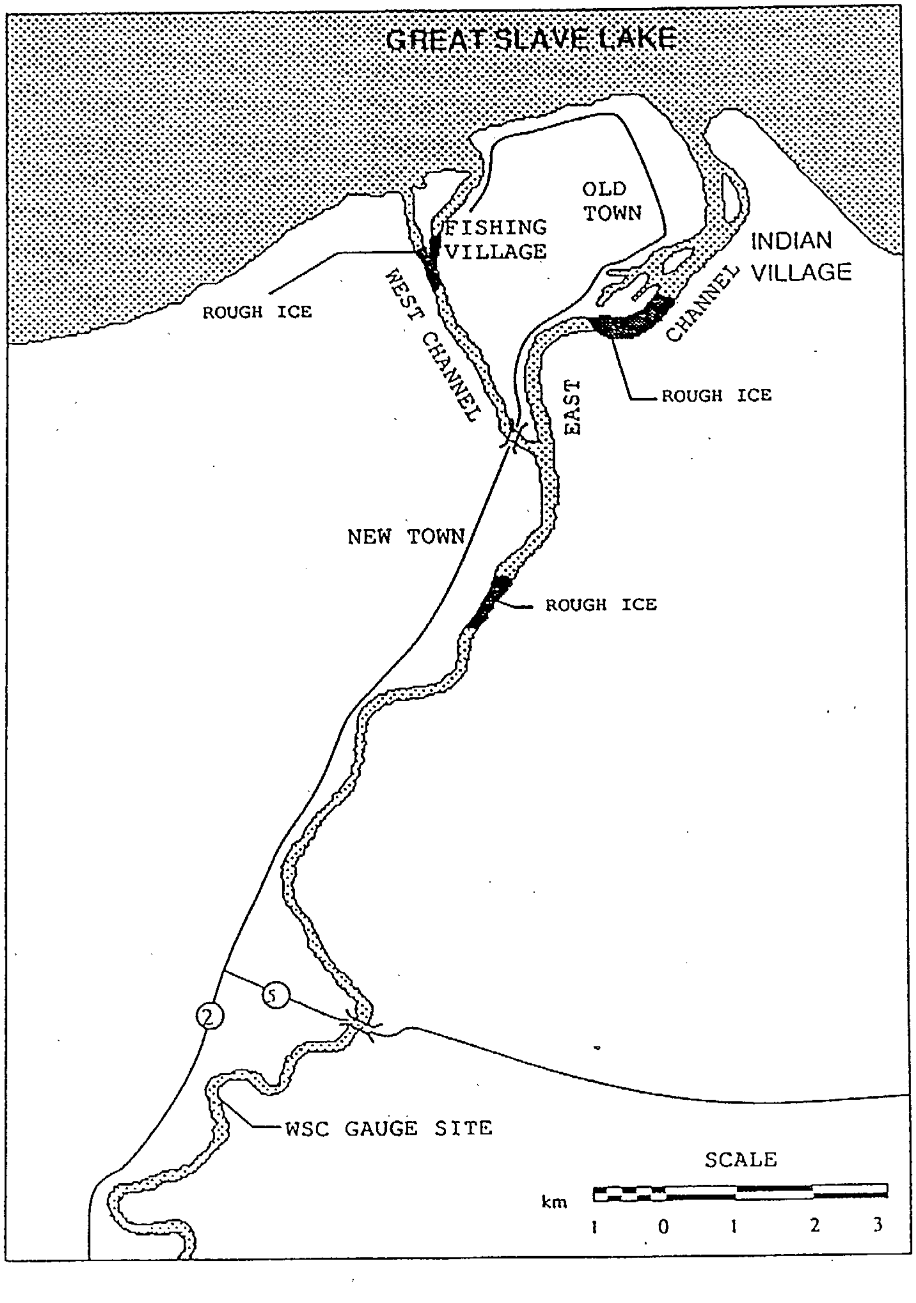


Figure C3. Lodgement points during freeze-up, Hay River, 1987.

Channel and east arm (km 1111.2), forming a 800 m pack of rough ice upstream. In both cases the lodgement was likely against solid sheet ice formed over the deep water at the channel mouths. At the time of the observations the solid ice on the Rudd Channel was 0.23 m thick and that near the East Channel mouth 0.25 m.

Upstream of the heads of both packs a smooth solid ice sheet, about 0.22 m thick, extended to km 1105.45, just upstream of the High School. Rough ice, likely indicating another lodgement point, extended 1.3 km above this location. Above this, smooth sheet ice, containing a number of small open leads, extended to km 1087.4, just upstream of the golf course, where the next accumulation of rough ice began. At km 1103.3 this solid ice above km 1087.4 was 0.08-0.12 m thick. At the WSC station it was 0.07 m. The pack of rough ice above km 1087.4 extended over 21 km to km 1066.4, just upstream of Paradise Gardens. The pack contained numerous open leads, with some up to 400 m in length and as wide as a third of the river width. Upstream of the head of this pack the river was open to Louise Falls. In this open water section shore ice extended about a quarter of a river width into the flow from each bank, and about 25% of the open portion of the river was covered with moving frazil pans. It appeared that the majority of the frazil was being produced in the rapids directly below the falls.

A profile of water level and ice thickness was surveyed from the lake to the WSC gauge site (km 1095.5), and is shown in Figure 15. To obtain each point on the profile, holes were augered through the ice. The water levels were surveyed, and the solid ice thickness and depth of frazil slush measured, at 3 or 4 locations across each cross-section.

The significant slush accumulations evident in Figure 15 tended to correspond to the rough ice locations. The combination of rough ice accumulation and slush deposits could be expected to result in somewhat thicker, stronger ice at break-up.

A complete cross section was taken in the West Channel just downstream of the West Channel bridge (km 1108.37), and is shown in Figure C4. The channel had not yet frozen to the bottom, but little flow was evident.

Another objective of the freeze-up observations was to determine if a pressure ridge had been initiated on the lake near the West Channel mouth this

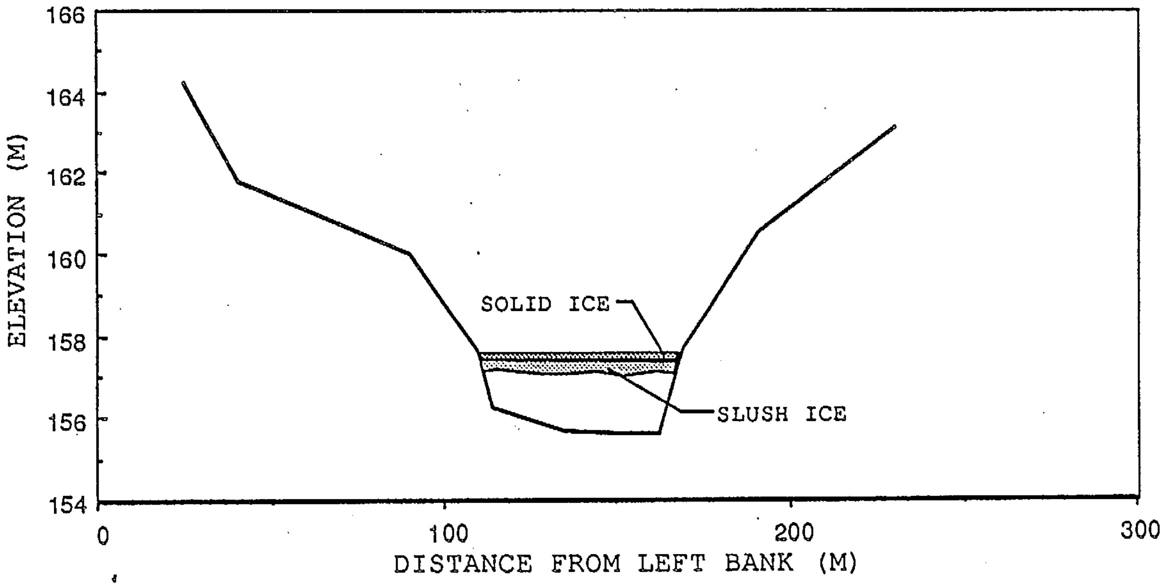


Figure C4. Cross-section just downstream of the West Channel bridge, November 17, 1987

early in the season. At the time of the field work shorefast ice extended for some 700 m out into the lake, about the same distance offshore as a shoal that was documented in the summer surveys, and which is evident in air photos of the site. Beyond this shorefast ice there were large free-floating ice sheets which were about 1 km in horizontal dimension, with open water beyond. The ice sheets were free to move so, depending on wind conditions, an open water lead could develop between the shore ice and the sheet ice. With the lead opening and closing, rubble ice would develop along the edge of the shore ice (or the bar). Frozen slush being driven onto the shoal by wave action would also likely contribute to this rubble ice. It was not possible to get out to this ridge, but from shore it appeared to be already close to a metre in height in places.

C.3 Late winter observations, 1988

The late winter field trip was undertaken from March 7-11, 1988 to document the offshore ice ridges. At the time there were two ridges on the lake near the West Channel mouth. Their locations, which were documented by resection to known locations onshore, and from photos taken from the air, are shown in Figure 16.

The ridge closest to shore was the rubble ice ridge noted at freeze-up. It is shown in Figure 17. It is evident the rubble ice formed on the offshore shoal. The height of the rubble in March varied from 0.8 m to almost 1.5 m.

The second ridge was an active pressure ridge, located over a kilometre offshore. It is shown in Figure 18. It was still active and growing, with the height varying from zero to about 2 m. The location of this pressure ridge was typical of that in other years (Arctec, 1980).

The section of the West Channel just below the bridge was again investigated. It was now frozen to the bed across the whole width.

C.4 Break-up observations, 1987

Break-up observations were made from April 25 to May 1, 1987. These included both ground and aerial observations, as well as detailed monitoring of water level variations in the lower Hay River. Discharge measurements were carried out at regular intervals at the Hay River gauging station by staff from Water Survey of Canada and Indian and Northern Affairs Canada.

A total of four flights were taken, the first on April 25 and the last on April 30. Two of the flights extended from the mouth of the Hay River to the confluence of the Hay and Chinchaga Rivers. Both of these flights were provided by the Town and were guided by Mr. 'Red' McBryan who shared his experience, identified physical features and described the normal series of events during break-up. A third flight was confined to the town area. One helicopter flight was taken with Town personnel to inspect the pressure ridge on the lake. On all flights photographs were taken using a 35 mm camera with an observer recording locations of the photographs and other features on 1:250,000 maps.

Extensive ground observations were made from the highway, which more-or-less follows the river from Hay River to Meander River. However, because the area of most interest is the Town of Hay River, most ground observations were confined to this reach. In addition to visual observations, break-up water levels were surveyed at numerous locations and times in the lower reaches of the river.

A major difficulty in most ice jam studies is obtaining reliable discharge measurements, as it is common for the usual Water Survey of Canada gauge installation to be disabled by an ice run. However, even if the gauge continues to operate satisfactorily, the rating curve for the station is largely unknown because of variable backwater effects due to ice. To overcome this problem Water Survey of Canada staff were on-site throughout break-up to ensure the satisfactory operation of the gauge and to take direct discharge measurements whenever possible.

C.4.1 Meteorological antecedents to break-up 1987

The 1986-87 winter was relatively mild. Figure C5 shows Hay River only experienced 2406°C days of frost, compared to a mean of 3147°C days. High Level had only 2243°C days compared to a mean of 2755°C days. Due to this mild winter, ice thickness in Hay River was somewhat less than usual.

Although temperatures were warmer than usual, the snowfall in the basin was generally above normal. The only station in the basin to show less than normal values was that of Hay River itself. As Figure C6 shows, snowfall in High Level was well above normal. Above average snowfall was also experienced in Fort Vermilion, where it was 127% of the median.

C.4.2 Flood mitigation activities

Prior to break-up, considerable work had been carried out on the river by Town personnel in the hope of minimizing ice jam flooding. This work included clearing the snow from the lower ends of both the East and West Channel to promote greater decay and melting of the ice. In addition, a 'ditch-witch' was used to cut 3 or 4 long narrow trenches in the ice of the East Channel from the mouth to the upstream end of Island B (km 1111.4). At the mouth of the Rudd Channel 3 snow dykes were built out onto the lake to constrain the flow in the hope that it would carry the broken ice out onto the lake over the inshore ice ridge, so preventing jamming at the channel mouth. These snow dykes were approximately 1.5 to 2 m in height and extended some 500 m out into the lake. A circular pattern of holes was drilled at the lake end of the dykes with the intent of blasting the lake ice, if necessary, to create a large hole into which the ice and water could flow. These mitigation activities are discussed further by Gerard and Stanley (1988).

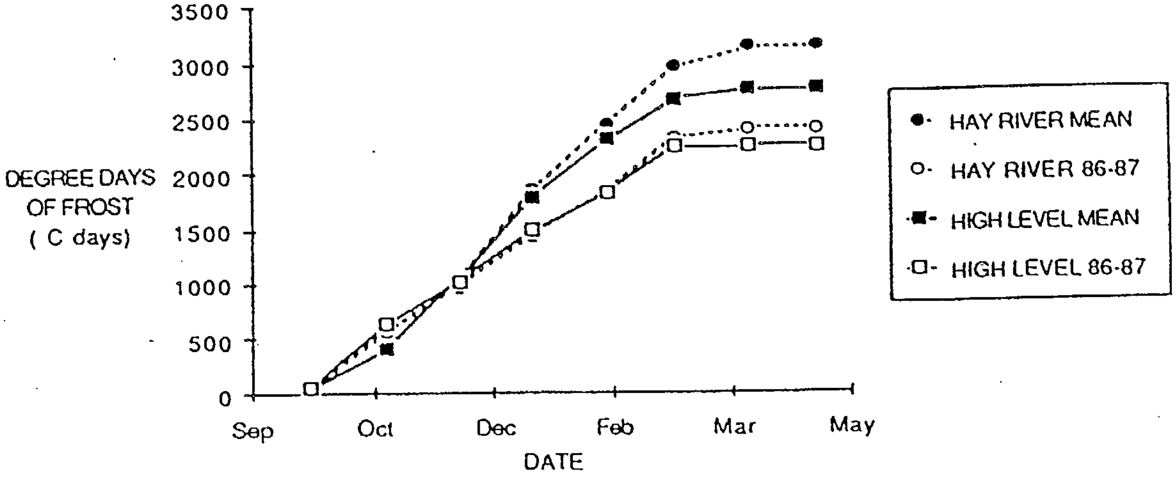


Figure C5. Accumulated degree-days of frost over the 1986-87 winter for Hay River and High Level (based on AES data).

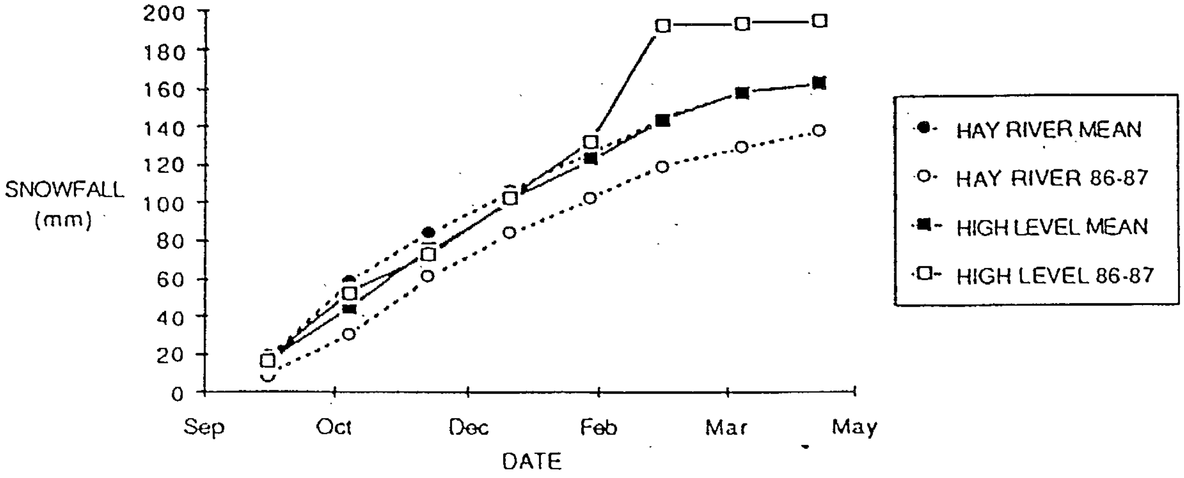


Figure C6. Accumulated snowfall over the 1986-87 winter for Hay River and High Level (based on AES data).

C.4.3 General break-up progression, 1987

When the first flight was taken on April 25, the ice cover was in place from the lake to the downstream end of the golf course (km 1092.5). Although some open water existed in this reach, it was infrequent, and occupied no more than 30 percent of the river width. Upstream of this solid ice cover there was open water for 800 m to the toe of an ice jam. This ice jam extended for 23 km to km 1069.2, near Paradise Gardens. Beyond this there was open water through Louise and Alexandra Falls. Above Alexandra Falls numerous small ice jams were present with sections of intact ice cover and sections of open water between each jam. This situation extended to km 834, where the head of the last jam was located. Above this point the river was open to the confluence of the Hay and Chinchaga Rivers, the upstream limit of the flight. There were not even fragments of ice moving on the water at this point so it was presumed there was little ice upstream. A summary of the conditions observed on this flight is given in Figure C7.

On the evening of the 25th, the jam located by the golf course broke, forming a new jam with the toe at km 1104.12. On April 26 two major movements took place in this jam. The first occurred at 16:20, when the jam moved to below the East-West Channel split. In the West Channel the toe was formed 400 m from the mouth of the Rudd Channel (km 1111.71) and just upstream of the Fishing Village in the east arm, while in the East Channel the toe stopped at km 1108.3, just downstream of the split. The second movement occurred at 17:50, when the toe in the East Channel moved to just upstream of Island B (km 1111.14). The toe region of this jam is shown in Figure 20.

Another flight was taken at 19:00 on April 27. No jams other than that in town existed on the river. However it was noted water levels began to increase above Alexandra Falls (km 1034.95) and remained high to Grumbler Rapids (km 988), beyond which point the levels began to diminish. There were quite heavy ice runs in the area of higher water. It was thought the high levels and ice runs were probably the result of the breaking of a large jam at Indian Cabins (km 920.6) that had been reported earlier in the day.

Over the next few days little movement occurred at either the East or West Channel toe of the jam. All changes were at the head of the jam. Figure C8 gives a detailed summary of the evolution of the jam in the townsite area. Overnight on April 27 the ice floes noted during the flight reached the

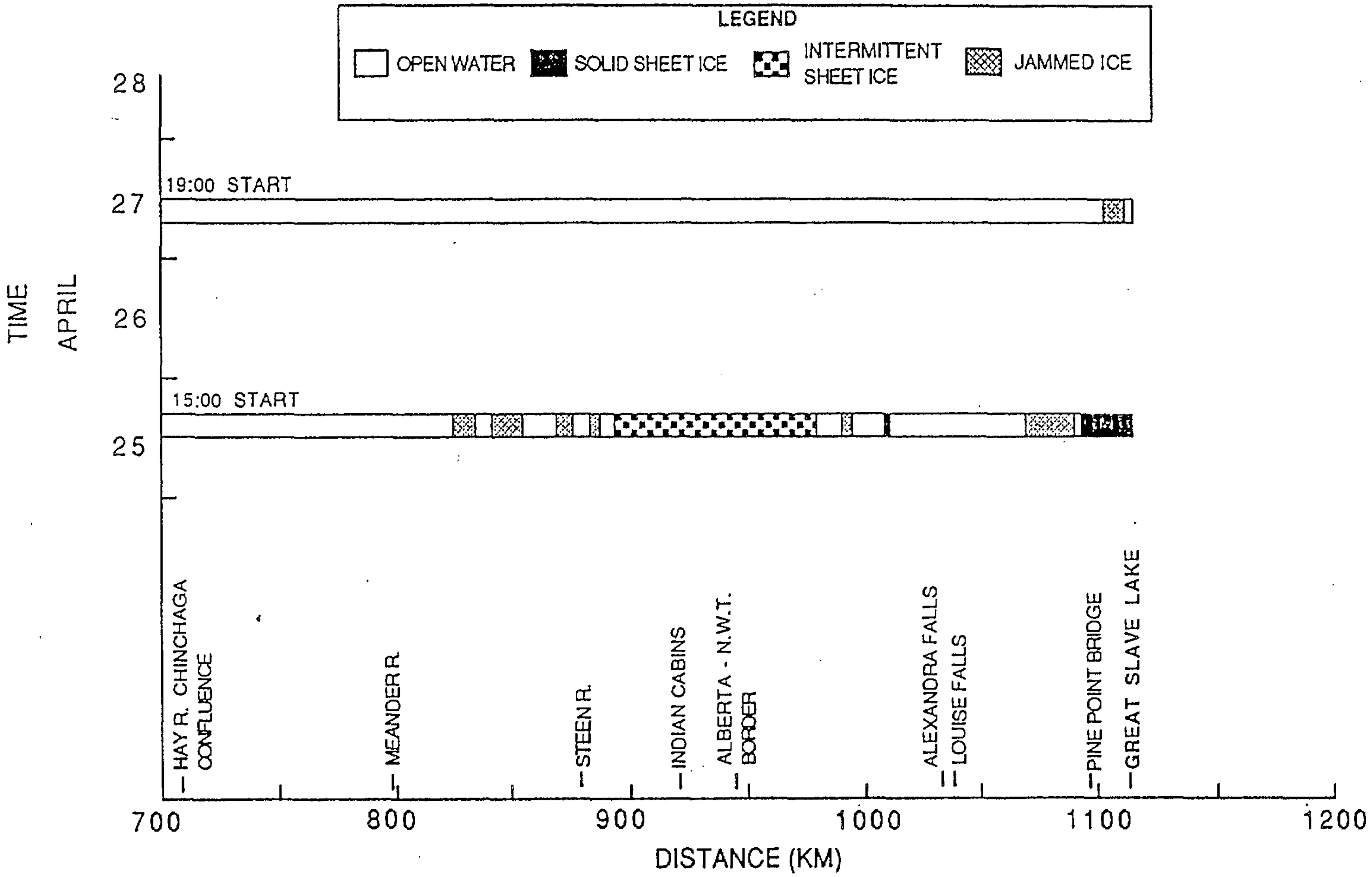


Figure C7 Progression of break-up, Hay River, 1987

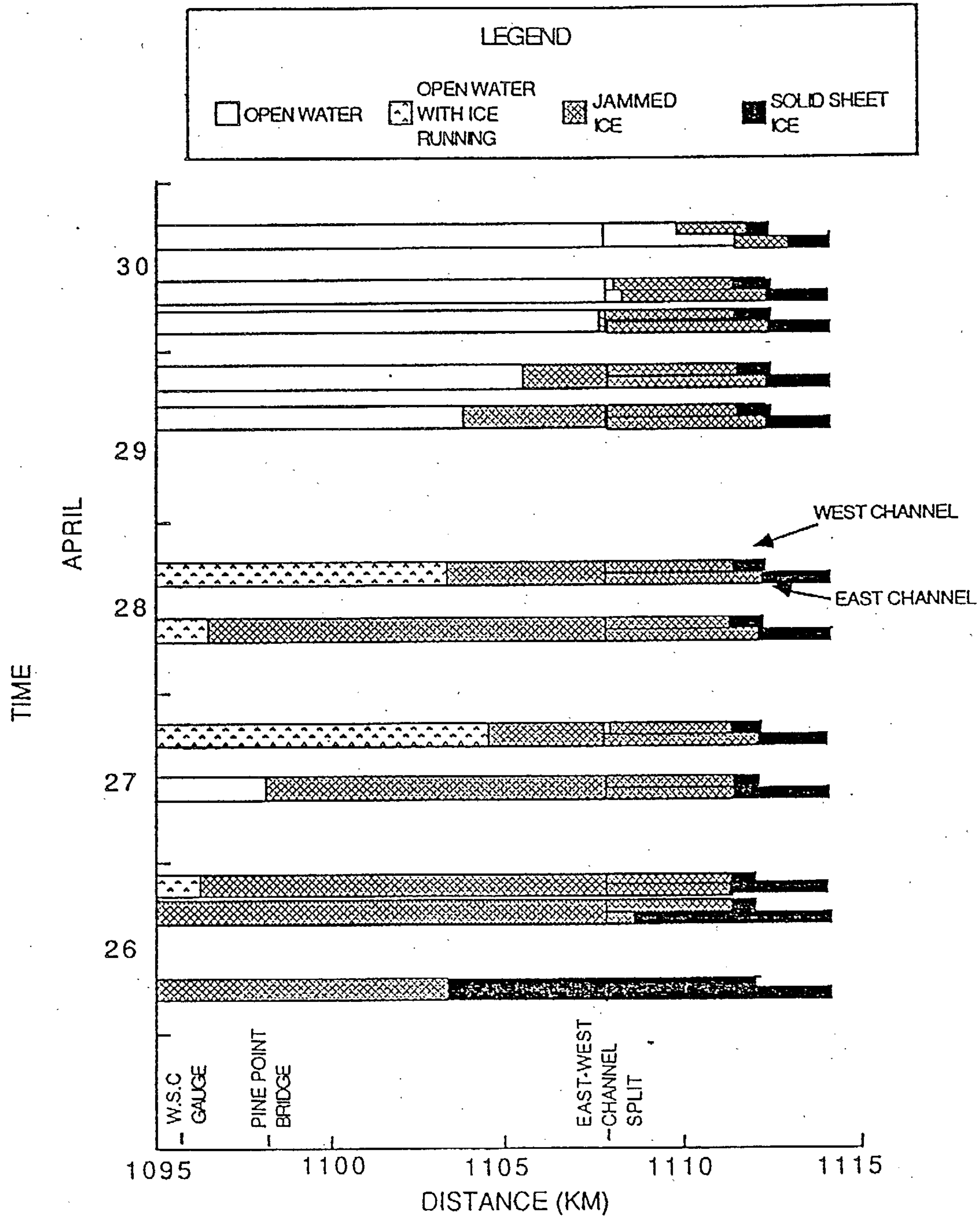


Figure C8 Progression of break-up in the delta, 1987 jam, building the head of the pack back to km 1096.39. (At 23:00 this was at a rate of approximately 0.2 km/h.) By noon on April 28 the arrival of ice floes from upstream had diminished and the head began to move downstream due to melting of the jam by the warm water. By midnight April 29th the water temperature at Pine Point bridge was 3.5°C. In response to the obvious significance of the water temperature other measurements were made as opportunity permitted. These are given in Table C1.

Table C1 Water temperature measurements during break-up, 1987

DATE		TEMPERATURE	LOCATION
DAY	TIME	DEGREE C*	
Apr-29	20:29	3.5	Pine Point Bridge - above jam
	21:04	0.0	Behind old hotel - E.C. - below jam
Apr-30	0:13	3.4	Pine Point Bridge - above jam
	0:59	0.1	NTCL docks - E.C. - below jam
	2:20	0.2	400m D/S West Channel bridge - W.C.
	8:10	0.1	NTCL docks - E.C. - below jam
	9:40	2.5	West Channel bridge
	10:30	2.3	Behind high school - above jam
	13:23	0.3	NTCL docks - E.C. - below jam
	16:22	4.5	Pine Point Bridge - above jam
	16:57	0.3	Ice bridge crossing - E.C. - below jam
	17:10	0.6	NTCL docks - E.C. - below jam
	17:22	0.4	Just D/S of Shell bulk station - E.C. - in jam
	22:39	2.0	ATL docks, just U/S of ice bridge crossing - E.C.
	22:49	3.5	NTCL docks - E.C. - now above jam
	22:55	2.4	Just D/S of Shell bulk station - E.C. - now above jam
May - 1	8:51	3.2	Fishing Village - W.C. - open water
	9:09	3.5	NTCL docks - E.C. - open water
	9:24	3.6	ATL docks, just U/S of ice bridge crossing - E.C.
	10:15	4.4	East - West Channel Branch - open water
	11:05	4.5	Behind high school - open water
	11:20	4.5	At Caboose - open water
	11:35	4.8	Pine Point Bridge - open water
	11:50	5.6	Golf Course - open water
	11:58	4.8	Riverside Gardens - open water

During April 29 and 30 the head continued to move downstream due to melting. Figure 23 shows what was left of the East Channel jam at 12:45 on April 30. In the West Channel at this time the head was 1.1 km below the split. By 16:00 on April 30th the pack in the East Channel was only 1.87 km long. At 17:00 ice began to move out into the lake. By 18:00 all threat of flooding had ceased and both the East and West Channels were open.

The effects on break-up progression of clearing the snow from the ice and cutting the ice with a ditch-witch could not be quantified. However it was noted that a large lead that developed in front of the toe of the jam in the East Channel did not follow any of the cut lines. The snow dykes on the West Channel fulfilled their purpose of conveying the flow out onto the lake ice, but their effectiveness in reducing flooding was not clear. There was a 'piping' failure of the western dike soon after the water began to move through the channel. The ice ridges on the lake seemed to have little influence on events.

During break-up, water levels were noted at various locations and times, from the mouths of the East and West Channels upstream to km 1089.57. Eleven sites were monitored in the East Channel, four in the West Channel and seven in the river above the split. Figures C9-11 show the variation in water level with distance through the East Channel and above the split at various times. Profiles for the West Channel are plotted separately in Figures C12-14. All results are tabulated in Table C2. For these surveys temporary bench marks were established at various locations along the reach. These were tied into Geodetic Survey of Canada datum during the field trip in July. All survey circuits were closed to ensure accuracy.

Discharge variation over the break-up period is given in Figure C15. The points shown represent actual discharge measurements by Water Survey of Canada staff. The peak discharge occurred on April 28 and was about 980 m^3/s. Discharge remained above 800 m^3/s from the 28th until after the ice was out.

C.5 Break-up observations 1988

Break-up observations were made from April 23 to May 2, 1988. As in 1987, these included ground and aerial observations along the river and detailed water level monitoring in the town. Water Survey of Canada and Indian and Northern Affairs Canada staff again made regular discharge measurements at the Hay River gauging station.

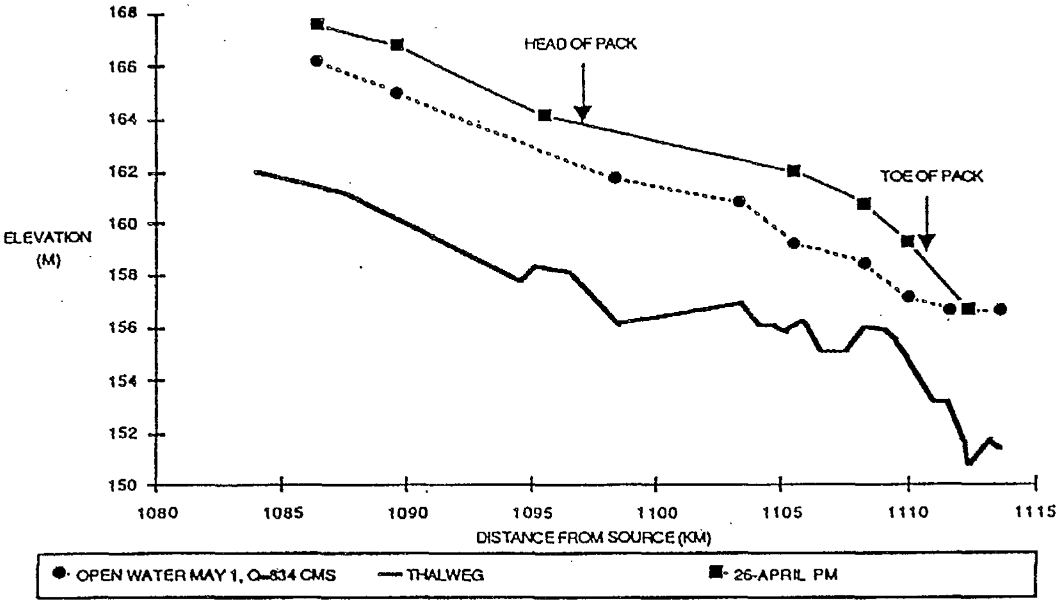


Figure C9. Water level profile along the East Channel, April 26 p.m., 1987.

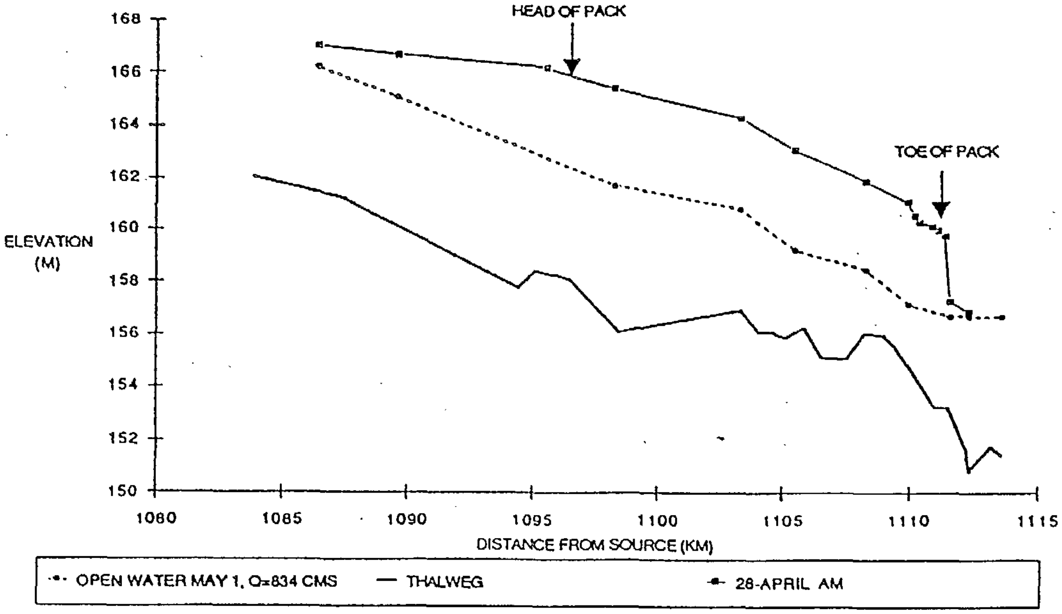


Figure C10. Water level profile along the East Channel, April 28 a.m., 1987.

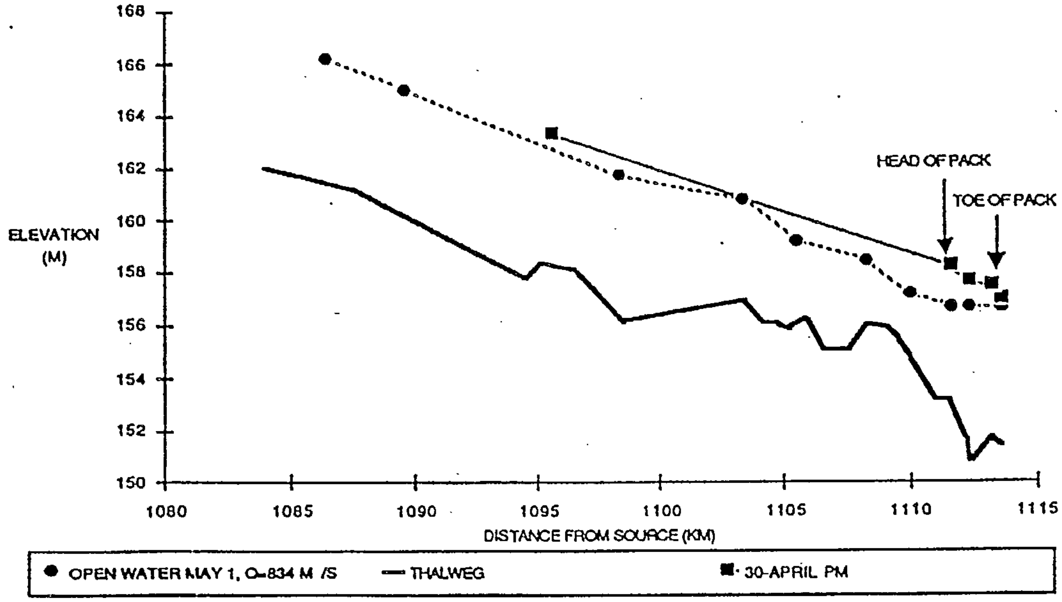


Figure C11. Water level profile along the East Channel, April 30 p.m., 1987

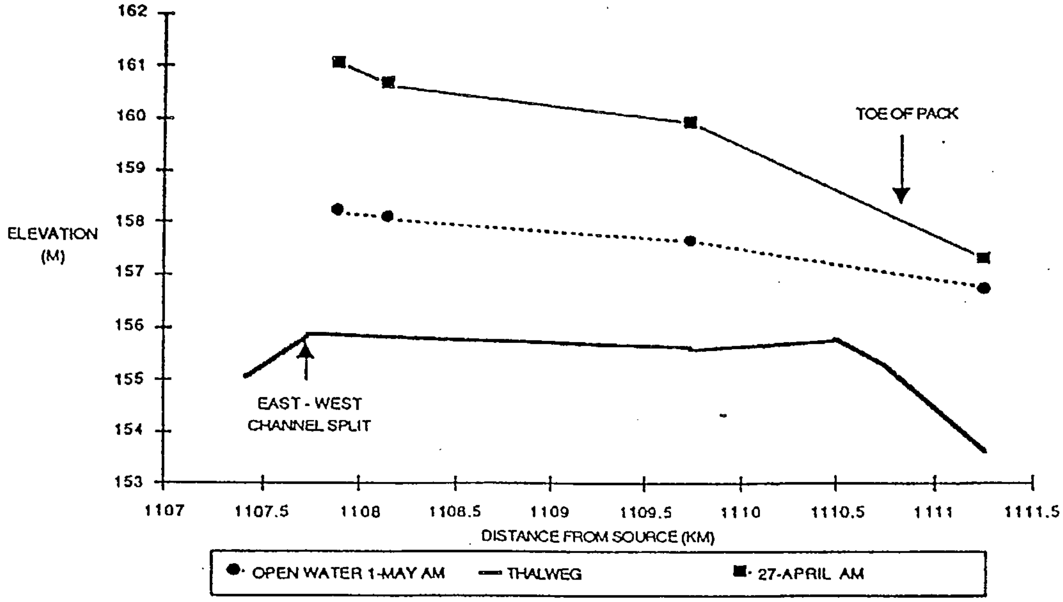


Figure C12. Water level profile along the West Channel, April 27 a.m., 1987

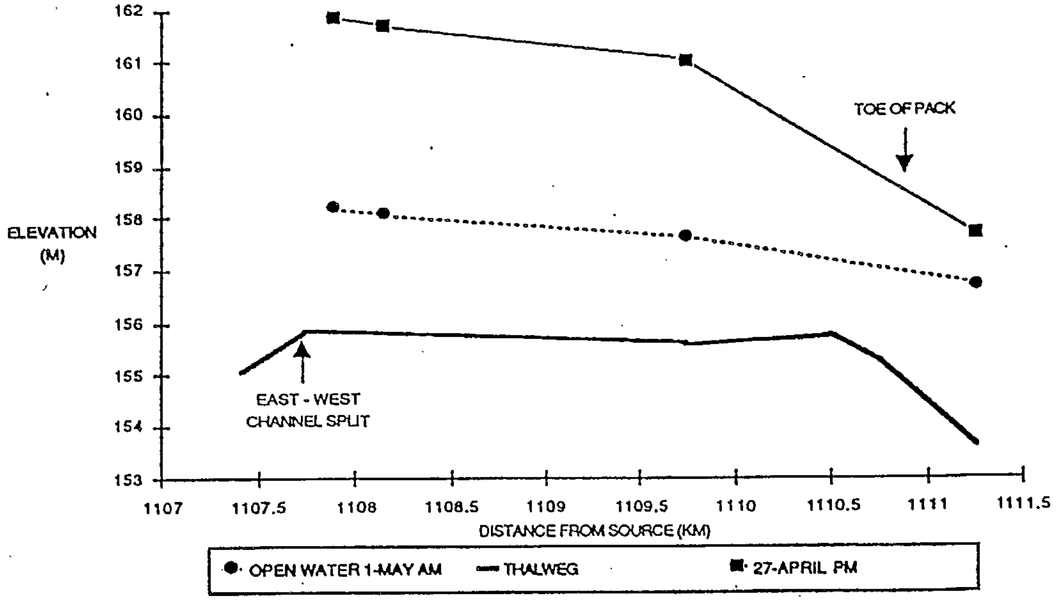


Figure C13. Water level profile along the West Channel, April 27 p.m., 1987

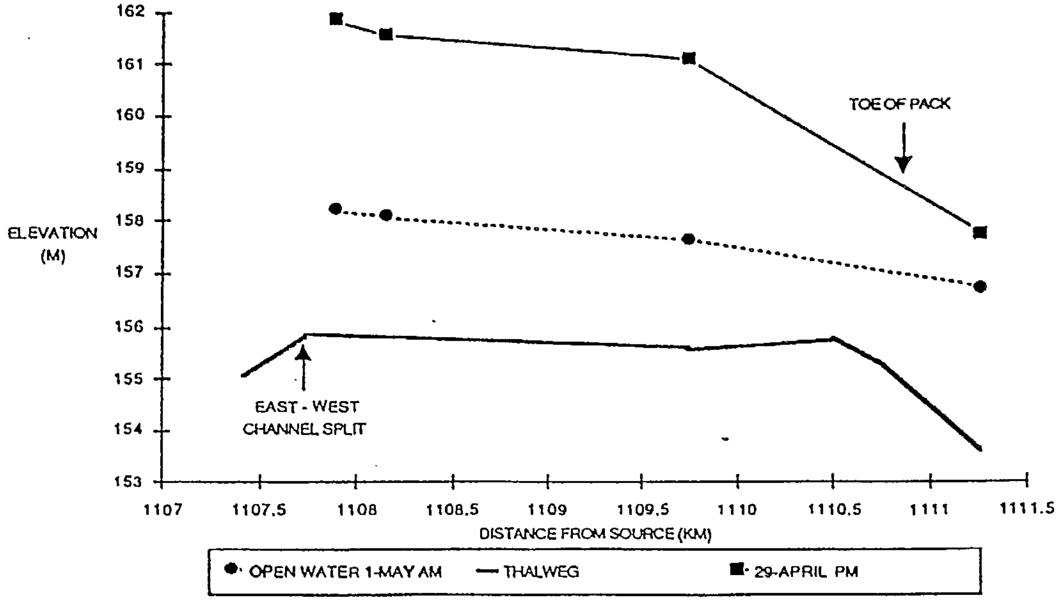


Figure C14. Water level profile along the West Channel, April 29 p.m., 1987

Table C2 Summary of water levels, break-up, 1987

Distance from source (km)	Water elevations April 26 PM GSC (m)	Water elevations April 27 AM GSC (m)	Water elevations April 27 PM GSC (m)	Water elevations April 28 AM GSC (m)	Water elevations April 29 PM GSC (m)	Water elevations April 30 PM GSC (m)	Water elevations May. 1 AM GSC (m)
EAST AND MAIN CHANNELS							
1113.61							156.671
1112.356	156.698			156.877		156.877	156.715
1111.612				157.278		157.278	156.715
1111.428				159.793		159.793	
1111.16				159.99		159.99	
1110.92				160.115		160.115	
1110.46				160.314		160.314	
1110.262				160.56		160.56	
1109.98	159.334			161.078		161.078	157.18
1108.3	160.758			161.92		161.92	158.481
1105.49	161.98			163.087		163.087	159.232
1103.318				164.29		164.29	160.786
1098.264				165.393		165.393	161.745
1095.531	164.201			166.17		166.17	
1089.57	166.833			166.678		166.678	165.08
1086.388	167.617			167.028		167.028	166.22
WEST CHANNEL							
1111.266		157.294	157.692		157.743		156.73
1109.74		159.932	161.052		161.118		157.65
1108.146		160.683	161.729		161.584		158.114
1107.892		161.069	161.868		161.868		158.24

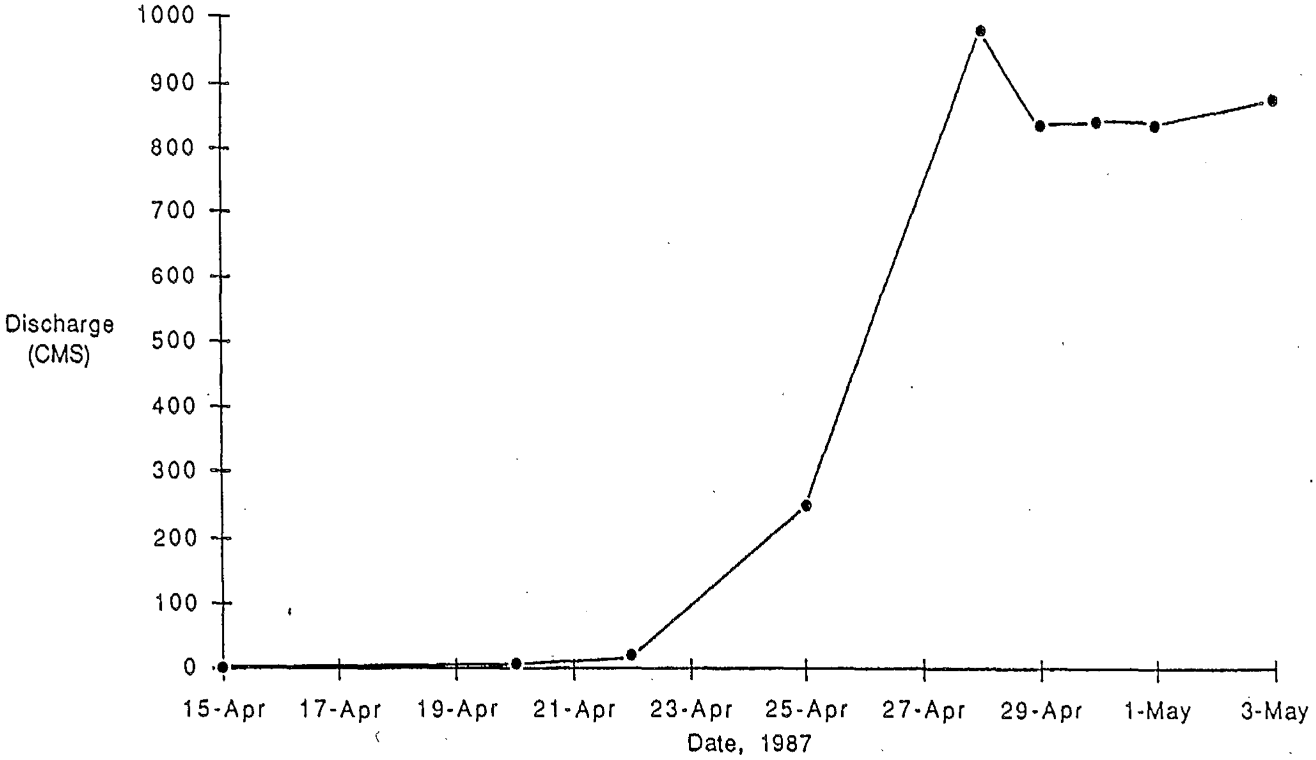


Figure C15. Discharge measurements during break-up, Hay River at Hay River, 1987 (from WSC)

C.5.1 Meteorological antecedents to break-up 1988

The 1987-88 winter was again relatively mild. Figure C16 shows that Hay River only experienced 2570°C days of frost compared to the mean of 3147. High Level had only 2080°C days compared to a mean of 2755.

In Hay River total precipitation from October 1 was a little lower than normal, as shown in Figure C17. High Level experienced somewhat greater than average precipitation, but much of this occurred early in the fall. Snow on the ground on April 1 was a little below normal.

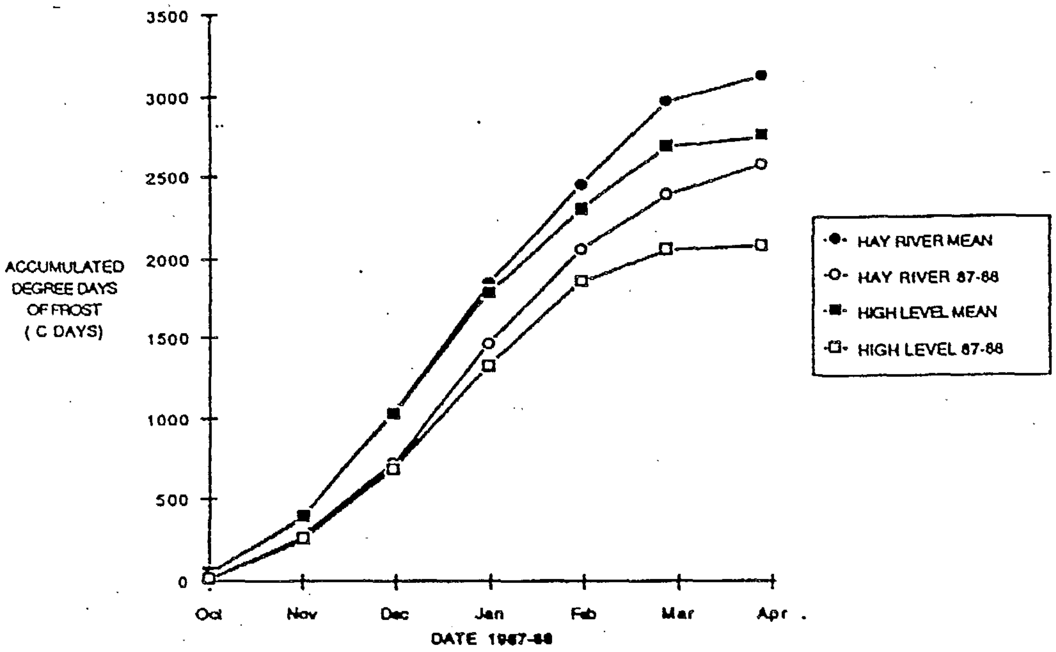


Figure C16 Accumulated degree days of frost for winter 1987-88, Hay River and High Level (from AES data)

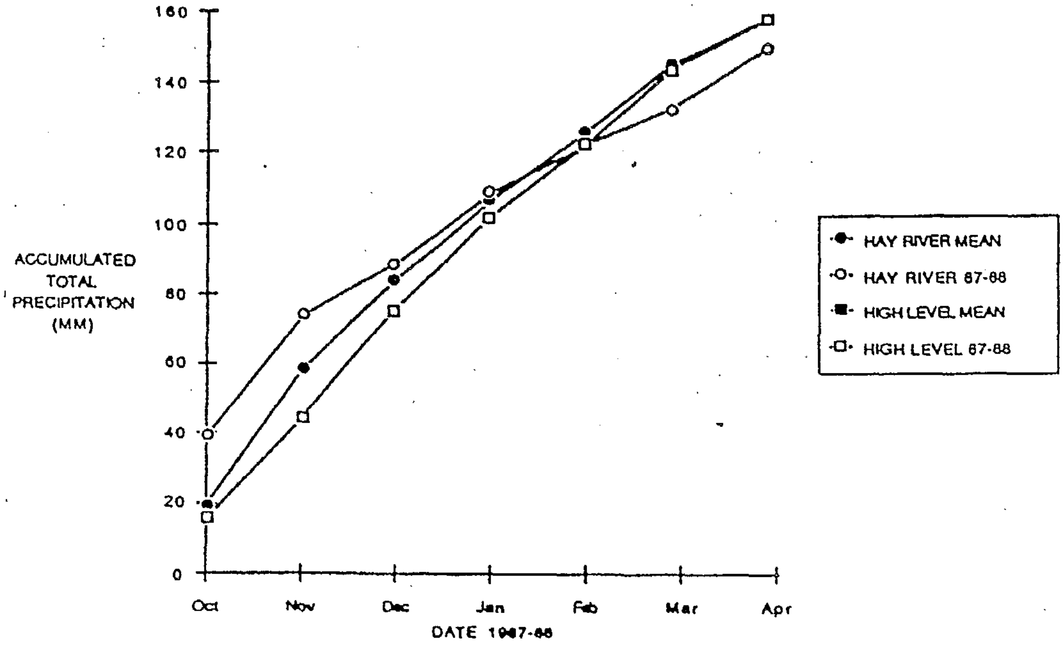


Figure C17 Accumulated snowfall for winter 1987-88, Hay River and High Level (from AES data)

C.5.2 Flood mitigation activities

Prior to break-up considerable work had again been carried out on the river by Town personnel to minimize ice jam flooding. All of this work was done on the West Channel, where snow dykes were again built out onto the lake to constrain the flow in the hope that it would carry the broken ice out into the lake and prevent jamming at the mouth. Figure C18 shows the location of the dykes and also the location of ice bridges that existed just prior to break-up. The snow dykes differed from those in 1987 in that one dyke was carried completely across the east arm of the West Channel.

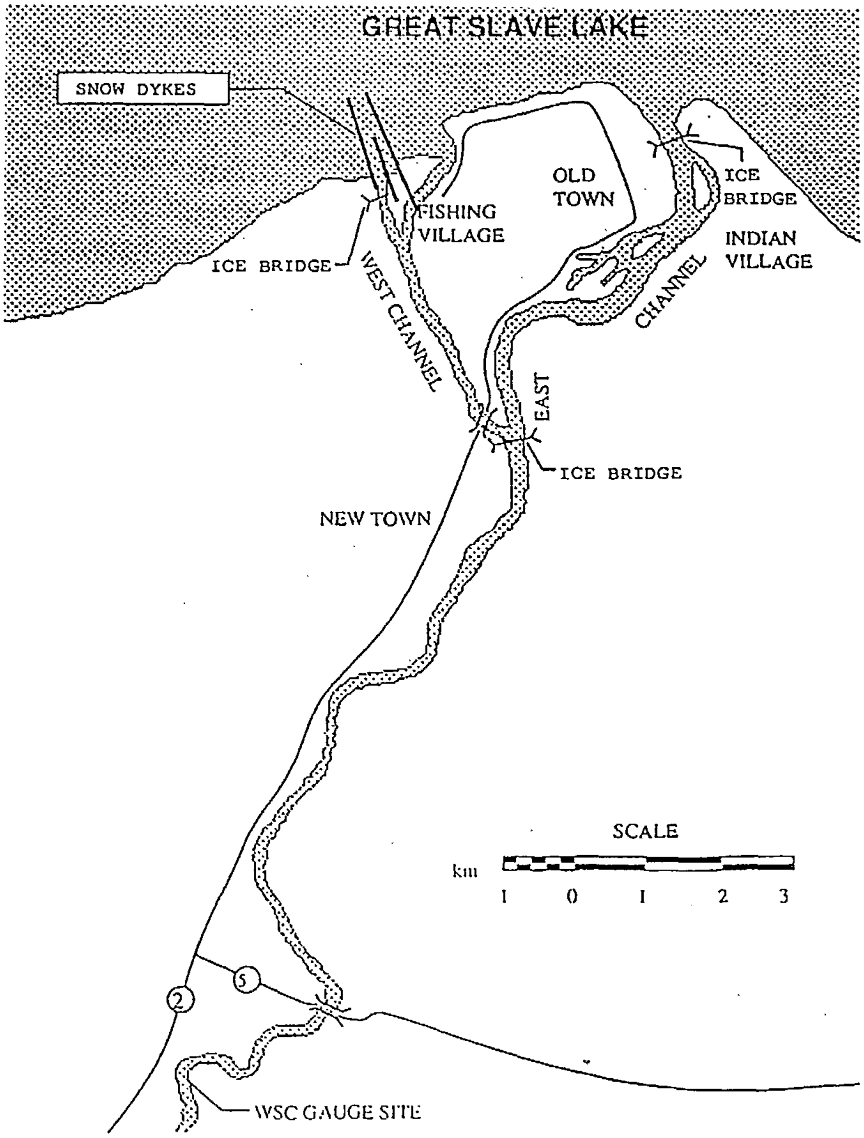


Figure C18 Location of snow dykes and ice bridges in Hay River, spring 1988

C.5.3 General break-up progression 1988

Ice conditions observed throughout break-up in the reach below the falls are summarized in Figure C19. At 15:00 on April 23 the Chinchaga River at the Highway 58 crossing (km 612.48) was open and the water temperature was 2.3°C. At the Highway 35 bridge near Meander River (km 814.73) the river ice was fractured but little movement had taken place. Although increased discharge from spring melt had caused water levels to rise, in Hay River solid ice existed through the Town except in the West Channel. In this channel the increased water level had caused water to flow **over** the bottomfast ice to the lake. The flow depth over the ice at the West Channel bridge was estimated to be 0.5 m.

On April 24 the bottomfast ice in the West Channel began to release from the bed and float to the top. This created a juxtaposed ice accumulation in the West Channel. The river was open between Alexandra and Louise Falls and for about 7 km upstream of Alexandra Falls. Below Louise Falls a small 2.8 km jam was present. Below this jam a solid ice sheet extended to the East Channel mouth. Small open water leads existed at Pine Point bridge (km 1098.26) and at the WSC gauge site (km 1095.50).

During the night of April 24-25 the ice below Louise Falls moved. By 09:30 the river was open for 4.1 km below the falls. An ice jam existed below the open water section, with its head just downstream of Enterprise (km 1041.38). The jam was 14.0 km long with the toe at km 1055.42. Directly below the toe a 400 m lead had developed. There was no change evident in ice conditions below this jam. These conditions remained constant during the day.

By the morning of the 26th the head of the jam had moved downstream 1.3 km so that open water existed from Louise Falls to km 1042.65. The toe of this jam had moved 4.1 km to km 1059.52. There was again an open water lead of about 500 m downstream of the toe. Some movement had occurred overnight in the ice cover downstream of this jam. A short jam 2.2 km had formed with its head at km 1063.02 and its toe at km 1065.27. At km 1066.97, just upstream of Paradise Gardens, there was 1.08 km of open water. Below this a solid ice sheet existed to km 1095.39, near the WSC gauge site, where there was another stretch of open water 2.25 km long. Downstream of this was another short jam 500 m long with its toe against solid ice. This solid ice extended to the lake.

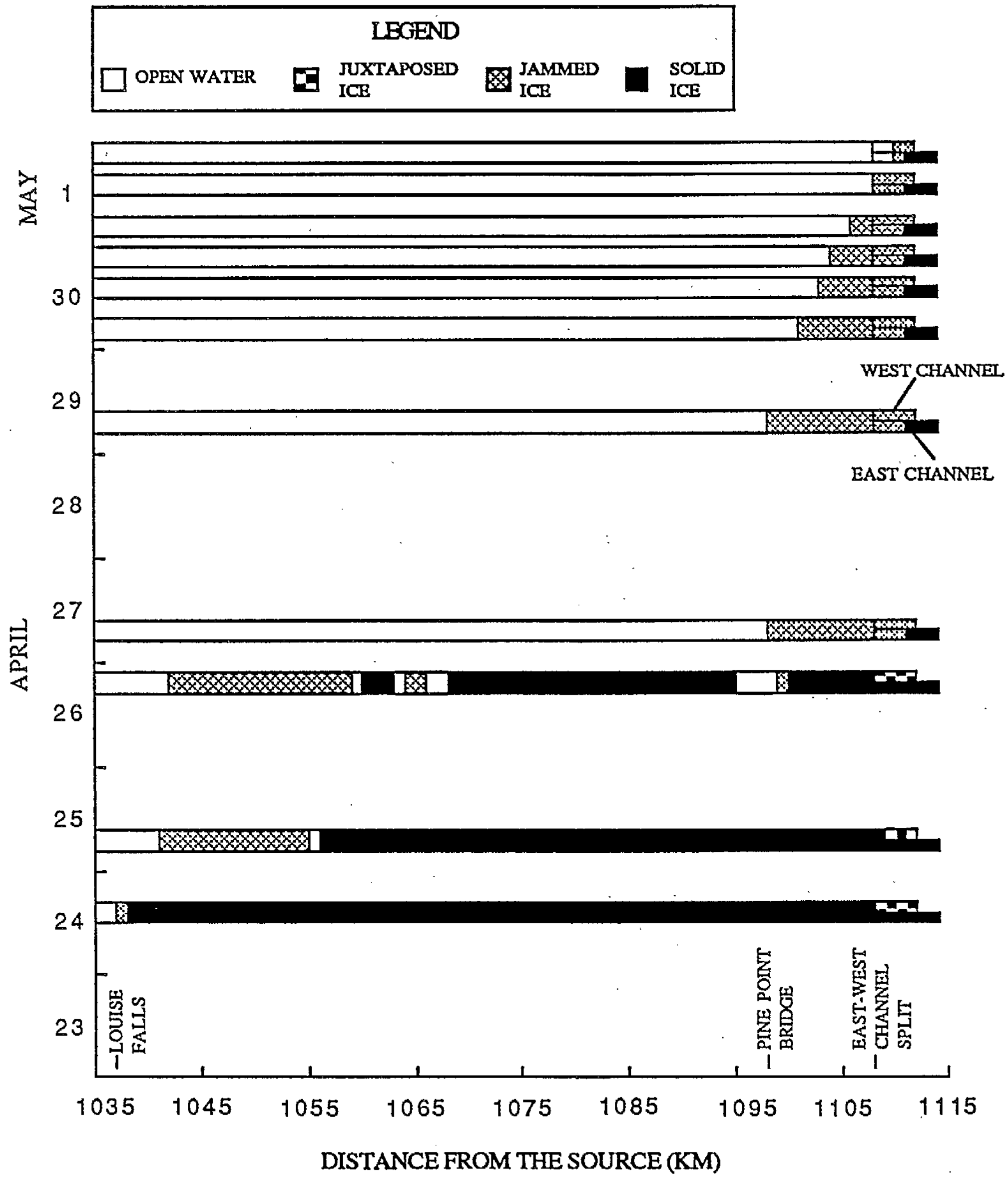


Figure C19 Progression of break-up, Hay River, 1988

A large scale movement began early on the morning of the 27th. Ice in the town began to breakup at 07:00. Ice broke down the East Channel to the upstream end of Island CD (km 1110.9), where the toe of a jam formed. In the West Channel, ice moved through the Rudd Channel and out **into** the lake, with the run breaking through the lake ice along the shore to the west of the mouth for about 2 km. As shown in Figure 21 and Figure C20, at the end of the run ice had fanned out on and through the lake ice for a distance of about 1 km from shore. In the east arm of the West Channel the toe of the ice jam had formed at the mouth of the channel, as shown in Figure 22. The high water for this year at this location occurred due to a momentary surge as the ice run moved into this arm and was stopped at the mouth. The head of the jam was located at km 1098.40, close to Pine Point bridge. Above this jam the river was open all the way to the falls. Because of the early flow down the West Channel and lifting of the bottomfast ice, the snow dykes were breached and seemed to have little influence on events in the West Channel.

There was no change on April 28. Air temperatures decreased such that the mean daily temperature for the 28th was below zero. With the cold temperatures the discharge in the river decreased, causing water levels in the town to fall steadily. Over the night of 28th-29th the head of the jam moved **upstream** to km 1097.6. Although air temperatures were cold in Hay River, they seemed to be the result of cold north winds off the lake because in the upper catchment air temperatures remained above zero. This caused water temperatures to increase a little from 0.0°C to 0.3°C at the head of the jam by 0900 on the 29th. This was followed by a relatively rapid increase over the next 29 hours to 2.8°C at 1350 on the 30th, after which it levelled off. Due to melt caused by the above-zero water temperatures, the head began to move downstream during the 29th and by 22:00 the head was at km 1098.46. At 07:30 on April 30th the head was still at km 1098.46, but by 22:00 it was at km 1104.46.

The jam continued to melt over night and by the morning of May 1 the head was below the East-West Channel split. The toes had still not moved in either channel, but a large open water lead about 700 m long and 150 m wide had formed in front of the toe in the East Channel. At 22:45 the toe in the East Channel moved, filling this open water lead. It stopped at the solid ice at the front of the lead. By this time, with the warm water continuing to melt

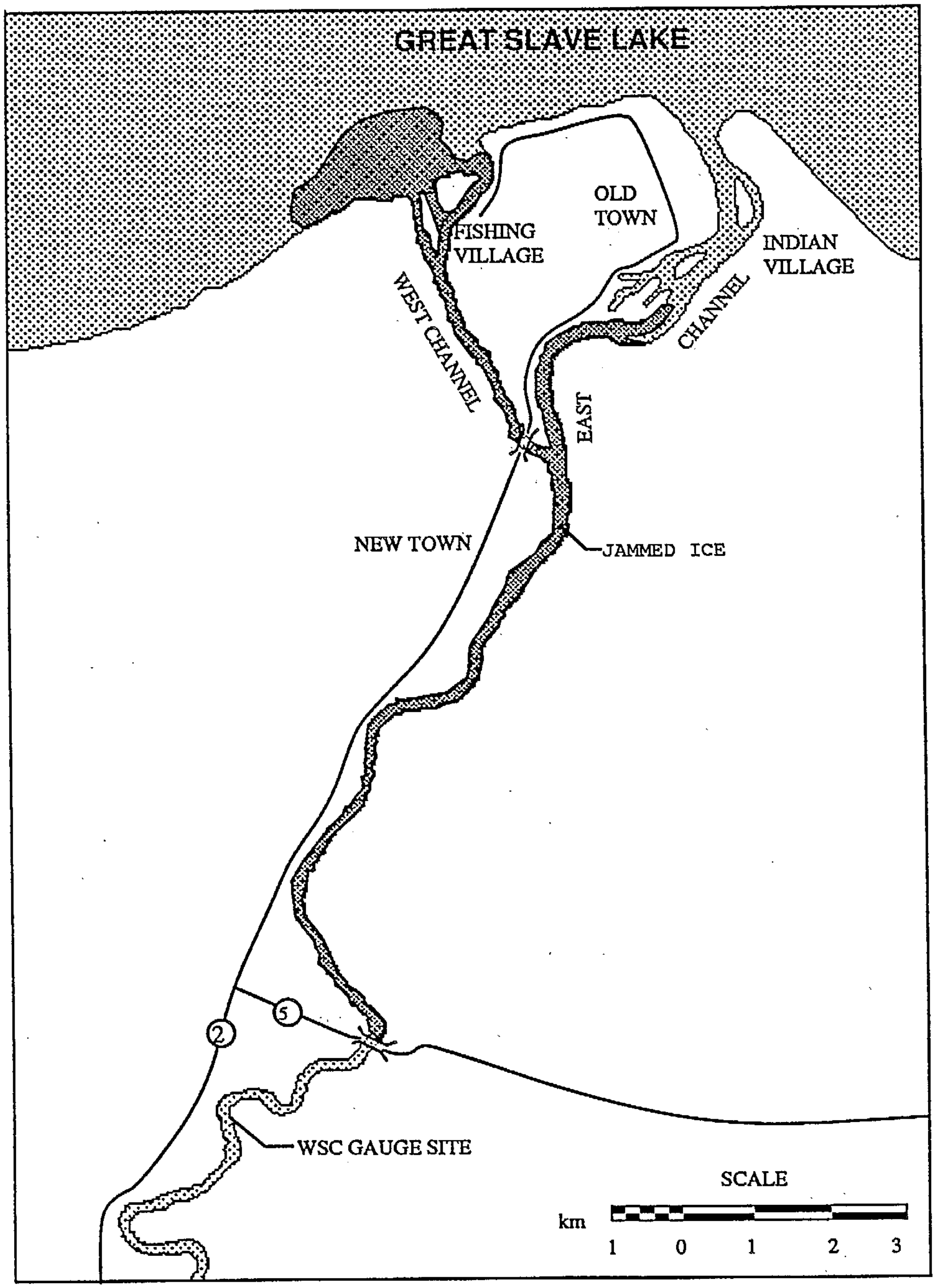


Figure C20 Location of ice jams, Hay River, April 27, 1988 the ice, the ice jam in the East Channel was less than 500 m long.

By the morning of May 2 the ice jam in the East Channel was almost completely melted, with just a solid ice cover from the downstream end of Island CD to the lake. In the West Channel there was still a short jam in the Rudd Channel and east arm.

The discharge variation over the break-up period is plotted in Figure C21. Again each point represents an actual discharge measurement by Water Survey of Canada staff. The normal rapid rise in the hydrograph is evident. The peak discharge, 750 m^3/s, was reached late on April 27. Discharges may have risen higher than this had air temperatures remained warm, with a significantly greater chance of flooding. As it was, daily mean temperatures dropped to just above 0°C from the 27th to May 1.

Water levels along the delta channels were again surveyed and are shown in Figure C22 and tabulated in Table C3.

C.5.4. Water temperature measurements

During the 1987 break-up the behaviour of the pack, and the few spot water temperature measurements taken, indicated the important role that pack melting may play in the ice jam regime of Hay River. Plans were therefore made to carry out much more extensive and elaborate temperature measurements as part of the 1988 break-up observations, with the aim of ultimately being able to derive a runoff thermograph for the catchment.

Accordingly, considerable effort was expended in adapting and calibrating digital data aquisition packages and temperature probes that had been used for river temperature measurements in a previous cooperative research effort with the Alberta Research Council. These probes were placed in the water at the Water Survey of Canada stations on the Chinchaga River, Steen River and Hay River and on the Hay River, just upstream of Alexandra Falls, at the start of the break-up period. When monitored during break-up the packages appeared to be operating satisfactorily, but when interrogated by computer after the field program, the data displayed was erratic and illogical and had to be discarded. However, some spot temperature measurements were taken using a digital thermocouple thermometer. These are given in Table C4.

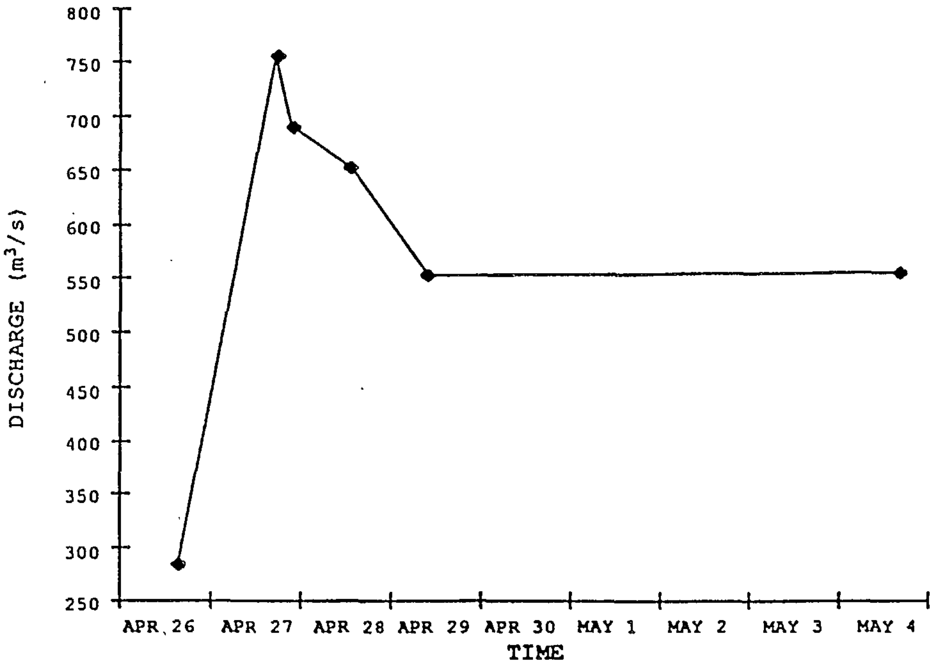


Figure C21 Discharge measurements during break-up, Hay River at Hay River, 1988 (from WSC)

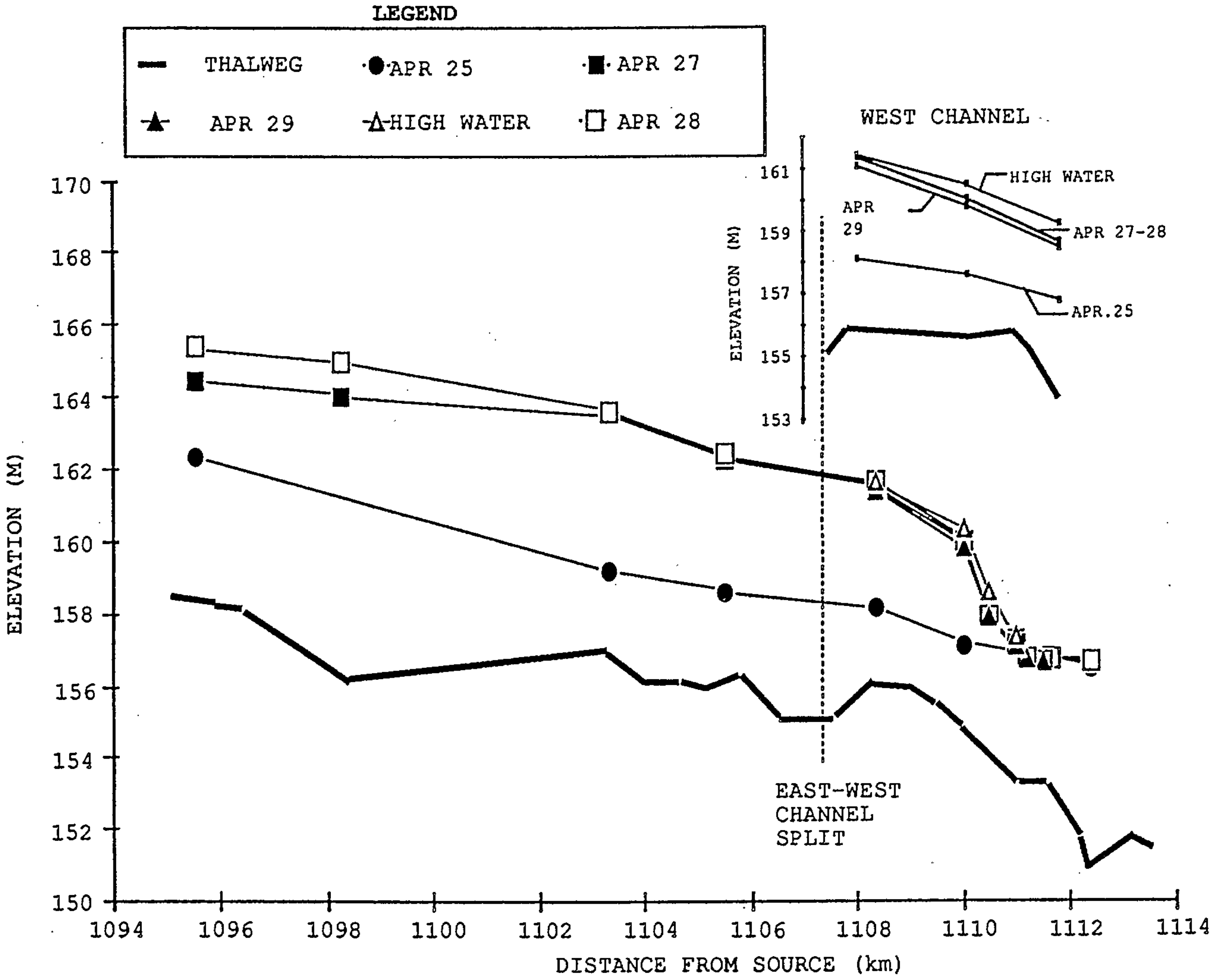


Figure C22 Break-up water level profiles, Hay River, 1988

Table C3 Summary of water levels, break-up, 1988

Distance from source (km)	Water elevations April 25. GSC (m)	Water elevations April 27. GSC (m)	Water elevations April 28. GSC (m)	Water elevations April 29. GSC (m)	Water elevations High Water GSC (m)
WATER LEVELS VIA EAST CHANNEL					
1112.36	156.55	156.68	156.73		
1111.61			156.76		
1111.43		156.79		156.73	
1111.16		156.83		156.78	
1110.92		157.3		157.12	157.36
1110.46		157.82		157.9	158.61
1109.98	157.18	160.02	160.05	159.83	160.38
1108.3	158.18	161.56	161.67	161.43	161.68
1105.49	158.67	162.34	162.44		
1103.318	159.22	163.53	163.64		
1098.26	162.38	164.08	165.01		
1095.53	162.38	164.47	165.42		
WATER LEVELS WEST CHANNEL					
1111.27	156.78	158.66	158.62	158.46	159.24
1109.74	157.61	160.05	160.01	159.79	160.48
1107.89	158.14	161.36	161.35	161.08	161.43

Table C4. Water temperature measurements during break-up, 1988.

WSC gauge site

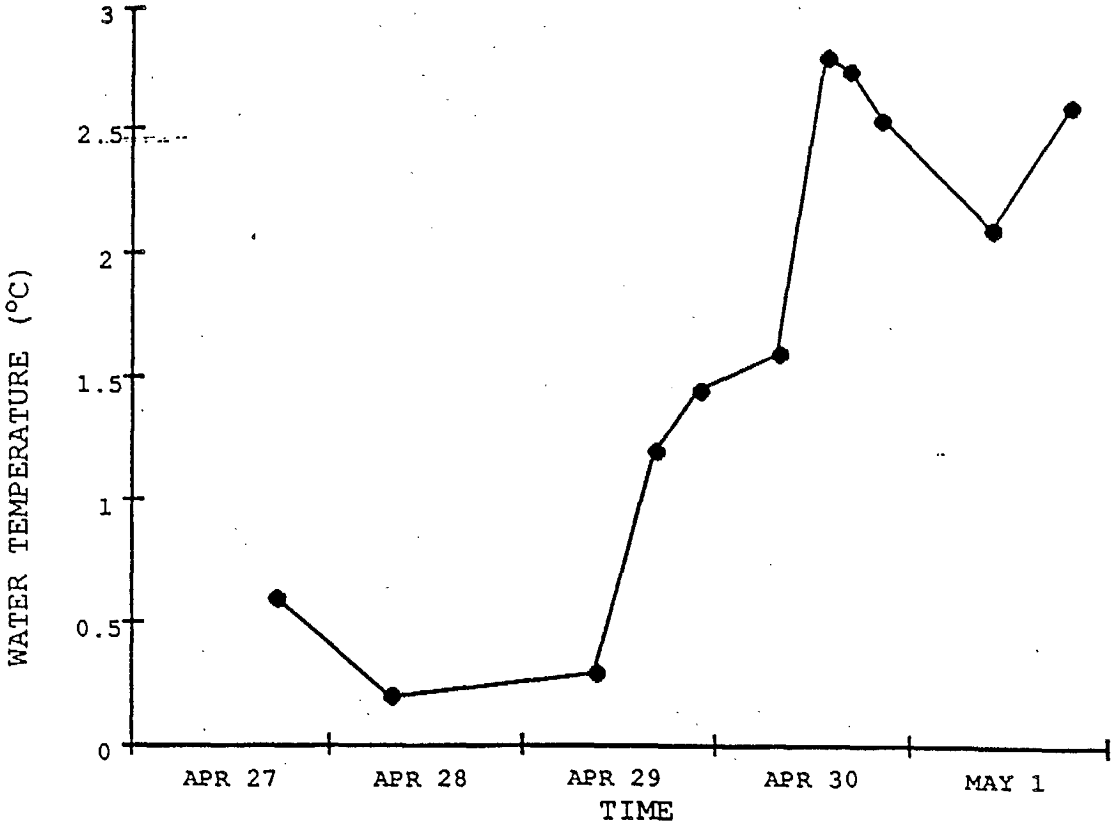
Date	Temperature (degree C)
4/27 17:40	0.6
4/28 7:50	0.2
4/29 9:00	0.3
4/29 16:40	1.2
4/29 22:10	1.45
4/30 7:45	1.6
4/30 13:50	2.8
4/30 16:30	2.75
4/30 20:30	2.55
5/1 10:00	2.1
5/1 19:30	2.6

Alexandra Falls

Date	Temperature (degree C)
4/26 11:00	1.1
4/28 11:35	0.5
4/29 17:20	2.55
4/30 15:50	3.2

Toe of Jam East Channel

Date	Temperature (degree C)
5/1 10:50	0.3
5/1 17:00	0.55



Water temperatures at WSC gauge, Hay River break-up, 1988

APPENDIX D

A DISTANCE DATUM FOR THE HAY RIVER

APPENDIX D

A DISTANCE DATUM FOR THE HAY RIVER

To provide a means of referring to locations along the Hay River directly and unambiguously and to assist in preparing a longitudinal profile of the river, the distances to various salient features along the river from the river source was determined by digitizing the plan configuration of the Hay River from 1:50,000 NTS maps.

The digitizer used was an Intergraph Graphics Workstation, linked to a Digital Equipment Corporation VAX 11/730 with 400 Mbytes of disk storage, operated by the Department of Geography at the University of Alberta.

Table D1 is a list of features and their distance from the source, which was taken as UTM 311280/6379670. Although this source lies on the Chinchaga watershed it was chosen because it is at the greatest river distance from the mouth at Great Slave Lake - a distance of 1114.24 km.

Table D1. Distance from the source to various features along the Hay River.

Feature	Distance from Source (km)
Mouth of Great Slave Lake (via East Channel)	1114.24
East-West Channel split	1107.92
Pine Point Bridge	1098.26
Louise Falls	1037.12
Alexandra Falls	1034.95
Grumbler Rapids	988.02
N.W.T. - Alberta Border	945.17
Indian Cabins	920.63
James Creek	911.78
Steen River Settlement	888.48
Dizzy Creek	887.47
Steen River	880.72
Little Rapids Creek	862.19
Lutose Creek	855.24
Roe River	828.52
Slavey Creek	824.96
Melvin River	822.84
Highway 35 Bridge Crossing near Meander River	814.73
Adair Creek	803.84
Meander River	799.10
Henderson Creek	781.07
Negus Creek	716.33
Hay and Chinchaga River Confluence	709.33
Highway 58 Bridge Crossing	612.48
Faria Creek	514.68
Haro River	426.96
Waniandy Creek	363.78
Tanghe Creek	102.65
Lennard Creek	96.41
Source at UTM 311280/6379670	0.00

APPENDIX E

GEODETIC BENCHMARKS IN HAY RIVER

APPENDIX E

GEODETIC BENCHMARKS IN HAY RIVER

In northern areas the reliability of geodetic benchmarks must be considered. Because of soil conditions, particularly permafrost, movement in benchmarks can occur regularly. The geodetic bench marks used in the field surveys were those judged to be reliable on the basis of Underhill and Underhill (1983) and conversations with the staff in Hay River.

In total five bench marks were chosen and all survey work was tied into at least two of these bench marks. A description and elevation for each of these bench marks, taken from Geodetic Survey of Canada, Vertical Control Data, Quad. No. 60115, February, 1985 revision, is as follows.

82T109..170.024 m

Lat. 60-47.2 Long. 115-49.3

Northwest Land Forest Service, tablet in north concrete foundation of kitchen quarters, about 100 m southeast of highway, 67 cm from east edge, 36 cm below wood siding.

67T019..167.728 m

Lat. 60-48.6 Long. 115-47.3

Post Office, Hay River, tablet in west concrete foundation, 1.8 m from southwest corner, 24 cm below siding.

67T022..168.017 m

Lat. 60-49.4 Long. 115-46.7

Steel truss bridge over West Channel, 2.5 km north of Post Office, tablet in top of north end of curve at northwest corner of bridge, 78 cm south of north end of steel railing, 21 cm east of west edge, 18 cm above deck level.

82T114..159.369 m

Lat. 60-51.6 Long. 115-44.2

N.T.C.L. Marine Maintenance Building and Syncrolift, 1.6 km north of Hay River Hotel, tablet in north concrete foundation, 108 m from east corner, 1.30 m below aluminum siding.

82T043..197.376 m

Lat. 60-40.5 Long. 115-58.3

Deep bench mark in manhole along Highway No. 2, 14.1 km southwest of junction with Highway No. 5, 122 m northeast of centre line of road to sawmill Patterson Enterprise, 23.0 m southeast of centre line of highway, 5.0 m south of power pole No. 26, 1 m below highway level.

The latter benchmark was used to tie in the temporary benchmark used during break-up observations at Patterson Sawmill. It was a nail in a poplar tree on the left bank, 8 m north of the road at the river. Its elevation was determined to be 170.737 m.

APPENDIX F

FIELD SURVEY OF THE DELTA CHANNELS AND NEARSHORE BATHYMETRY

APPENDIX F

FIELD SURVEY OF THE DELTA CHANNELS AND NEARSHORE BATHYMETRY

F.1 Introduction

For the analysis of flooding in Hay River it was necessary to know the hydraulic geometry of the delta region. This was documented during summer field work from July 6 to July 22, 1987. Included in this work was hydrographic surveys of the delta channels and the nearshore lake bathymetry at the delta; and surveys to tie into Geodetic Survey of Canada (GSC) datum the temporary benchmarks used during the break-up observations. (Problems existed with some GSC bench marks because of the unstable soil in the area. On the basis of a 1983 report on the reliability of bench marks in the area by Underhill and Underhill (1983) and conversations with the staff, six GSC benchmarks were selected for use. These benchmarks are listed in Appendix E.)

F.2 Cross-Sections

Channel cross-sections were surveyed over a reach extending from just upstream of the Water Survey of Canada gauge site to the mouths of both the West and East Channels, as shown in Figure F.1. The cross-section locations were chosen to give good representation of the channel geometry. A temporary bench mark was established at each cross-section and tied into GSC datum.

The cross-sections were surveyed using a 14 foot Lund aluminum boat powered by a 35 HP Johnston outboard motor, fitted with a jet leg to allow use in shallow water. Water depths were measured using a Ratheon DE-719B Fathometer, with the transducer mounted on the side of the boat. Distance across the channel was measured with a 'Topofil'. Bank profiles were surveyed using the standard rod and level technique. At each cross section an estimate of the bed material was made where possible, and the type and height of vegetation on the banks noted. Details of the surveyed cross-sections are given in Figures F.2-33.

Profiles of the delta channel thalwegs were also sounded and used to develop the thalweg profiles shown in Figure 11.

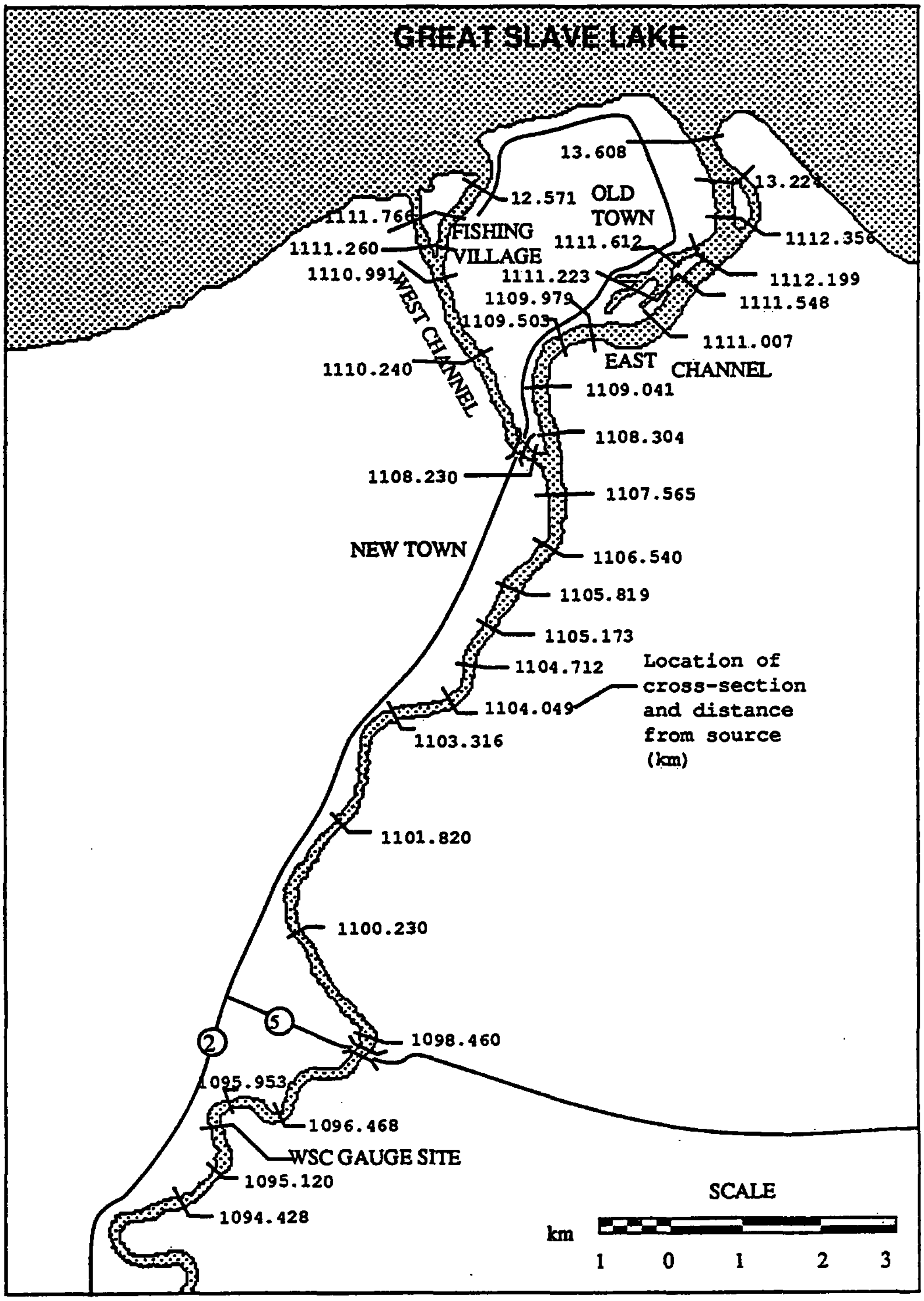
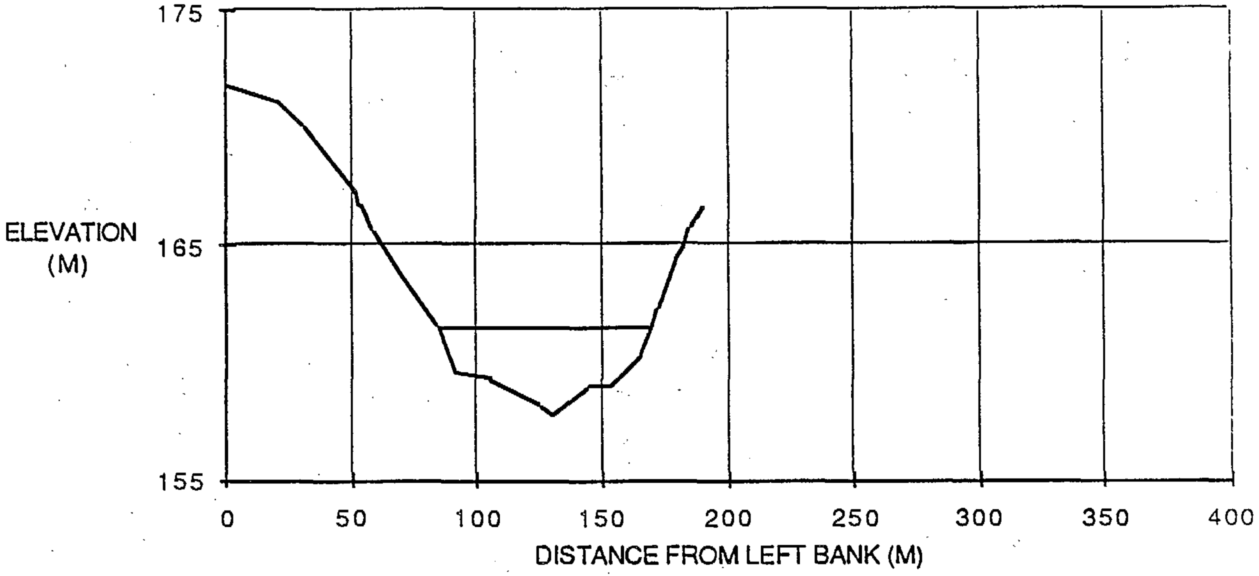


Figure F.1 Locations of cross-sections surveyed in summer 1987.

F.3 Nearshore lake bathymetry

To analyze flow from the river into the lake, and to understand the nearshore ice regime, information was needed on the lake bathymetry in the region of the two channel outlets. These areas were surveyed with the same sounding equipment used in the river survey. Perpendicular lines were run from shore out to a depth of about 5 m, with the boat being kept on line through use of a transit on shore and two-way radio communication. Generally this required a line over one kilometre long. Distance from shore was determined with the 'Topofil'. Lines were also surveyed parallel to shore, with the boat position again being tracked by transit.

The bathymetry of the area surveyed is shown in Figure 13. It can be seen that a bar was found to exist off shore, varying from about 750 m off shore directly in front of the West Channel to less than 500 m near the East Channel. This bar is also evident in airphotos of the area.



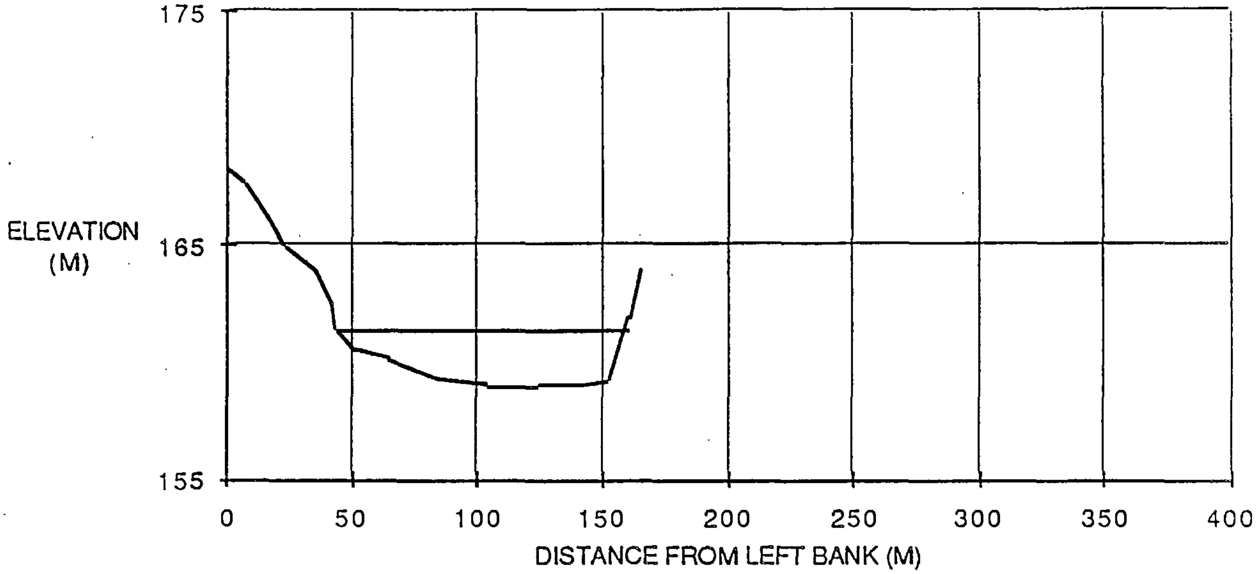
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	171.9
20	171.2
30.5	170.12
51	167.29
53	166.71
58.3	165.65
69	163.9
84.5	161.5
91	159.54
105	159.24
125	158.13
130	157.78
145	158.94
153	159.04
165	160.36
169.5	161.5
172.5	162.39
179	164.34
182.6	164.91
185	165.8
190	166.69

CROSS SECTION KM 1094.43

DESCRIPTION: This cross section is 1.1 km U/S of the Water Survey gauge site. The left bank is covered by poplar up to 51 m, after which the cover is willows to the water level. The right bank is grassed from the water level to 185 m, beyond which the trees start. The bed material had a D_{50} of 130 mm. Water level on the day of survey, July 18, 1987, was 161.50 m.

TBM: Spike in tree, top of left bank, 0.0 m on the cross section. Elevation 172.50 m.

Figure F.2 Cross-section km 1094.43



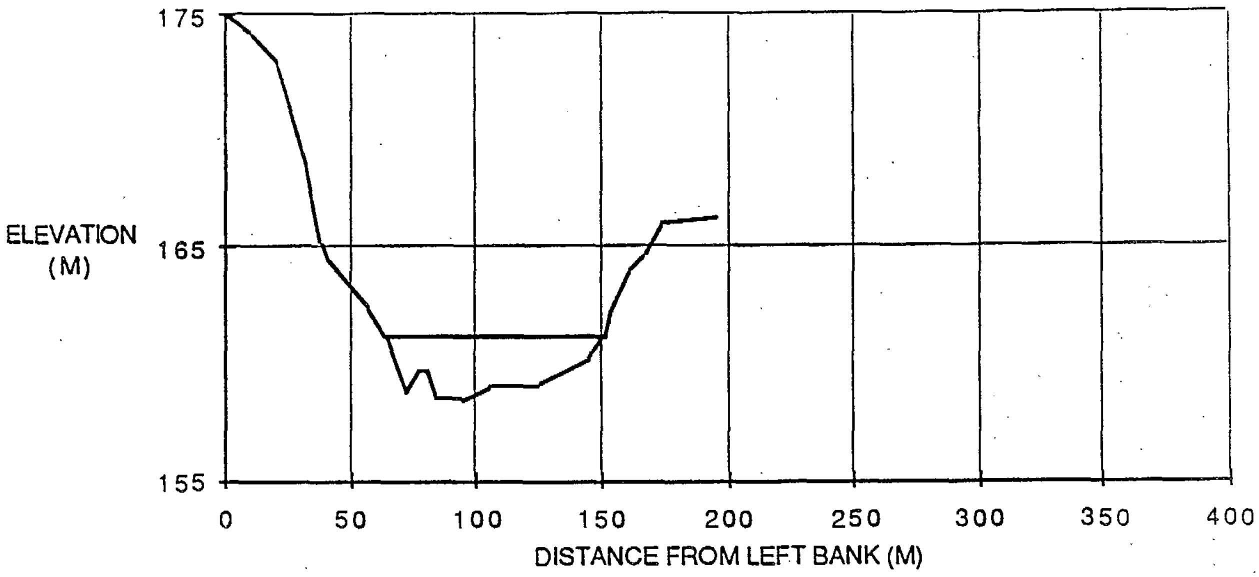
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	168.25
7	167.63
17	166.01
23	164.92
35	163.89
42	162.41
44	161.33
51	160.52
64	160.11
84	159.29
104	158.99
124	159.09
144	159.1
152	159.3
160	161.96
160.5	161.96
165	164.08

CROSS SECTION KM 1095.12

DESCRIPTION: This cross section is just U/S from the WSC gauge site. The left bank is treed to 23 m and from there willows extend to 37 m, with grass beyond to the water level. The right bank is grassed from the water level to 167 m, beyond which it is treed. The bed material has a D_{50} of 130 mm and the water level on the day of survey, July 18, 1987, was 161.33 m.

TBM: Spike in tree top of left bank, at 5 m on the cross section. Elevation 168.588 m.

Figure F.3 Cross section km 1095.12



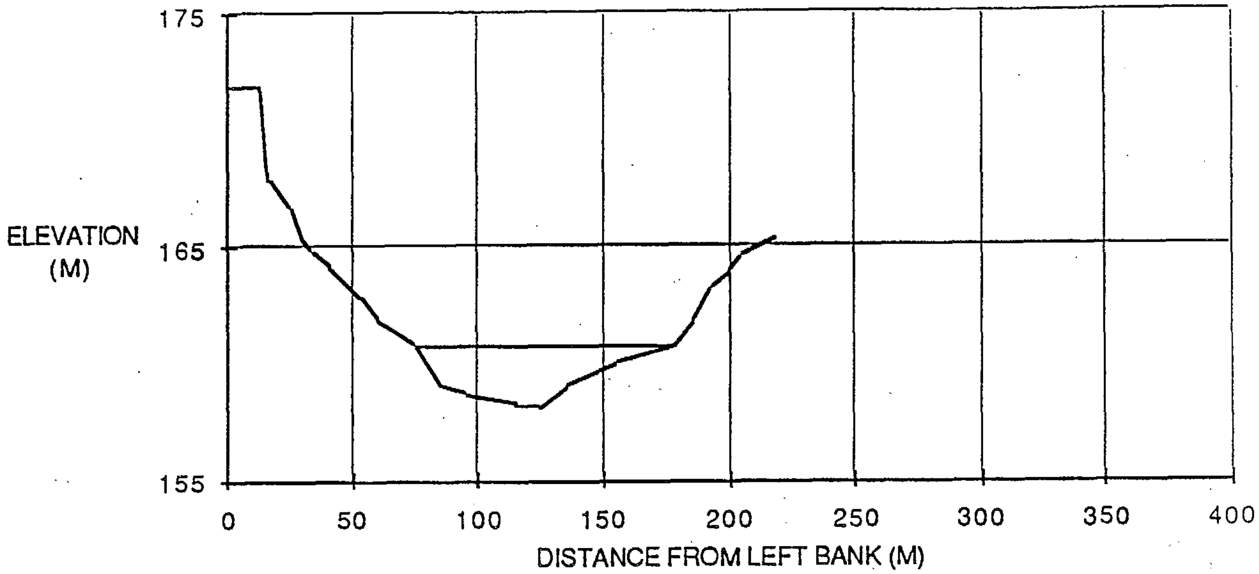
DISTANCE FROM LEFT BANK (M)	ELEVATION (M).
0	175
10	174.14
20	172.96
32	168.41
38	165.19
40.5	164.45
57	162.38
64.2	161.22
72	158.78
78	159.79
80	159.8
84	158.58
94	158.47
105	159.08
125	159.19
145	160.3
150,8	161.22
153	162.27
161	164.04
167	164.71
174	166.01
196	166.25

CROSS SECTION KM 1095.95

DESCRIPTION: This cross section is 450 m D/S of the Water Survey gauge. The left bank is treed to 33 m after which it is gravel to the water level. The right bank is grassed from the water level to 160 m, at which point the trees begin. The bed material has a D_{50} of 125 mm with some stones having a diameter up to 400 mm. Water level on the day of survey, July 18, 1987, was 161.22 m.

TBM: Spike in tree on the left bank at 35 m on cross section. Elevation - 168.564 m.

Figure F.4 Cross section km 1095.95



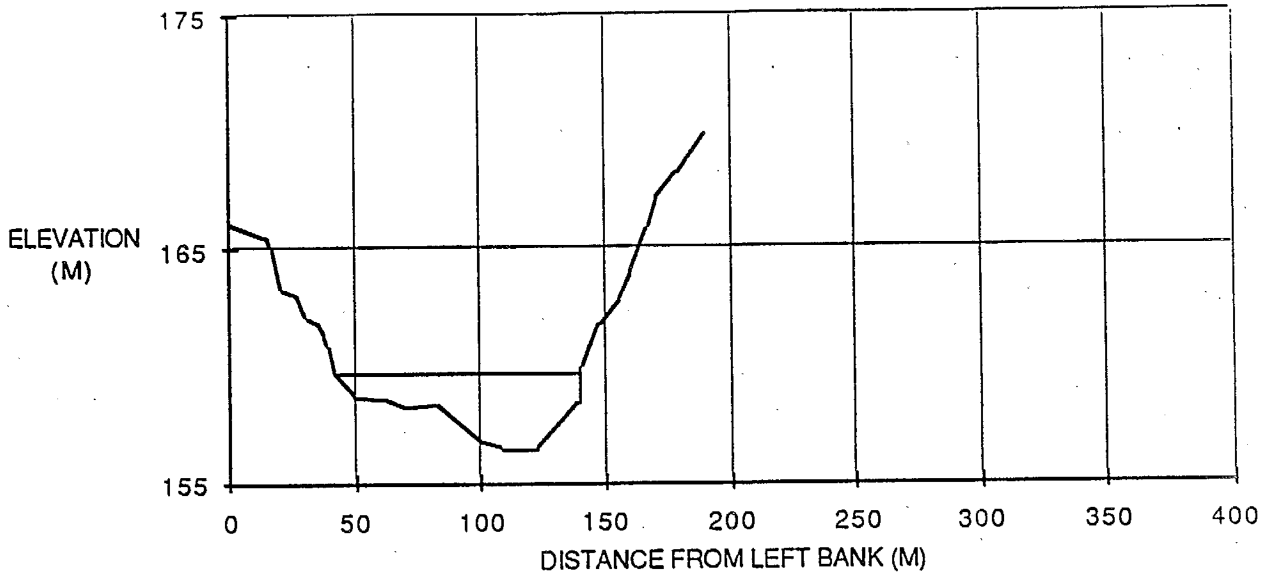
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	171.83
13	171.86
17	167.81
25.5	166.61
30	165.33
34	164.78
41	164.18
53	162.9
60	161.95
75	160.84
85	159.06
95	158.66
115	158.25
124	158.15
135	159.06
145	159.57
155	160.07
178	160.84
186	161.935
193	163.38
200	164.03
205	164.7
218	165.4

CROSS SECTION KM 1096.47

DESCRIPTION: This cross section is 1 km D/S of the Water Survey gauge. The left bank is covered with poplar up to 35 m. From 35 m to the water level the bank is gravel with no vegetation. The right bank consists of a gravel surface from the water to 190 m where willows start, with the trees starting at 200 m. The bed material had a D_{50} of 125 - 175 mm. The water level on the day of survey, July 18, 1987, 160.84.

TBM: Hub in ground on left bank at 60 m on cross section. Elevation - 162.006 m.

Figure F.5 Cross section km 1096.47



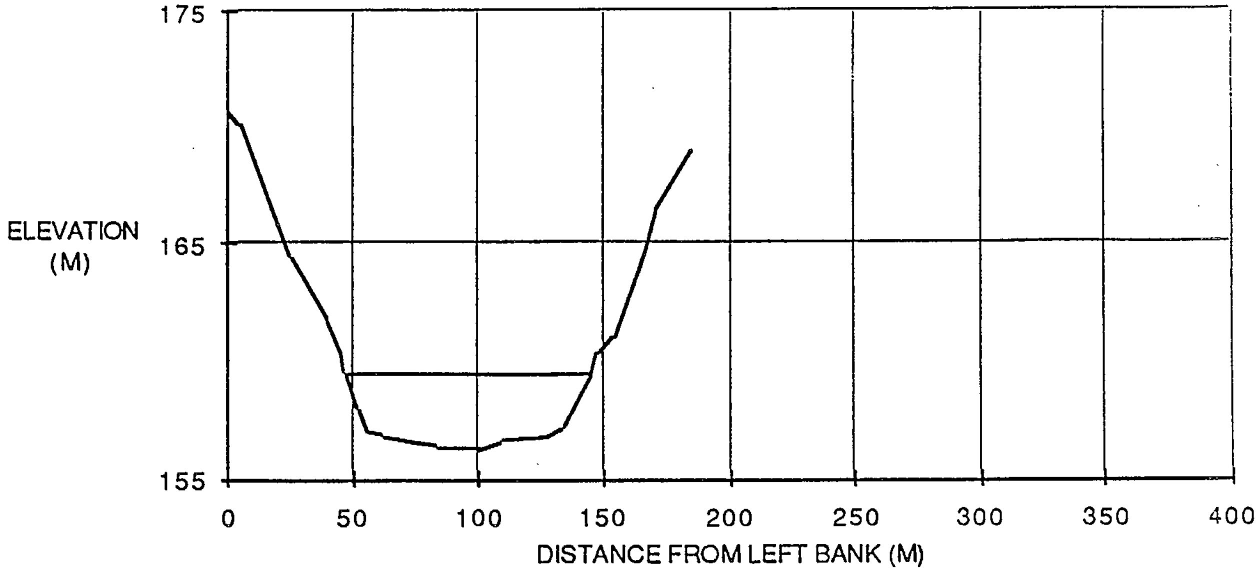
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	166.091
15	165.48
17	165.09
21	163.3
26.5	162.97
30.4	162.07
35	161.739
37.6	161.2
39	160.82
41.5	159.69
49	158.68
62	158.57
70	158.17
82	158.37
100	156.74
108	156.44
122	156.54
139	158.47
139.2	159.69
140	160
147.5	161.84
155	162.94
160	164.056
167	165.96
171	167.12
179	168.23
190	169.96

CROSS SECTION KM 1098.46

DESCRIPTION: This cross section is located 200 m D/S of Pine Point bridge. The left bank is treed with poplar from 0.0 m to 15 m; from there to 30 m the bank is covered with willows after which it is grassed to the water level. The right bank is grassed from the water level to 150 m where small poplars begin and at 180 m large spruce start. The bed material had a D_{50} of 100 mm to 120 mm. On the day of survey, July 18 ,1987, the water level was 159.69 m.

TBM: Spike in tree, top of left bank, directly D/S of Pine Point bridge, 180 m U/S of cross section. Elevation - 167.980 m.

Figure F.6 Cross section km 1098.46



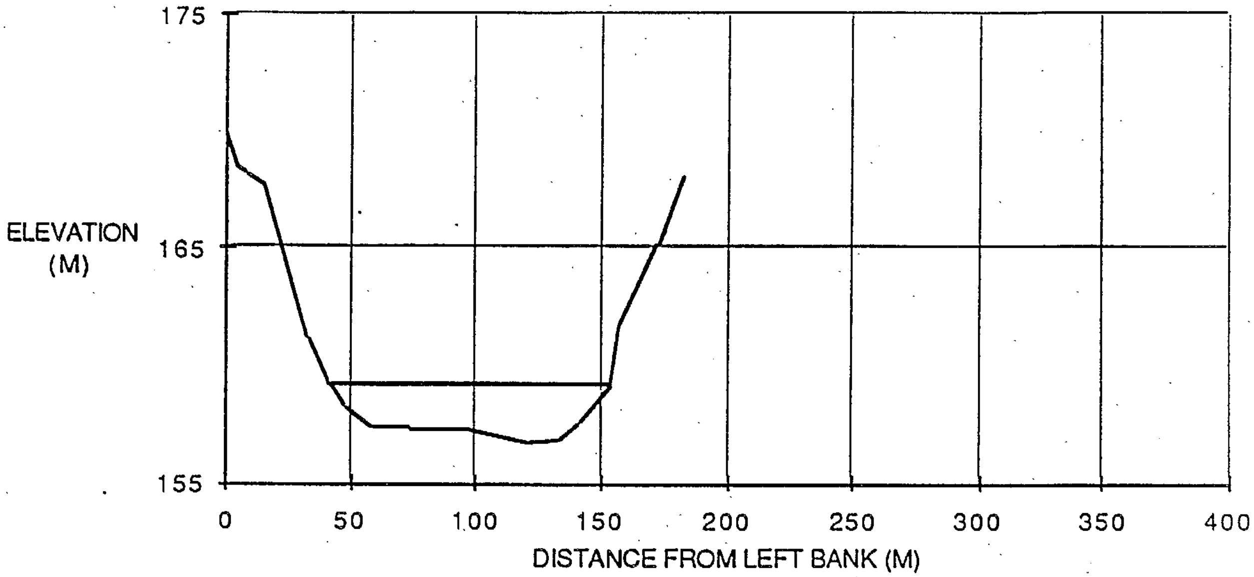
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	170.7
5	170.1
25	164.4
39	161.71
45	160.29
47	159.41
52	157.9
56	156.93
62	156.71
74	156.48
83	156.3
100	156.19
109	156.63
127	156.78
134	157.2
145	159.41
148	160.31
154	161
166	164.65
171	166.51
186	169

CROSS SECTION KM 1100.23

DESCRIPTION: This cross section is 2 km D/S of the Pine Point Bridge. The left bank is treed to 5 m from which point the bank is covered by tall grass until 25 m. Beyond this little vegetation exists on the bank to the water level. The right bank has little vegetation from the water level to 154 m where grass begins. Tree growth starts at 170 m. The bed material has a D_{50} of 100 mm and the water level on the day of survey, July 10, 1987, was 159.41 m.

TBM: Hub in ground on left bank at 23 m on cross section. Elevation - 164.984 m.

Figure F.7 Cross section km 1100.23



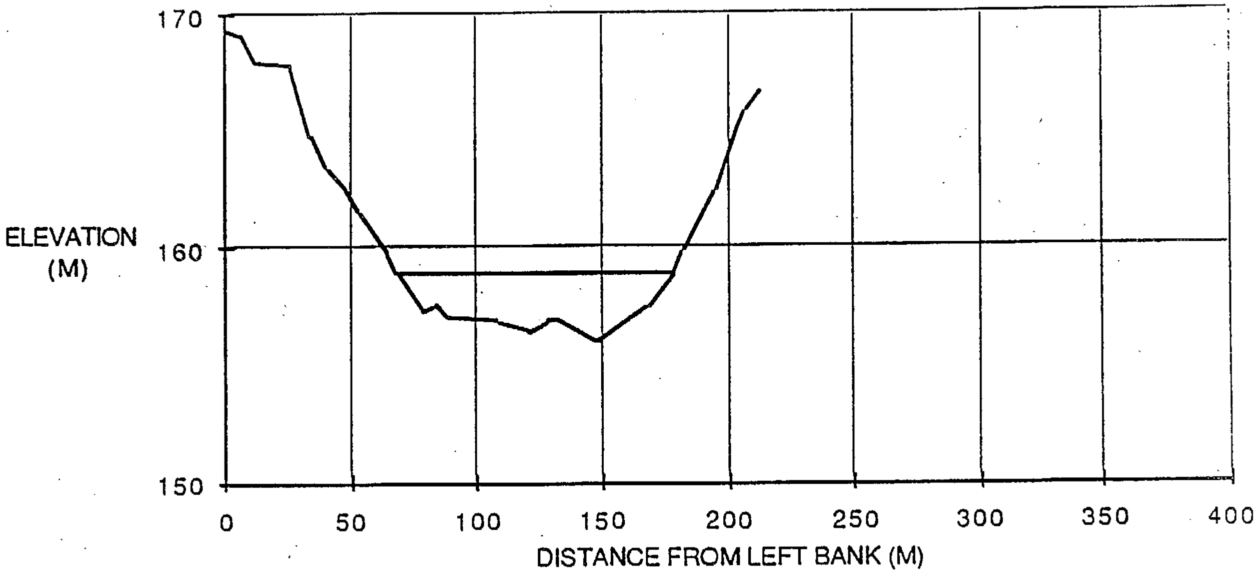
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	170
4.5	168.5
8	168.2
15	167.7
33	161.1
41	159.2
42	159.16
48	158.2
58	157.4
74	157.3
96	157.3
120	156.7
133	156.9
141	157.6
153	159.16
157	161.72
173	165.21
183	168.21

CROSS SECTION KM 1101.82

DESCRIPTION: This cross section is 1.5 km U/S of the Caboose. The left bank is treed from 0.0 m to 8 m. From 8 m to 15 m the bank has willows beyond which it is grassed to the water level. The right bank is gravel from the water level to 141 m after which the bank is grassed, with some small willows. The trees start at 175 m. The bed material had a D_{50} of about 100 to 120 mm with larger boulders present. the water level on the day of survey July 10, 1987, was 159.16 m.

TBM: Spike in tree on the top to the left bank, at 3 m on the cross section. Elevation - 169.351 m.

Figure F.8 Cross section km 1101.82



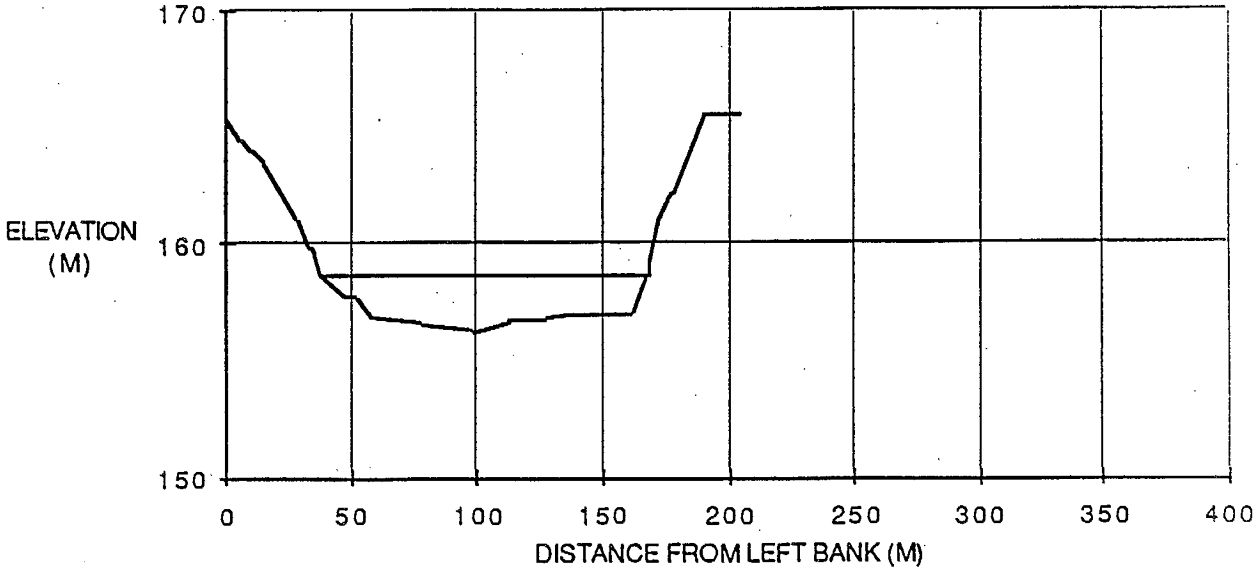
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	169.4
6	169.12
12	167.97
26	167.76
34.5	164.81
40.5	163.46
47	162.62
53	161.54
64.6	159.75
68.2	158.92
78	157.29
83	157.6
88	156.99
108	156.79
120	156.38
128	156.89
132	156.9
148	155.97
168	157.5
178	158.92
182	159.91
189	161.29
195	162.5
204	165.33
207	165.97
213	166.83

CROSS SECTION KM 1103.32

DESCRIPTION: This cross section is directly across from the Caboose. The left bank is grassed from 0.0 m to 35 m. From 35 m to the water level the bank is gravel with little growth on it. The right bank was gravel, but with much more grass growth. At 195 m small willows began and at 207 m poplars started. The bed material had a D_{50} of 100 mm. On the day of survey, July 10, 1987, the water level was 158.92 m.

TBM: Cut off post, north side of trail to river, at approximately 26 m on cross section. Elevation - 166.016 m.

Figure F.9 Cross section km 1103.32



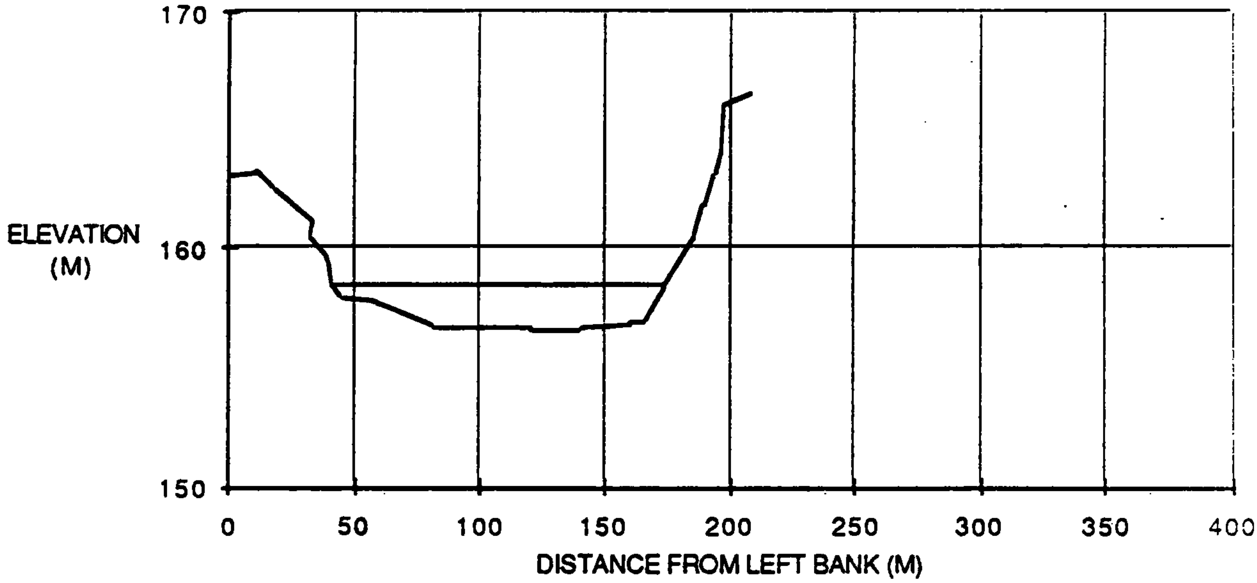
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	165.27
6	164.36
10	163.91
14.5	163.38
23.5	161.81
28.6	160.92
32	160.02
33.8	159.77
35.4	159.48
37.6	158.68
48	157.76
52	157.68
58	156.85
78	156.54
98	156.24
113	156.75
128	156.85
137	157.06
157	157.06
162	157.1
168	158.68
168.5	159.26
172	160.9
178	162.15
190	165.49
205	165.5

CROSS SECTION KM 1104.05

DESCRIPTION: This cross section is 700 m D/S of the Caboose. The left bank contains poplar up to 14.5 m, after which the bank is covered with willows up to 24 m. The bank is then grassed to the water level. The right bank is grassed from the water level to 190 m, at which point the trees start. The estimated D_{50} of the bed material is 100 mm. The water level on the day of survey, July 10, 1987, was 158.68 m.

TBM: Spike in tree on the top of the left bank, at 0.0 m on the cross section. Elevation - 165.56 m.

Figure F.10 Cross section km 1104.05



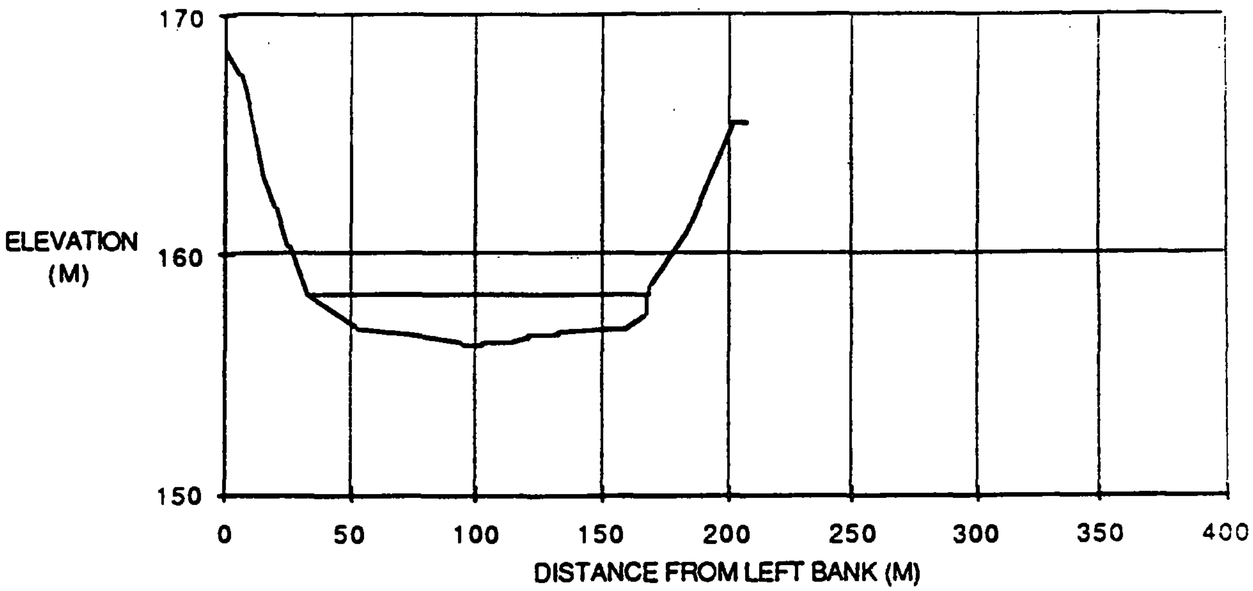
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	163.08
11	163.27
18	162.55
33.5	161.12
31.5	160.5
38	159.68
39.2	159.33
40.8	158.46
44.8	157.95
57	157.84
81	158.73
120	156.82
140	156.73
160	156.93
166	157.03
173.5	158.46
186	160.57
190	161.81
194	163.14
196.5	164.05
198	166.09
208	166.58

CROSS SECTION KM 1104.71

DESCRIPTION: This cross section is 1.4 km D/S of the Caboose. From 0.0 m to 11 m, the left bank is covered by poplar. Willows extend from 11 m to 38 m. The right bank is grassed from the water level up to 195 m where some willows start and at 198 m poplar growth begins. The bed material had a D50 of 70 -80 mm and a number of larger rocks were present, up to 500 mm in diameter. The water level on the day on survey, July 10, 1987, was 158.68 m.

TBM: Spike in tree on top of left bank, at 0.0 on the cross section. Elevation - 163.585 m.

Figure F.11 Cross section km 1104.71



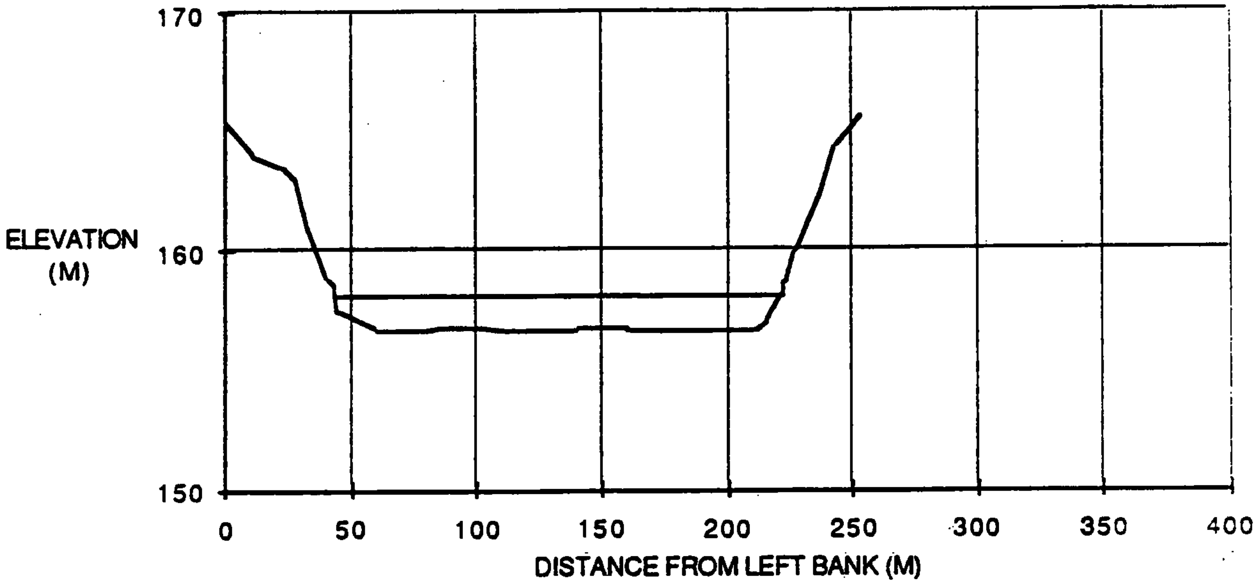
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	168.58
6	167.56
9.5	166.25
15	163.29
20	161.99
25	160.35
32.2	158.38
52.2	156.96
73	156.65
94	156.25
102	156.35
112	156.35
120	156.65
132	156.75
152	156.86
159	156.96
167	157.56
168	158.38
169	158.8
163	160.94
189	162.27
202	165.48
208	165.46

CROSS SECTION KM 1105.17

DESCRIPTION: This cross section is 2.7 km U/S of the East - West Channel split.The left bank is a steep slope with gravel and some grass present. The right bank is grassed with patches of gravel from the water level until 202 m at which point poplars begin. The bed material was estimated to have a D_{50} of 70 - 80 mm. Water level on the day of survey, July 9, 1987, was 158.38.

TBM: Hub in ground at 25 m on cross section. Elevation 160.440 m.

Figure F.12 Cross section km 1105.17



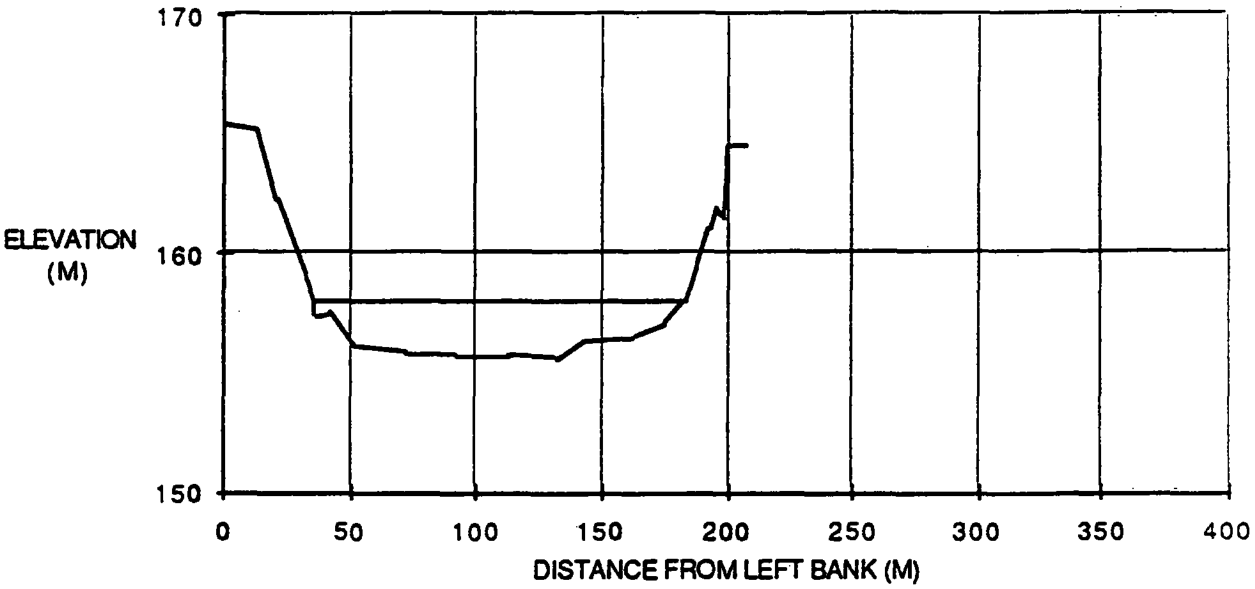
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	165.44
11	163.99
22	163.51
28	162.85
32.5	161.02
40	158.84
42.9	158.51
45	157.44
60	156.73
80	156.63
86	156.83
100	156.82
110	156.63
120	156.73
140	156.83
160	156.73
180	156.73
200	156.63
211	156.73
216	157.13
222	158.15
223	158.73
227	160.02
237	162.39
243	164.36
253	165.6

CROSS SECTION KM 1105.82

DESCRIPTION: This cross section is directly across from the tennis courts in New Town. The left bank is clear from 0.0 m to 32 m, beyond which tall grass and small willows extend to the water level. The right bank has a small cut bank at the water level after which the bank is grassed with small willows until 243 m, where poplar growth begins. The bed material is a gravel with a D_{50} of about 75 mm. On the day of survey, July 9, 1987, the water level was 158.15 m.

TBM: Hub in ground at 29 m on cross section. Elevation 162.604 m.

Figure F.13 Cross section km 1105.82



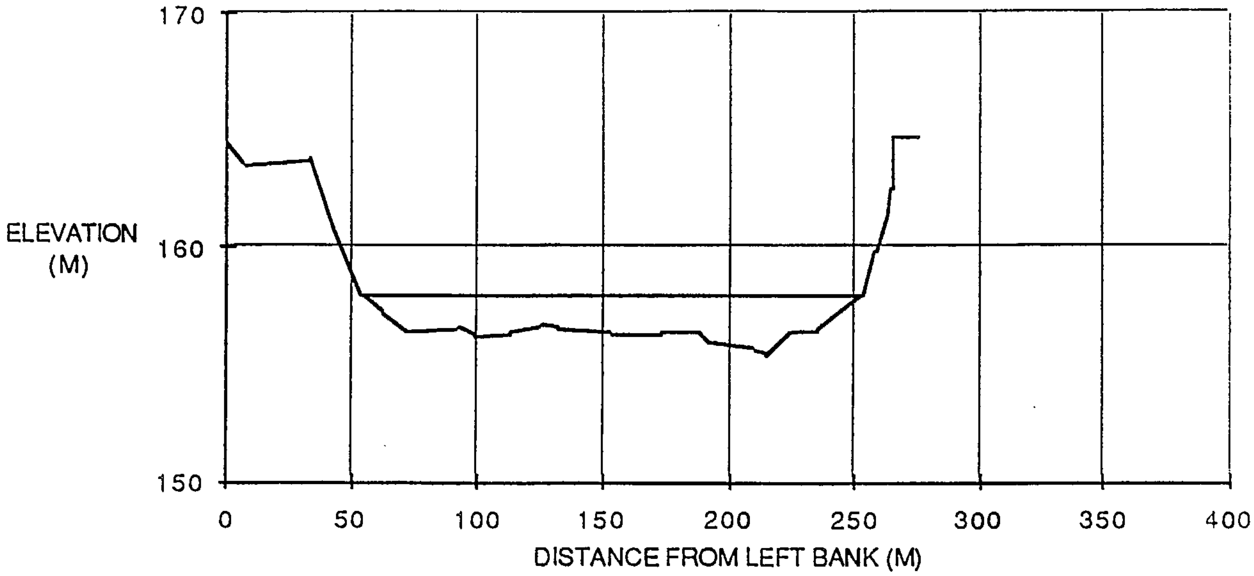
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	185.47
13	165.16
21	162.23
32	159.03
35.5	158
35.8	157.39
42	157.58
52	156.07
72	155.77
92	155.67
113	155.77
132	155.56
143	156.38
163	156.58
175	157.08
183	158
188	159.55
193	161.08
195.5	161.96
198	161.52
200	164.47
208	164.55

CROSS SECTION KM 1106.54

DESCRIPTION: This cross section is 1.4 km U/S of the East - West Channel split. The left bank is treed from 0.0 m to 13 m. From there to the water level the bank supports high grass with some small willows. The right bank is gravel, with some grass extending from the water level to 198 m, where there is a cut bank. Above this the bank is treed. The bed material was gravel with a D50 of 75 mm. The water level on the day of survey, July 9, 1987, was 158.00 m.

TBM: Hub in ground at 10 m on the cross section. Elevation - 165.312 m.

Figure F.14 Cross section km 1106.54



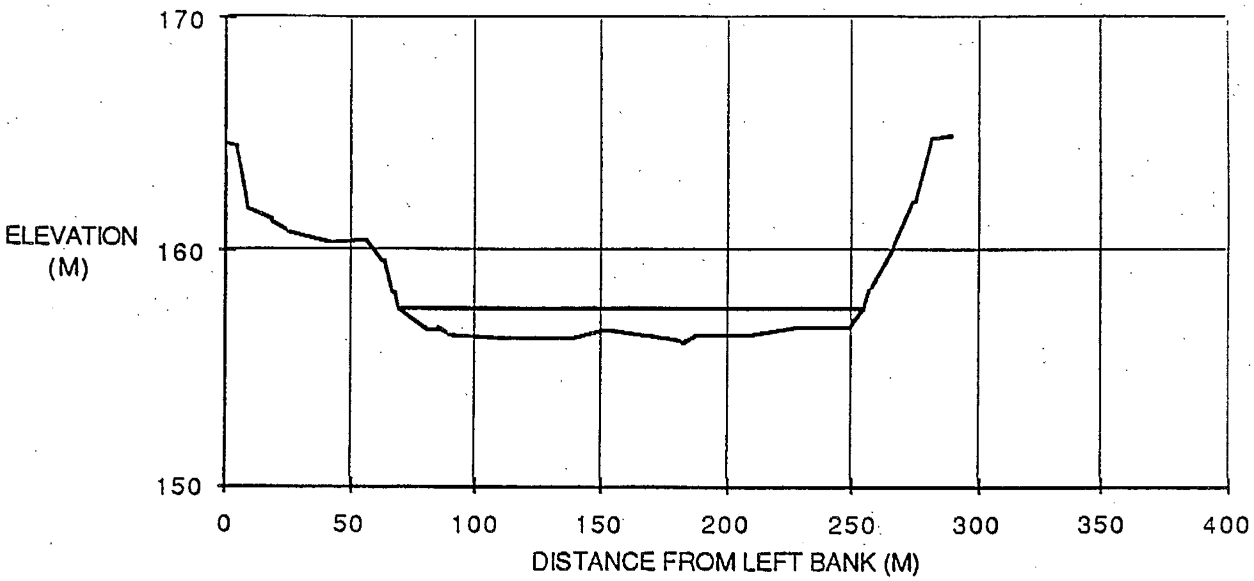
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	164.55
7	163.56
33	163.87
43	160.73
54	157.88
62	157.17
72	156.37
92	156.57
99	156.16
113	156.37
125	156.67
132	156.46
153	156.26
173	156.36
188	156.36
193	155.86
210	155.55
215	155.35
225	156.37
235	156.4
253	157.88
258	159.85
263	161.42
265	162.56
265.5	164.76
276	164.82

CROSS SECTION KM 1107.57

DESCRIPTION: This cross section is just U/S of the East - West Channel split. The far left bank is the edge of Riverview Drive. From 7 m to 43 m the land is covered by large trees and the steep portion of the left bank (43 m to 54 m) is grassed with a few small willows. The right bank is grassed from the water level to 265 (m). At this point a cutbank exists, above which tree growth begins. The bed material had a D_{50} of 75 mm. Water level on the day of survey, July 9, 1987, was 157.88 m.

TBM: Hub in ground at 42 m on cross section. Elevation 163.943 m.

Figure F.15 Cross section km 1107.57



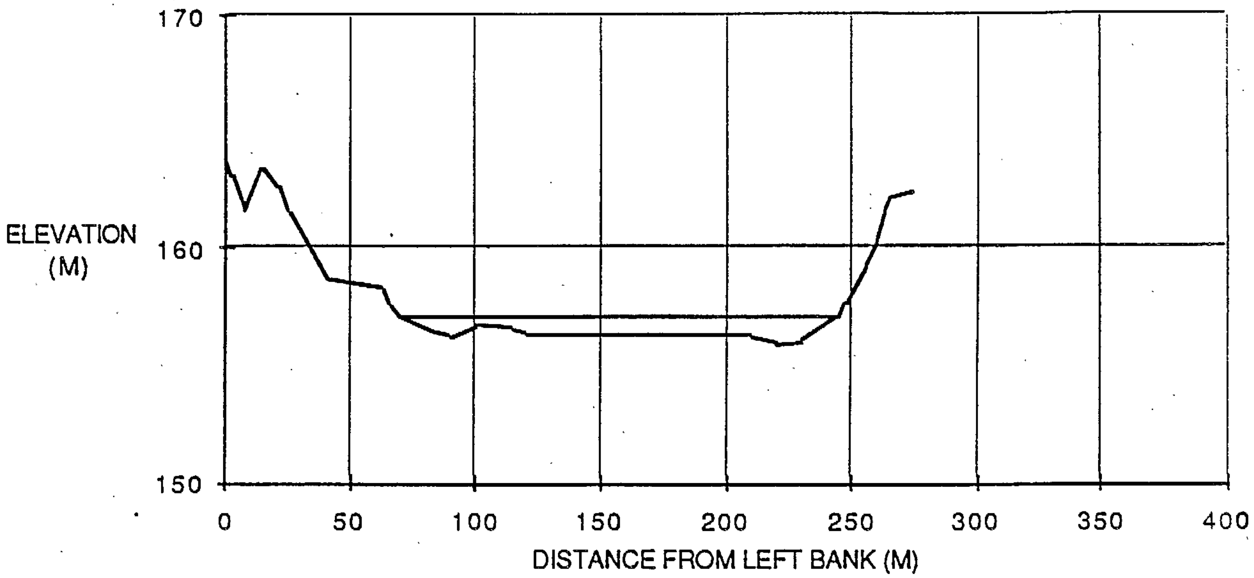
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	164.67
4	164.49
8.8	161.81
18.5	161.27
24.3	160.87
42	160.41
56	160.54
63	159.64
67	158.27
68.5	157.62
80.5	156.71
85	156.81
89	156.5
108.5	156.3
128.5	156.3
138	156.3
151	156.71
167	156.4
182	156.09
188	156.5
209	156.4
228.5	156.81
249	156.81
254.5	157.62
257	158.5
266.5	160.22
274.5	162.19
281.5	164.89
289.5	165.01

CROSS SECTION KM 1108.30 EAST CHANNEL

DESCRIPTION: This cross section is of the East Channel just D/S of the East-West Channel split. The left bank (0.0 m to 65 m) contains willows, tall grass, and a few small poplar. The right bank is quite steep with grass from 255 m to 281 m and poplar beyond. The bed material was gravel with a D_{50} of 70 mm. Water level on the day of survey, July 10, 1987, was 157.62.

TBM: Spike in tree on top of left bank, at 0.0 m on the cross section. Elevation - 164.21 m

Figure F.16 Cross section km 1108.30 East Channel



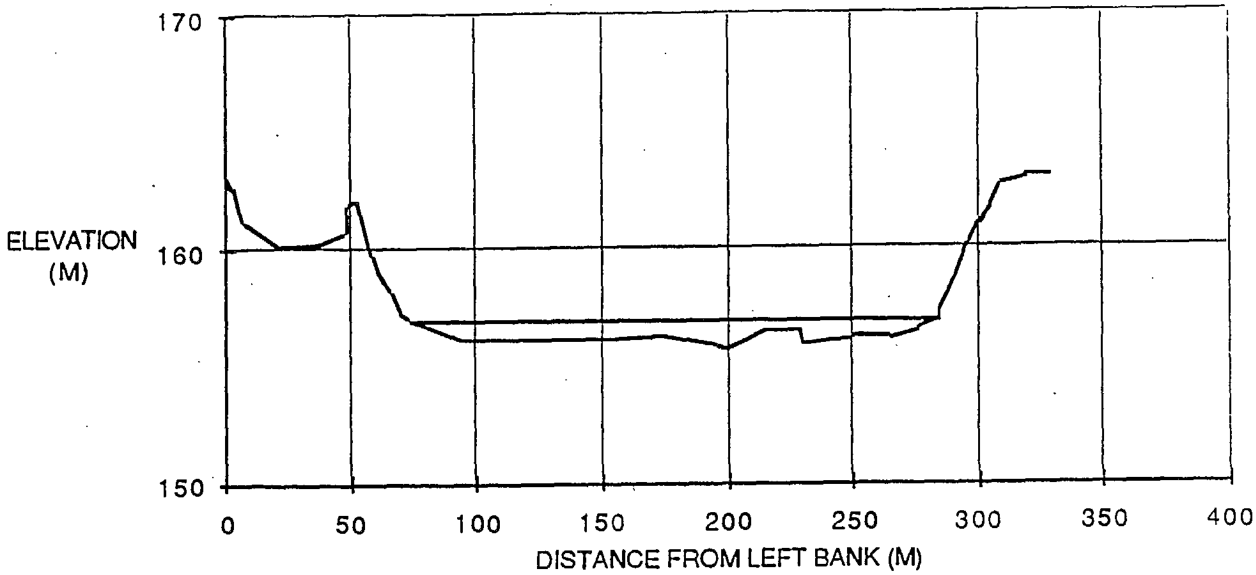
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	163.75
3	163.05
7.7	161.61
15	163.45
21	162.57
25	161.49
41	158.68
63	158.26
66	157.63
70	157.15
85	156.44
90	156.24
100	156.74
115	156.54
120	156.34
150	156.34
210	156.24
220	155.93
230	156.14
245	157.15
247.5	157.74
255	159.3
259.5	160.29
263	161.57
266	162.16
274	162.43

CROSS SECTION KM 1109.04 EAST CHANNEL

DESCRIPTION: This cross section is of the East Channel, 1.1 km D/S of the East - West Channel split. The far left of the section is the edge of the highway. A narrow band of poplar exists from 15 m to 21 m, beyond which willows and tall grass extend to the water level at 70 m. The right bank supports willows from the water to 266 m, beyond which poplar growth begins. The estimated bed material is gravel with a D50 of 50 to 70 mm. The water level on the day of survey, July 10, 1987, was 157.15 m.

TBM: Spike in telephone post on the left bank at 3 m on cross section. Elevation - 164.206 m.

Figure F.17 Cross section km 1109.04 East Channel



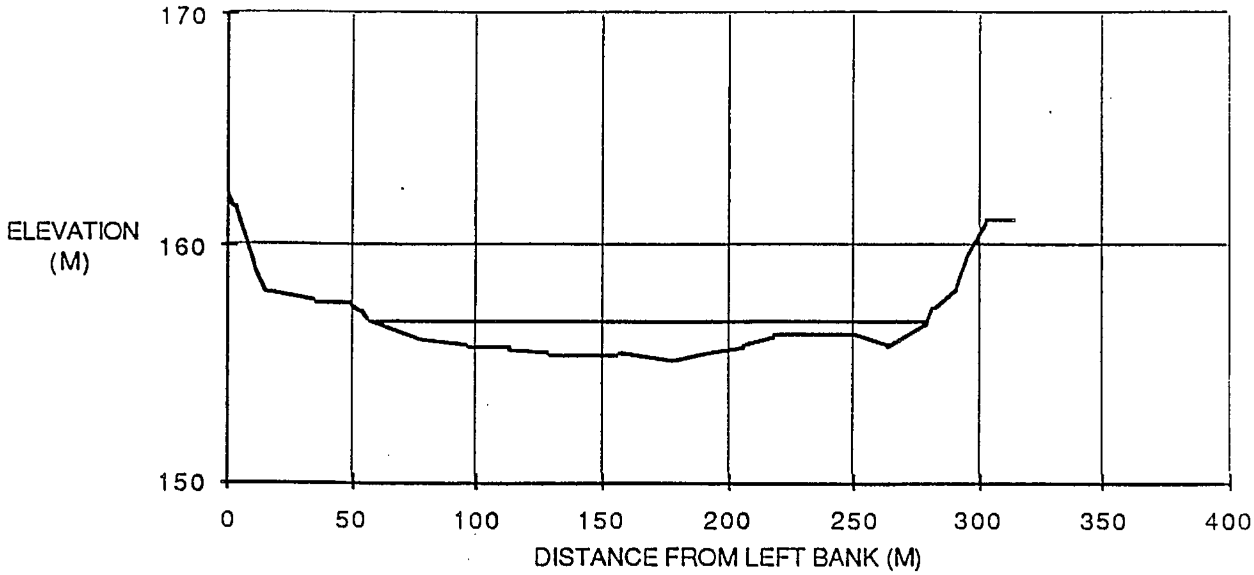
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	163.03
3	162.57
6.8	161.21
21.7	160.2
37.5	160.31
48.2	160.86
49	161.92
52	162.04
58.4	159.71
61	159.03
65.8	158.14
70	157.29
73.9	156.95
94	156.14
115	156.14
134	156.15
155	156.15
174	156.28
194	155.94
199	155.63
215	156.44
228	156.4
230	155.93
250	156.24
265	156.14
276	156.54
284	156.95
284.5	157.33
291	158.82
296	160.25
300	161.09
305	161.87
309	162.71
319	163.03
329	163.02

CROSS SECTION KM 1109.50 EAST CHANNEL

DESCRIPTION: This cross section is of the East Channel. The far left of the section (0.0 m) is the edge of the highway. A narrow strip of poplars are present from 49 m to 52 m and from 52 m to the water level the bank contains willows. Tall grass and willows extend from the water level to 309 m on the right bank with poplar beyond. Estimated bed material was gravel with a D_{50} of 50 - 70 mm. The water level was 156.95 on the day of survey, July 11, 1987.

TBM: Spike in telephone post #31 on east side of highway, left bank, at 2 m on the cross section. Elevation - 163.001 m.

Figure F.18 Cross section km 1109.50 East Channel



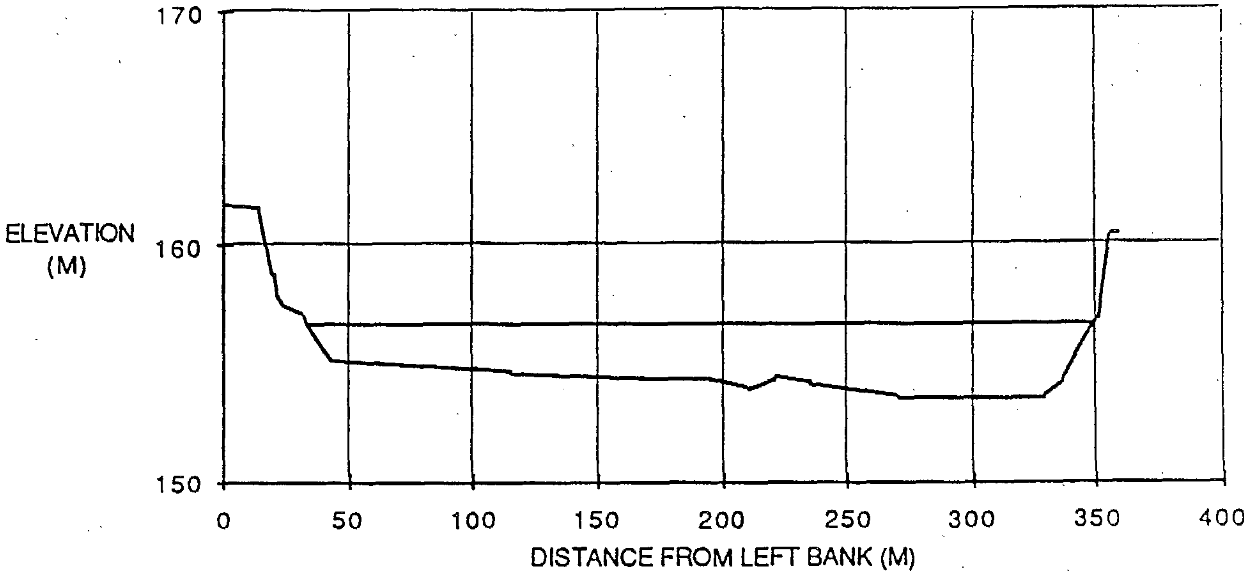
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	162.31
3	161.71
10.7	159.06
15.8	157.97
35	157.6
49.6	157.5
53.3	157.19
56.4	156.79
77	155.98
96	155.67
113	155.57
129	155.37
156	155.47
178	155.06
192	155.47
206	155.77
218	156.18
250	156.2
263	155.67
279.2	156.79
281.7	157.36
290.3	158.22
295.2	159.6
303	161.16
314	161.18

CROSS SECTION KM 1109.98 EAST CHANNEL

DESCRIPTION: This cross section is of the East Channel U/S of Island C-D. The far left bank (0.0 m) is the edge of the highway. Willows extend from the highway to the water level (50 m). Willows also extend from the water level (282 m) to 303 m on the right bank, with poplar beyond. The bed material is gravel , but the D_{50} was not determined. On the day of survey, July 11, 1987, the water level was 156.79 m.

TBM: Spike in third telephone post south of the railway crossing of the road, at 2 m on the cross section. Elevation - 162.193 m.

Figure F.19 Cross section km 1109.98 East Channel



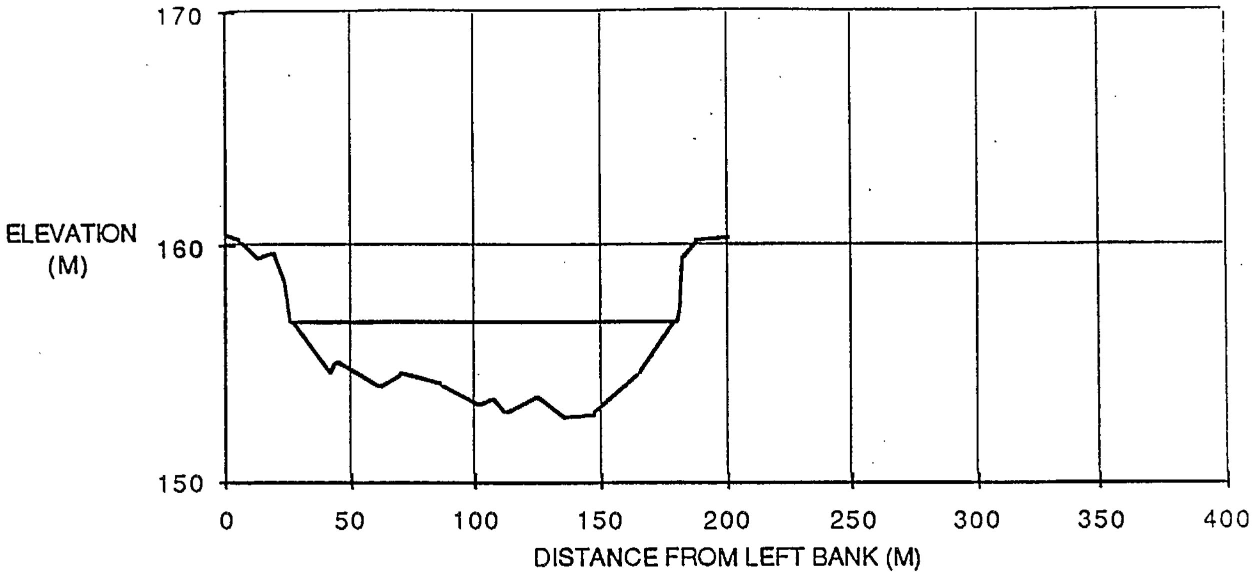
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	161.7
14	161.53
19.6	158.79
21.5	157.91
23.8	157.41
32.2	157.07
33.3	156.73
43	155.1
115	154.59
173	154.29
195	154.3
210	153.88
221	154.39
235	154.09
270	153.58
328	153.68
336	154.29
349	156.73
351	156.92
356	160.49
359	160.52

CROSS SECTION KM 1111.01 EAST CHANNEL

DESCRIPTION: This cross section is of the East Channel, about at the middle of Island C-D. The left bank is the grassy man made berm,, that surrounds Island C-D. A high cut bank is present on the right bank (355 m). The top of the cut bank is a grassed area which contains a number of houses. The bed material is gravel but a D_{50} was not determined. Water level of the day of survey, July 11, 1987, was 156.73 m.

TBM: Spike in tree on the left bank on the west side of the berm, at -5 m on the cross section. Elevation - 160.391 m.

Figure F.20 Cross section km 1111.01 East Channel



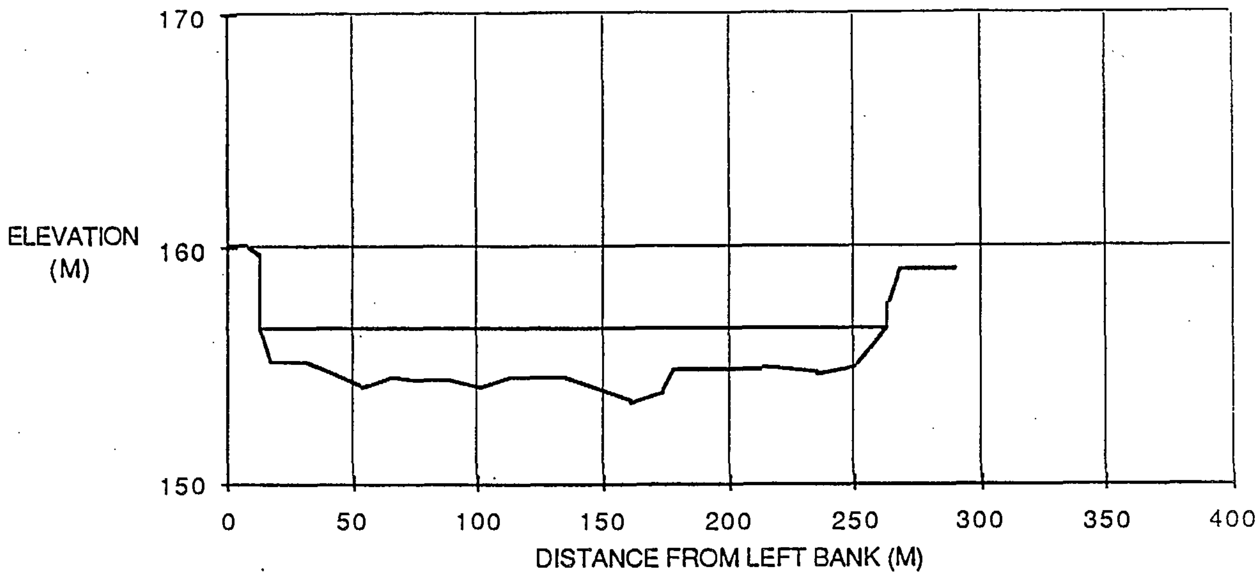
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	160.54
6	160.21
13	159.45
19.1	159.74
23.5	158.45
26.6	156.74
42	154.61
45	155.11
62	154.1
70	154.61
87	154.1
102	153.29
107	153.59
112	152.98
124	153.69
135	152.78
147	152.98
165	154.61
179.6	156.74
181.5	157.22
182.7	159.51
188.1	160.23
201	160.43

CROSS SECTION KM 1111.22 EAST CHANNEL

DESCRIPTION: This cross section is of the East Channel between the D/S end of Island C-D and the U/S end of Island B. The left bank consists of a man-made berm which is grassed. The right bank is Island B and has a high cut bank at 180 m. The top of the cut bank is heavily treed. Estimated bed material was a gravel with a D_{50} of 50 - 70 mm. Water level was 156.74 m on the day of survey, July 11, 1987.

TBM: Spike in tree on the left bank, at -6 m on the cross section. Elevation - 161.003 m.

Figure F.21 Cross section km 1111.22 East Channel



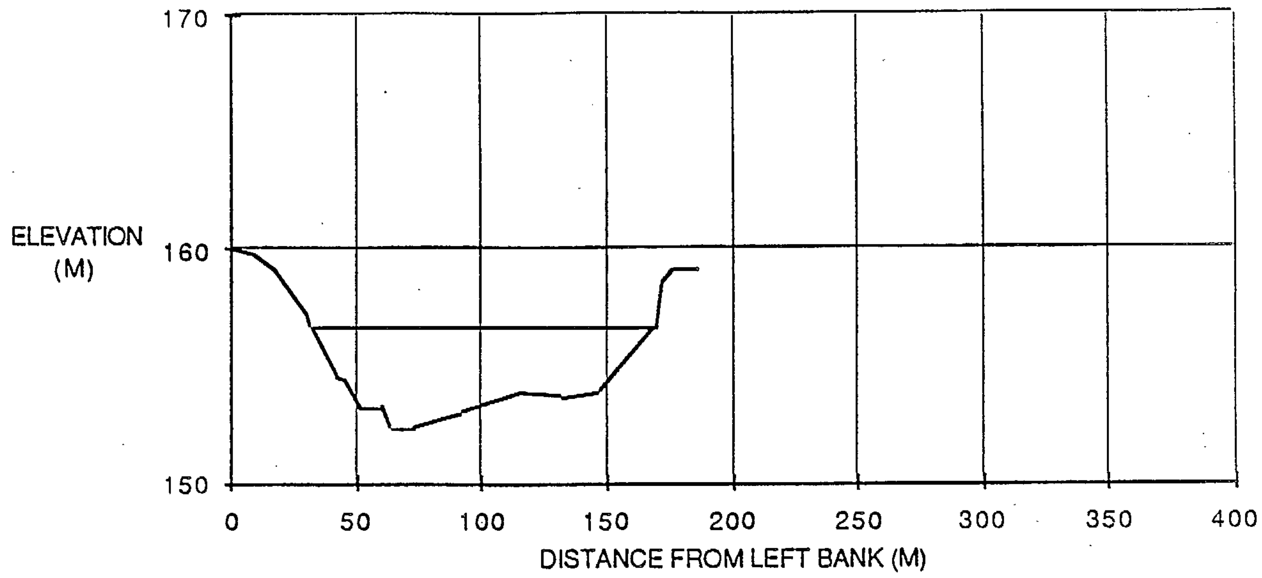
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	160.15
8	160.08
12.5	159.74
13	156.73
18	155.21
31	155.2
53	154.09
65	154.6
73	154.4
88	154.49
101	154.08
113	154.6
134	154.55
161	153.48
174	153.98
179	154.9
213	155
235	154.7
251	155.1
263	156.73
264	157.8
267.5	158.9
269	159.14
278	159.2
290	159.15

CROSS SECTION KM 1111.55 EAST CHANNEL

DESCRIPTION: This cross section is of the East Channel on the U/S end of Island B. The left bank is the east side of Island B which has a high cut bank at 13 m. The top of the left bank is treed with poplar. The right bank has a small cut bank above which it is heavily treed. The bed material was gravel but the D_{50} of the material was not determined. Water level was 156.73 m on the day of survey, July 11, 1987.

TBM: Spike in tree directly on top of the cut bank on the left bank, at 1 m on the cross section. Elevation - 161.01 m.

Figure F.22 Cross section km 1111.55 East Channel



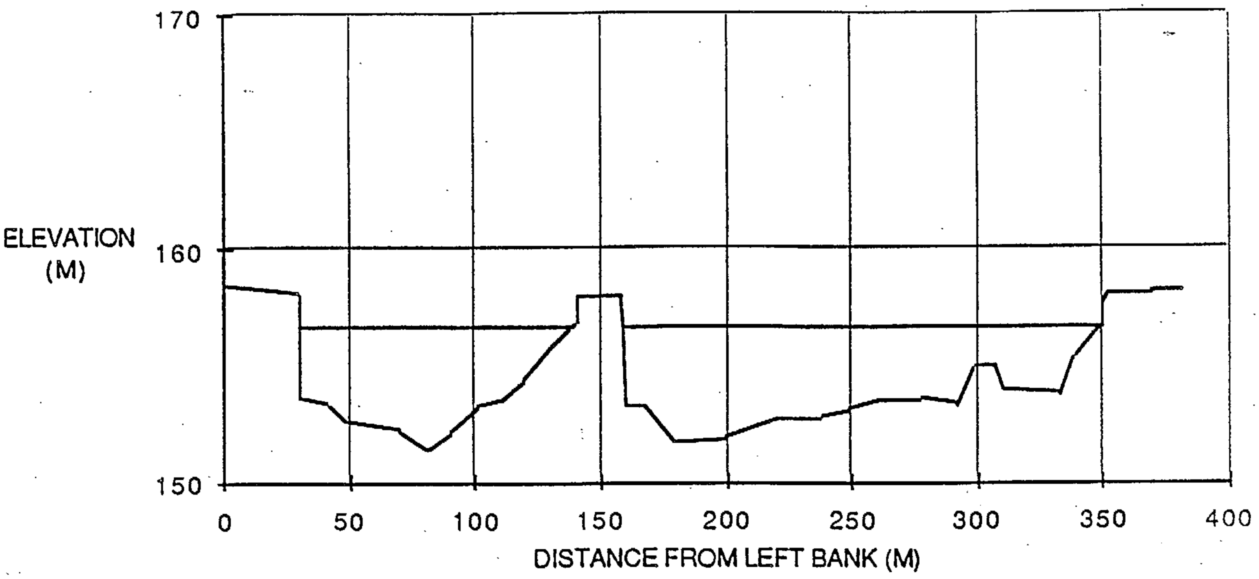
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	160.09
8.4	159.85
17	159.16
30.1	157.23
31.9	156.68
41.9	154.59
44.9	154.48
52	153.17
60	153.27
64	152.36
73	152.46
92	153.07
115	153.88
132	153.68
147	153.98
169.2	156.68
171.4	158.57
176.2	159.15
186	159.21

CROSS SECTION KM 1111.61 EAST CHANNEL

DESCRIPTION: This cross section is of the East Channel, immediately D/S of the Shell Bulk Station. The left bank is a graveled industrial area with a number of buildings along it. The right bank is the west side of Island B, which has a cut bank just above the water level (170 m). Above the cut bank is treed with large poplar. The estimated bed material was gravel with a D_{50} of 50 mm. Water level on the day of survey, July 11, 1987, was 156.68 m.

TBM: East-most angle iron on back of abandoned large boat on left bank, at 15 m on the cross section. Elevation - 161.043 m.

Figure F.23 Cross section km 1111.61 East Channel



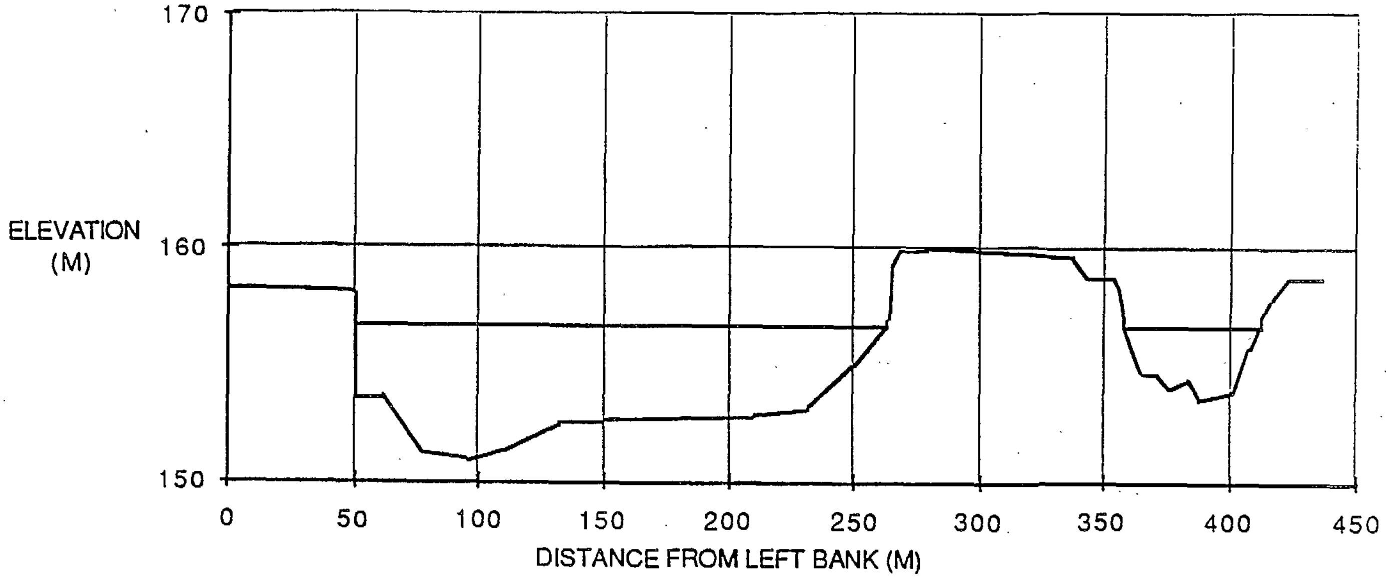
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0.0	158.50
30.0	158.06
30.1	156.68
30.2	153.68
42.0	153.37
49.0	152.66
70.0	152.25
81.0	151.44
90.0	152.15
101.0	153.27
110.0	153.57
119.0	154.39
130.0	155.81
138.0	156.68
140.0	156.86
140.5	158.04
148.0	158.08
157.5	158.04
159	156.68
161	153.27
167	153.37
179	151.75
200	151.95
221	152.76
238	152.86
249	153.17
261	153.58
278	153.68
292	153.37
299	154.99
307	155.00
311	153.98
333	153.78
339	155.40
349.5	156.68
350	157.68
352.5	158.18
369.5	158.23
382	158.28

CROSS SECTION KM 1112.20 EAST CHANNEL

DESCRIPTION: This cross section is of the East Channel at the D/S end of Island B and cuts across the tip of the island. The left bank consists of a dock with its edge at 30 m, with a gravel yard to the left of the dock. The island at this section is covered with high grass. The far right bank is heavily treed from the water level (350 m) on upward. The bed material is gravel but the D_{50} of the material was not determined. On July 12, 1987, the water level was 156.68 m.

TBM: Top of bollard #7 on the left bank, at 29 m on the cross section. Elevation - 158.373 m.

Figure F.24 Cross section km 1112.20 East Channel



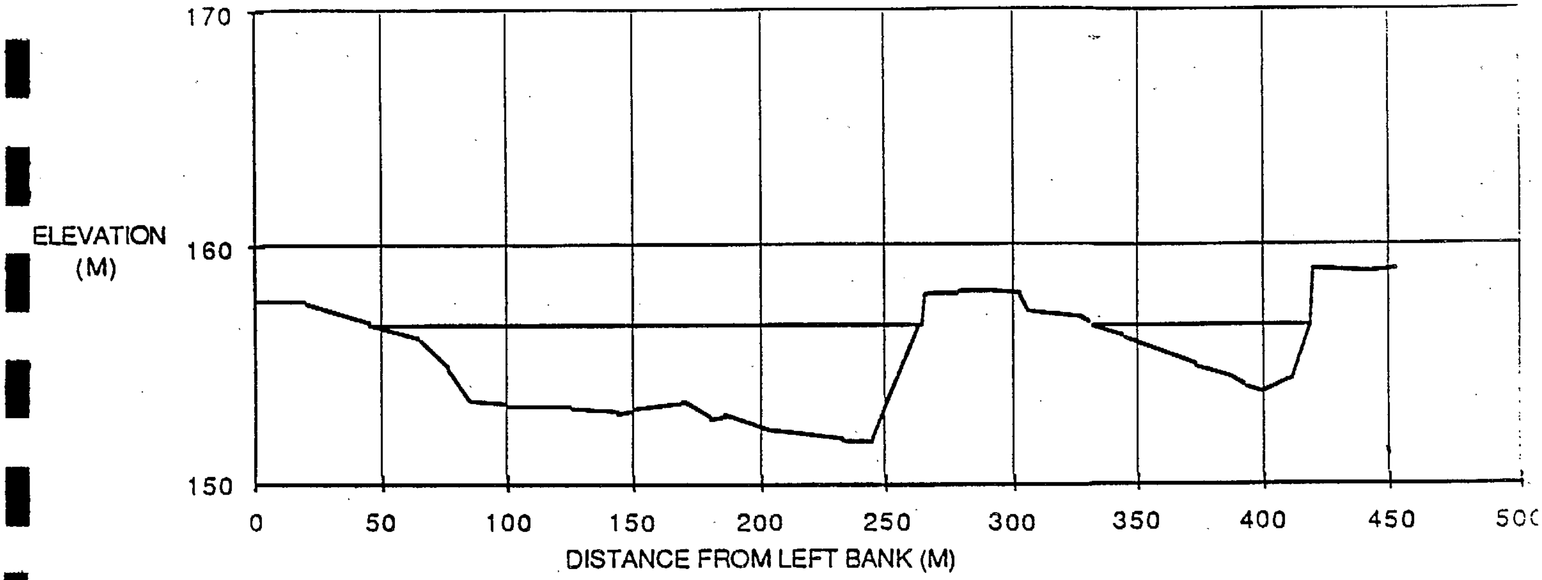
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	158.25
13	158.22
50	158.08
50.1	156.69
50.2	153.59
61	153.68
78	151.15
95	150.84
110	151.35
132	152.57
150	152.67
210	152.87
232	153.18
250	155
263	156.69
263.5	156.97
265.5	159.22
269	159.98
279	160.01
337	159.65
343	158.85
353	158.82
355.5	158.33
357.8	157.09
358	156.69
365	154.7
370	154.71
376	153.99
383	154.4
388	153.59
402	153.99
408	155.82
412	156.69
412.3	157.13
416.5	157.91
424	158.82
436	158.91

CROSS SECTION KM 1112.36 EAST CHANNEL

DESCRIPTION: This cross section is of the East Channel at the U/S end of Island A, just crossing the tip of the island. The left bank consists of a dock with its edge at 50 m, with a large graveled yard to the left of it. The island is heavily treed and the far right bank of the section is also heavily treed. The trees start almost immediately at the water (412 m). The D_{50} of the bed material was not determined but it was noted that it was gravel. Water level on July 12, 1987, the day of survey was 156.68 m.

TBM: Lip of dock on the SE corner of the dock, at 50 m on the cross section. Elevation - 158.092 m.

Figure F.25 Cross section km 1112.36 East Channel



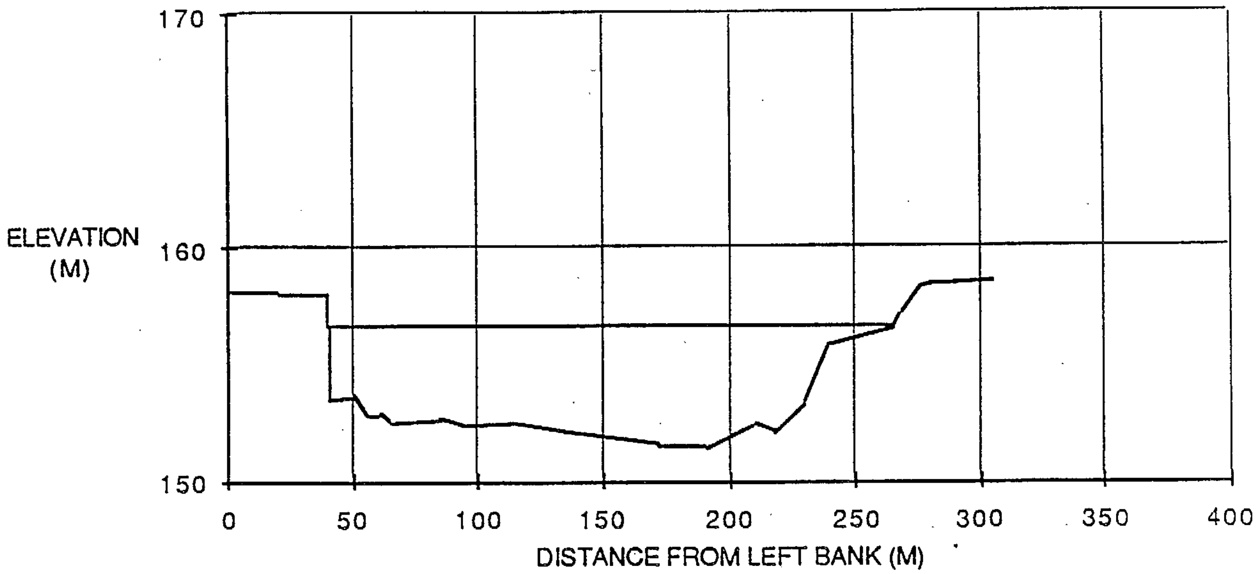
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	157.68
20	157.57
45	156.71
65	156.04
76	154.82
85	153.4
100	153.2
125	153.1
144	152.89
150	153.1
169	153.4
180	152.69
186	152.89
205	152.18
233	151.78
245	151.88
264	156.71
265.5	157.86
267.5	158.07
279	158.15
290	158.18
303	157.96
307	157.27
316	157.13
326	156.98
330	156.71
330	156.71
345	156.15
373	154.93
387	154.42
393	154.01
400	153.71
411	154.32
419	156.71
421	159.08
441	158.88
452	159.03

CROSS SECTION KM 1113.22 EAST CHANNEL

DESCRIPTION: This cross section is of the East Channel at the D/S end of Island A, just crossing the tip of the island. The left bank is at the ATL yards and consists of gravel, with no dock present. The island is heavily treed. The far right bank (420 m) is a cut bank with a large grassed area on the top. The bottom was rocky with an estimated D_{50} of 50 mm. On the day of survey, July 12, 1987, the water level was 156.70.

TBM: Top of bollard on the NE corner of Department of Public Works dock, at 40 m on the cross section and 40 m upstreamof the cross section. Elevation - 158.350 m.

Figure F.26 Cross section km 1113.22 East Channel



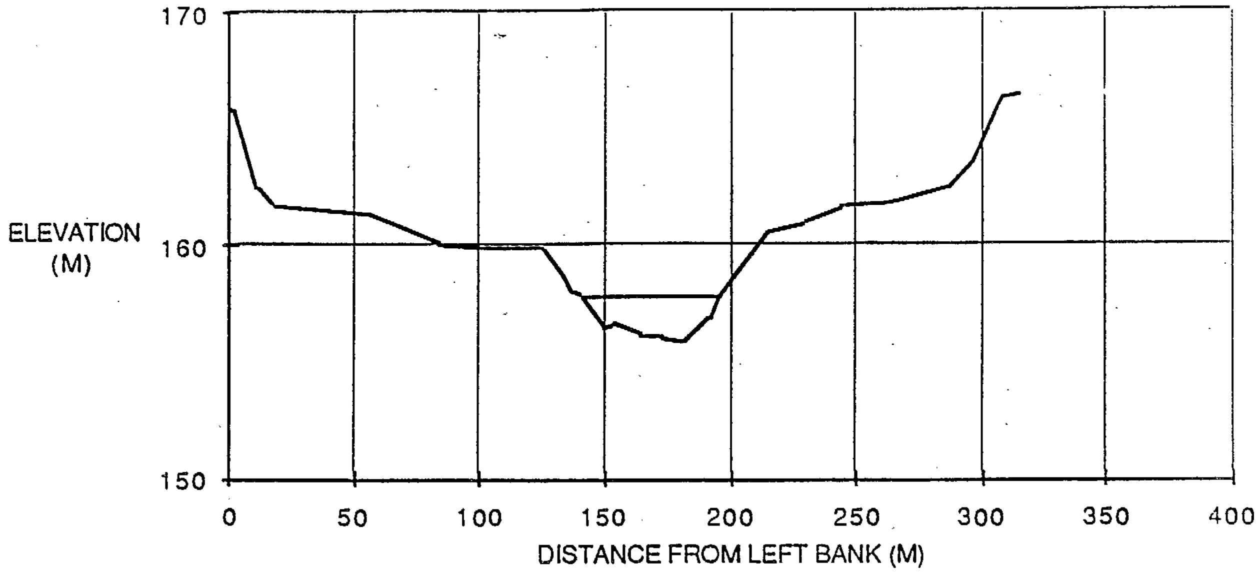
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	158.15
20	158.08
39.9	158.05
40	156.7
40.1	153.58
50	153.79
56	152.88
61	152.98
65	152.57
85	152.78
95	152.38
115	152.56
140	152.07
172	151.56
191	151.46
210	152.48
218	152.07
230	153.39
240	155.93
265	156.7
268	157.25
276	158.39
281	158.52
305	158.67

CROSS SECTION KM 1113.61 EAST CHANNEL

DESCRIPTION: This cross section is of the East Channel at the NTCL syncro-lift. The edge of the NTCL docks are at 39.9 m across the section with a flat gravel yard to the left of the docks . The right bank is just north of the Roman Catholic Mission in the Indian Village and is composed of sand. Small willows extend from the water level to 276 m, with poplar beyond. The bed material is gravel but because of the difficulty in obtaining a sample the D_{50} was not determined. Water level on the day of survey, July 12, 1987, was 156.70 m.

TBM: Top of bollard on the SE corner of syncro-lift, on the left bank, at 35 m on the cross section. Elevation - 158.369 m.

Figure F.27 Cross section km 1113.61 East Channel



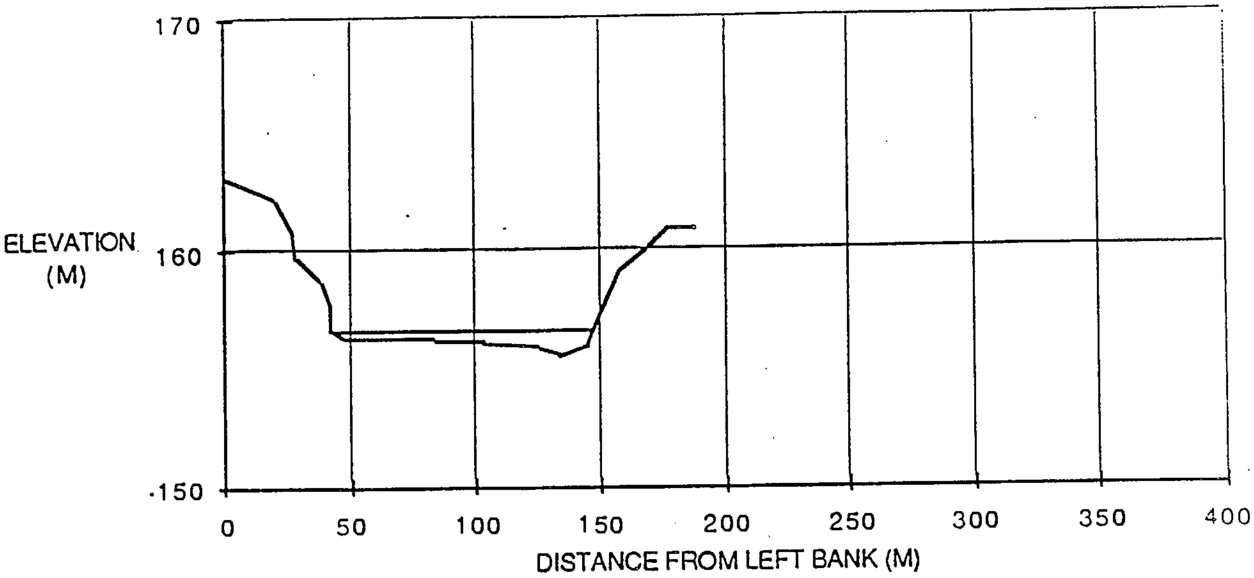
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	166.028
1.8	165.87
11.2	162.47
17.6	161.72
55.7	161.34
84	160.05
101	159.91
125	159.84
133	158.66
137	157.98
140	157.79
149	156.47
153	156.67
164	156.16
173	156.06
181	155.86
191.5	156.88
195	157.79
215	160.63
229	161.07
243.4	161.68
263	161.79
286.2	162.48
296.4	163.61
306.3	165.97
309.4	166.44
315	166.61

CROSS SECTION KM 110 . 3 WEST CHANNEL

DESCRIPTION: This cross section is of the West Channel, just U/S of the West Channel bridge. The far left of the section (0.0 m) is the edge of Riverview Drive. The left bank is covered with willows and small poplars from 10 m to the water level. The right bank is grassed from the water level to 215 m after which willows start. The top of the right bank (306 m) is a graveled parking area. The bed material is gravel but the D_{50} was not determined. The water level on the day of survey, July 10, 1987, was 157.79 m.

TBM: Hub in ground very top of left bank, at 1 m on the cross section. Elevation 166.098 m.

Figure F.28 Cross-section km 1108.23 West Channel



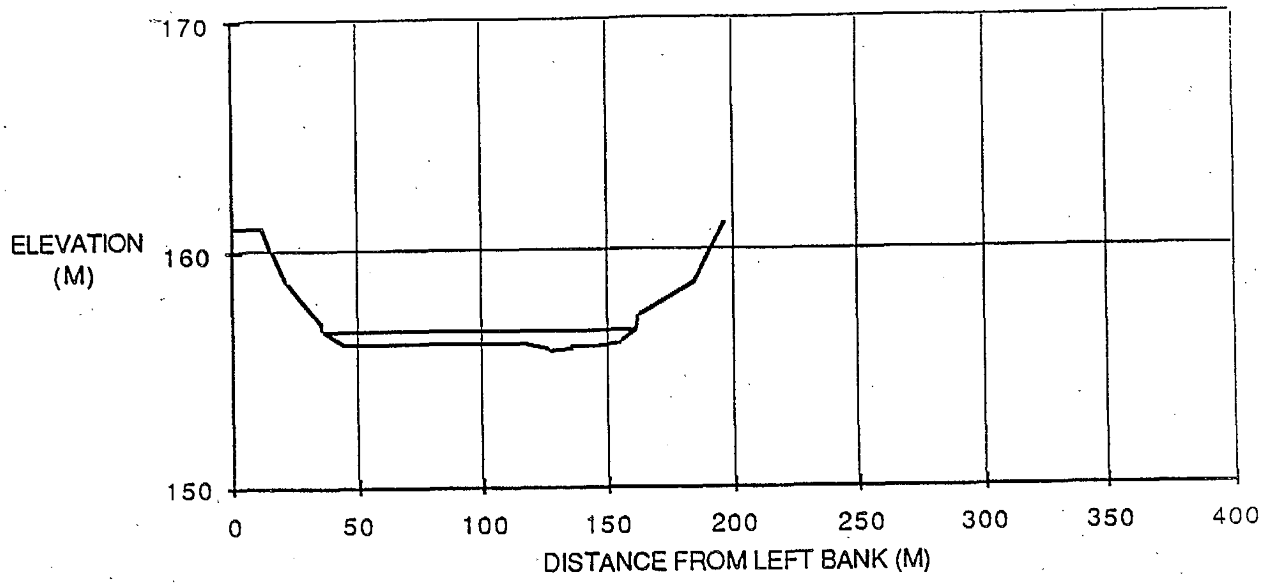
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	163.15
20	162.22
27	160.83
29	159.67
38	158.68
41.8	157.71
42	157.74
42.2	156.7
47.2	156.29
83	156.19
103	156.09
125	155.88
133	155.58
145	156.09
147.2	156.7
158	159.19
169	160.19
177	160.99
188	161.02

CROSS SECTION KM 110 4 WEST CHANNEL

DESCRIPTION: This cross section is of the West Channel, 1.8 km D/S of the East - West Channel split. The left bank is treed from 0.0 m to 20 m, with grass from there to the water level. The right bank is grassed from the water level all the way up. No trees are present on this bank since the top is the airport runway. The bed material is gravel but the D50 was not determined. Water level on the day of survey, July 16, 1987, was 156.70 m.

TBM: Spike in tree on the top of the left bank at NE edge of the clearing, at 0.0 m on the cross section. Elevation - 163.745 m.

Figure F.29 Cross-section km 1110.24 West Channel



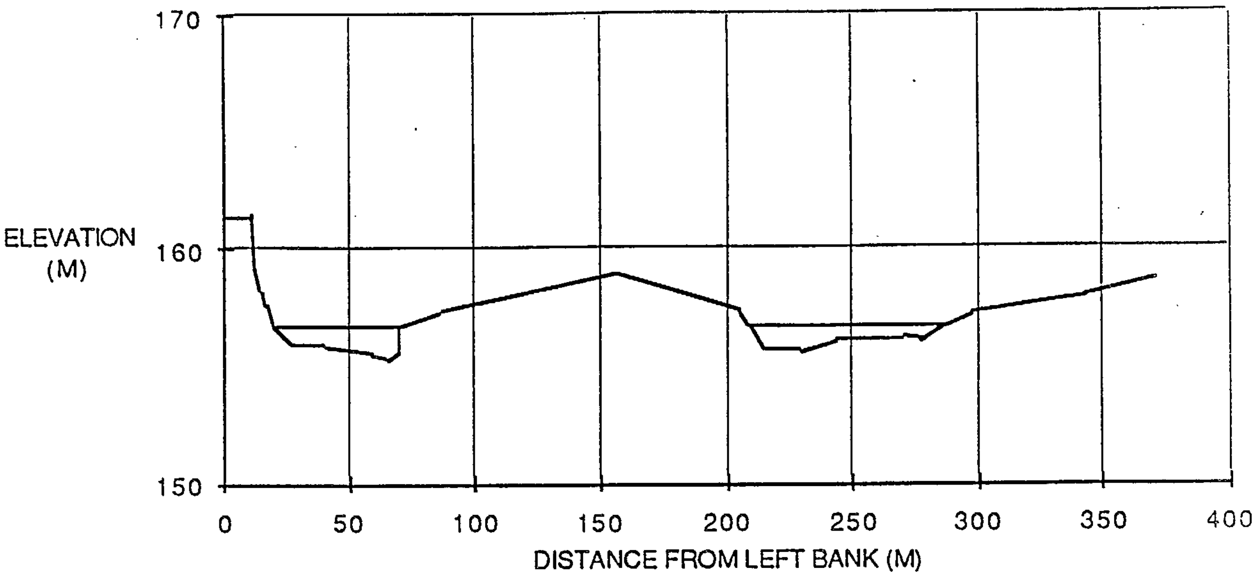
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	161.09
12	161.03
16	160.02
22	158.73
35	157.02
36	156.7
44	156.1
116	156.13
126	155.79
135	155.99
146	156.05
155	156.18
161	156.7
162.5	157.33
184.5	158.74
196.5	161.22
	158.57
	159.15
	159.21

CROSS SECTION KM 1110. 9 WEST CHANNEL

DESCRIPTION: This cross section is of the West Channel, just upstream of the island. The left bank is treed up to 12 m, after which tall grass extends to the water level. The right bank is grassed from the water level on up. The top of the right bank is a grassed field, part of the Hay River airport. The bed material was rocky with an estimated D_{50} of 100 mm. The water level on the day of survey, July 16, 1987, was 156.70 m.

TBM: Spike in tree on the top of left bank, at 0.0 m on the cross section. Elevation - 161.87 m.

Figure F.30 Cross-section km 1110.99 West Channel



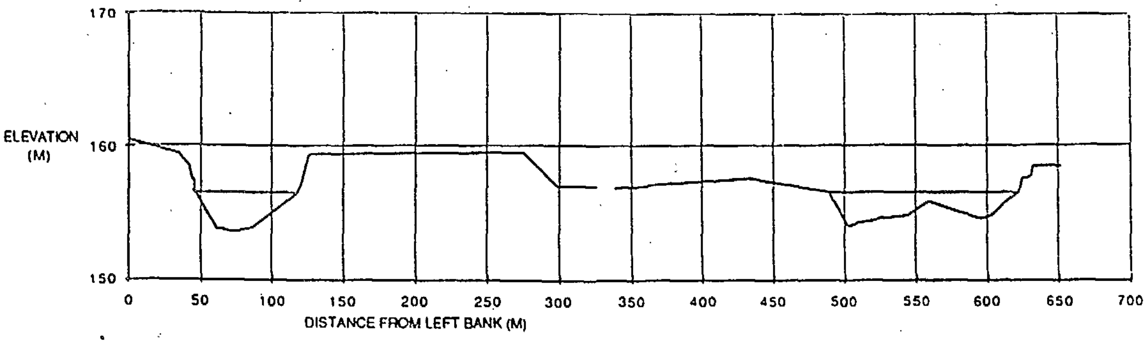
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	161.39
10	161.49
12	159.27
15	158.15
17	157.56
19.5	156.69
28	155.87
40	155.77
59	155.47
65	155.27
70	155.67
71	156.69
87	157.31
156	158.93
205	157.27
209	156.69
215	155.67
229	155.57
244	156.08
270	156.18
277	155.98
287	156.69
297	157.22
342	157.92
344	158.07
370	158.81

CROSS SECTION KM 111 5 WEST CHANNEL

DESCRIPTION: This cross section is of the West Channel. It is just downstream of the split of the Rudd Channel. The left bank is treed up to 10 m, at which point a high cut bank exsists. The island contains high grass and some small willow at this section. The far right bank is a grassed field which is part of the airport. The bed material is gravel with a D_{50} of 100 mm. Water level on the day of survey, July 16, 1987 was 156.70 m.

TBM: Spike in tree top of left bank, at 0.0 m on the cross section. Elevation - 161.89 m.

Figure F.31 Cross-section km 1111.26 West Channel

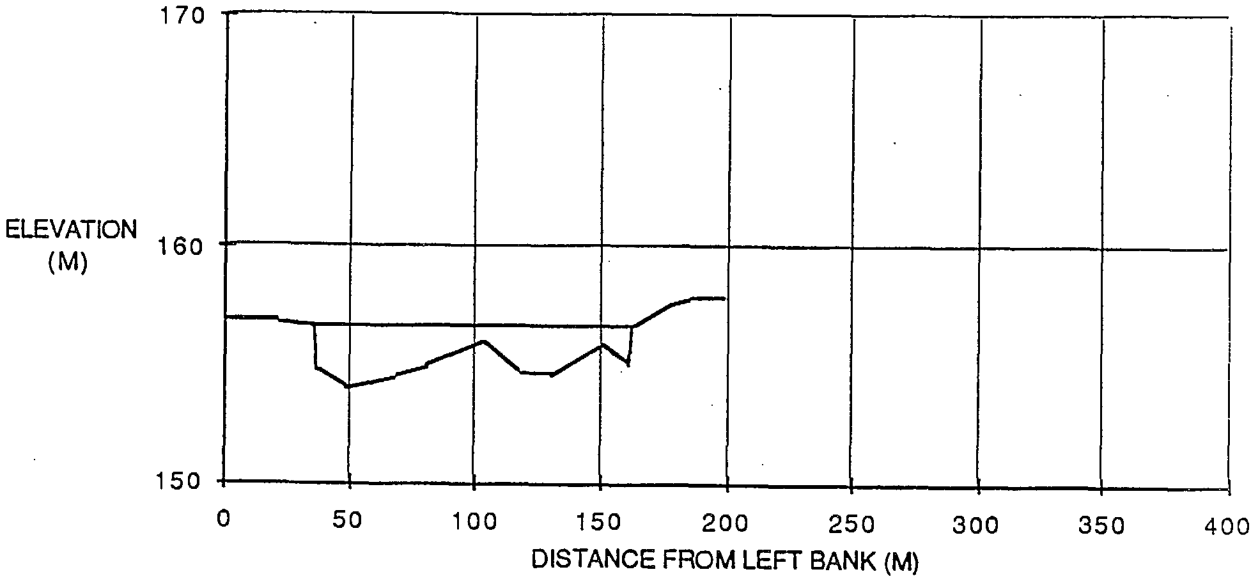


DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	160.44
35.5	159.35
42	158.51
45	157.59
45.5	156.67
59.5	153.92
65.5	153.82
74	153.61
86	154.02
117.5	156.67
120.5	157.37
126.5	159.46
140	159.52
275	159.65
299	157.12
338	157.06
361	157.2
433	157.71
490	156.67
493	155.96
502.6	154.13
508	154.33
523	154.64
544	154.94
559	156.06
583	155.14
595	154.64
603	154.94
612	155.86
622	156.67
625	157.68
630	157.86
632	158.55
652	158.63

CROSS SECTION KM 1111. WEST CHANNEL

DESCRIPTION: This cross section is of the West Channel, 200 m from the mouth of the Rudd Channel. The left bank is grassed all the way down to the water level. The island is treed with small poplar from 125 m to 275 m after which it is grassed with a few small willows persisting up to 490 m. The far right bank is an earth bank with no vegetation on it. The bed material is gravel, but a D_{50} was not determined. The water level on the day of survey, July 16, 1987, was 156.68 m.

Figure F.32 Cross section km 1111.76 West Channel



DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	156.86
13	156.88
21	156.84
35	156.68
37	154.74
48	154.03
68	154.54
80	154.95
103	155.96
118	154.64
130	154.54
150	155.86
161	155.04
163	156.68
177	157.63
185	157.91
198	158.01

CROSS SECTION KM 1112. 7 WEST CHANNEL

DESCRIPTION: This cross section is of the West Channel just before it enters Great Slave Lake. The left bank is a marshy section of the island. The right bank is a grassy area which contains a number of residences. The bed material is gravel but the D50 was not determined. The water level on the day of survey, July 16, 1987, was 156.68 m.

TBM: Hub on right bank at 200 m on cross section. Elevation - 158.294 m.

Figure F.33 Cross-section km 1112.57 West Channel

APPENDIX G

CALIBRATION OF ICE JAM WATER LEVEL PROFILE ALGORITHM

APPENDIX G

CALIBRATION OF ICE JAM WATER LEVEL PROFILE ALGORITHM

G.1 Ice jam profile model

A typical longitudinal profile through an ice jam is shown in Figure G1. The increase in water level across the jam is basically the result of the change in ice cover roughness and thickness, from the relatively smooth, solid ice downstream, to the rougher, fragmented ice of the pack. The lower conveyance capacity under the pack and the thicker 'ice cover' requires a substantially higher water level for a given discharge. The water level profile through the jam is a function of the interaction between the flow hydraulics and the 'geotechnical' behaviour of the pack.

An important feature of the profile shown in Figure G1 is the so-called equilibrium section. The depth in this section is the maximum caused by the jam. The pack thickness and waterway depth is uniform throughout this section, making its analysis simpler. A pack long enough to have developed such a section is called 'fully-developed'. The situation within the equilibrium section can be analyzed directly, without knowledge of the transition profile from downstream.

The exact configuration of the transition from the water level downstream of the pack toe to the maximum water level within the pack is somewhat more complex. A numerical algorithm, called ICEJAM, for calculation of such profiles was recently developed by Flato and Gerard (1986). This algorithm was adapted and calibrated for use on the East Channel, utilizing data collected during the 1987 and 1988 break-up observations.

G.2 Discharge apportionment in the delta channels

The first requirement for application of the model is a discharge estimate. Quite reliable estimates are available for the main channel discharge at the WSC station at Hay River. The problem lies in assessing the apportionment of this discharge between the East and West Channels.

As described in Section G.3 below, for the ice jam toe at its usual initial location in the East Channel near Island CD, a pack long enough to extend upstream of the East-West Channel split would be fully-developed. This

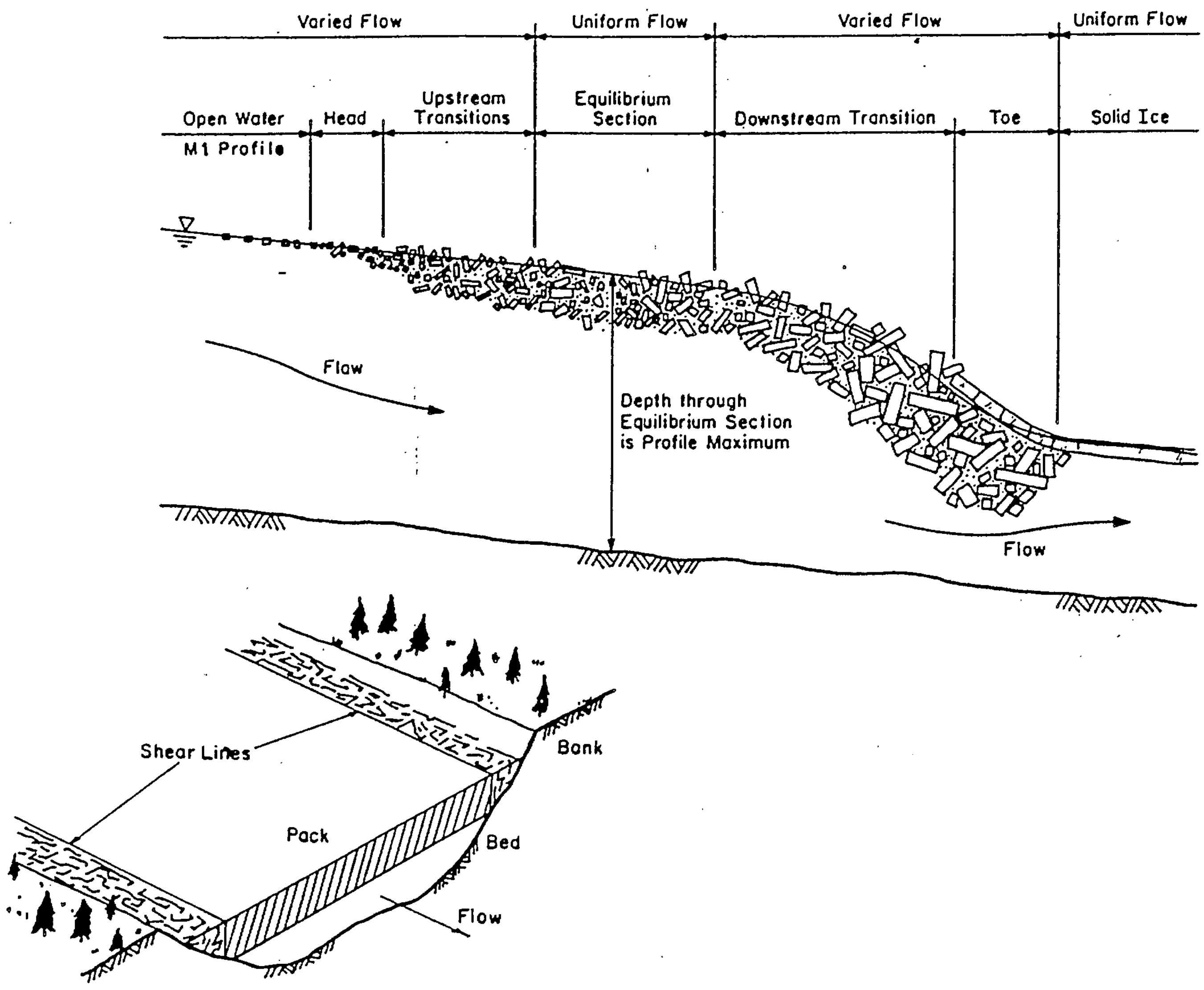


Figure G1 Typical longitudinal profile through an ice jam allowed application of the simple equilibrium ice jam relations to develop water-level-discharge relations for the East and West Channels when ice jams exist on both. Another extreme occurs when there is a pack through the split on the East Channel but the West Channel is open. For this situation a relation between open water level and discharge in the West Channel is needed. This was developed using standard hydraulics.

The West Channel open water and ice jam rating curves were based on varied flow calculations utilizing the standard HEC 2 program, beginning at the channel mouth. The channel roughness, the pack roughness, and its internal friction - porosity parameter were taken as the same as for the East Channel described below. Because at some time during the ice run the water is running over bottomfast ice in the West Channel, it could be argued a smaller roughness should have been used. However the smoother surface tends to be compensated by the loss in waterway area associated with the bottomfast ice, so it was judged adequate to neglect the bottomfast ice. The resulting rating curves are given in Figure 34.

These channel rating curves, together with the constraint that the water level at the split is common to both channels, allow an estimate of the apportionment of flow between the two channels for the two circumstances. Given the discharge in the main channel and the estimate in the West Channel, that in the East Channel is given by the difference.

G.3 Ice jam model calibration for the East Channel

This calibration was based on the water level profiles surveyed through in-place ice jams in the East Channel in 1987 and 1988.

In both years a fully developed jam was present in both channels at the split so discharges in the West Channel were simply read from the ice jam curve of Figure 34 and the remainder allocated to the East Channel. The bed roughness used was 0.18 m. This was determined from open water profiles taken in the summer of 1987. All other parameter values used in the model are given in Table G1. The pack strength parameters used are such as to give the commonly-used value of μ of 1.3*.

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* See Flato and Gerard (1986) for a discussion of this parameter.

Table G.1 Parameters used in ICEJAM model (refer to Flato and Gerard (1986) for term definition)

Solid ice thickness at toe of jam	0.80 m
Angle of internal friction	50°
Ice density	920 kg/m^3
Porosity	0.40
Shear coefficient	0.240
Passive pressure coefficient	7.55
Tolerance	0.01
Maximum velocity	1.6 m/s
Pack roughness	1.1 m
Bed roughness	0.18 m

The hydraulic roughness of the pack was used to calibrate the model to the measured water levels, keeping all other parameter values fixed. It was found that a pack roughness of 1.1 m was needed to match the measured profiles. This seems reasonable as the hydraulic roughness should be somewhere in the region of 1 to 3 times the average height of the ice projections on the underside of the jam. Field observations noted that the projections on top of the pack were about 0.5 m in height (see Figure 20). Presumably the bottom is not unlike the top.

In calibrating the model it was also found that to have the simulated toe in the same positions as observed in 1987 and 1988, a pack erosion velocity under the toe (see Flato and Gerard, 1986) of 1.6 m/s was needed in both years. This is consistent and seems reasonable, although there are no direct field or laboratory measurements to support it. It is noted that the streamwise step size used in calculations in the toe region had to be quite small (50 m) to achieve stability.

As seen in Figures G2 and G3, the model gave results quite close to the measured values.

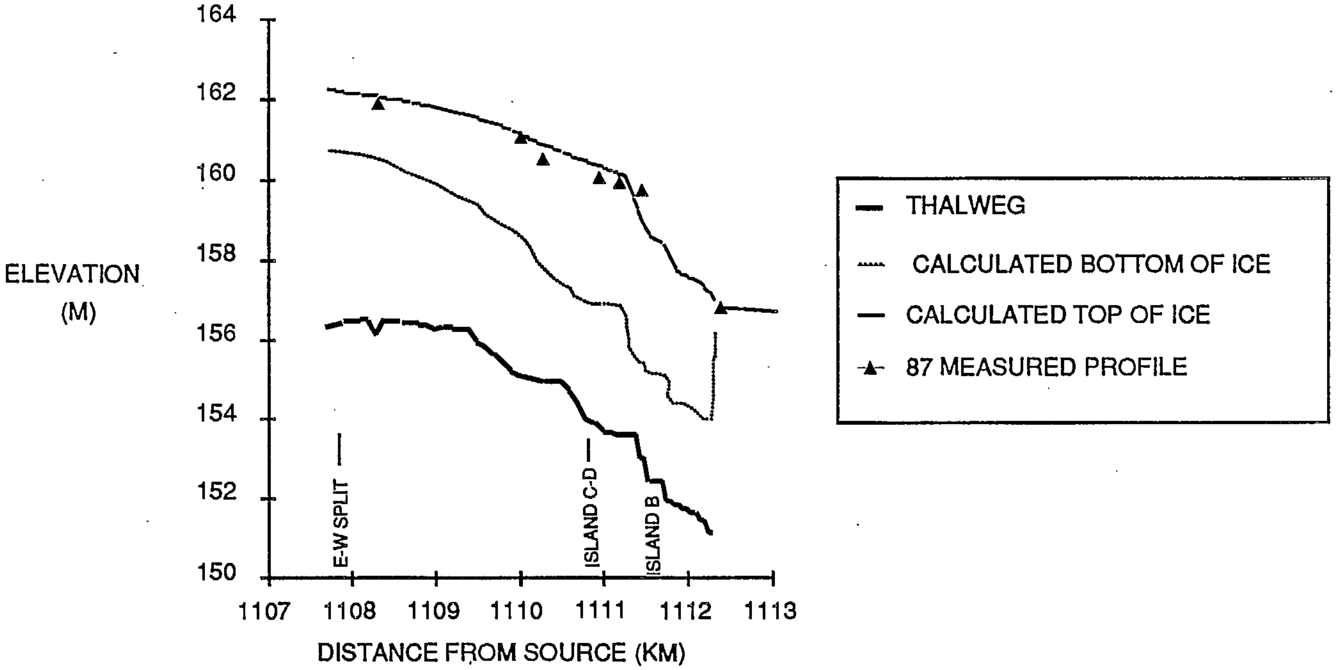


Figure G2. Comparison of numerical model output with field data, East Channel, 1987.

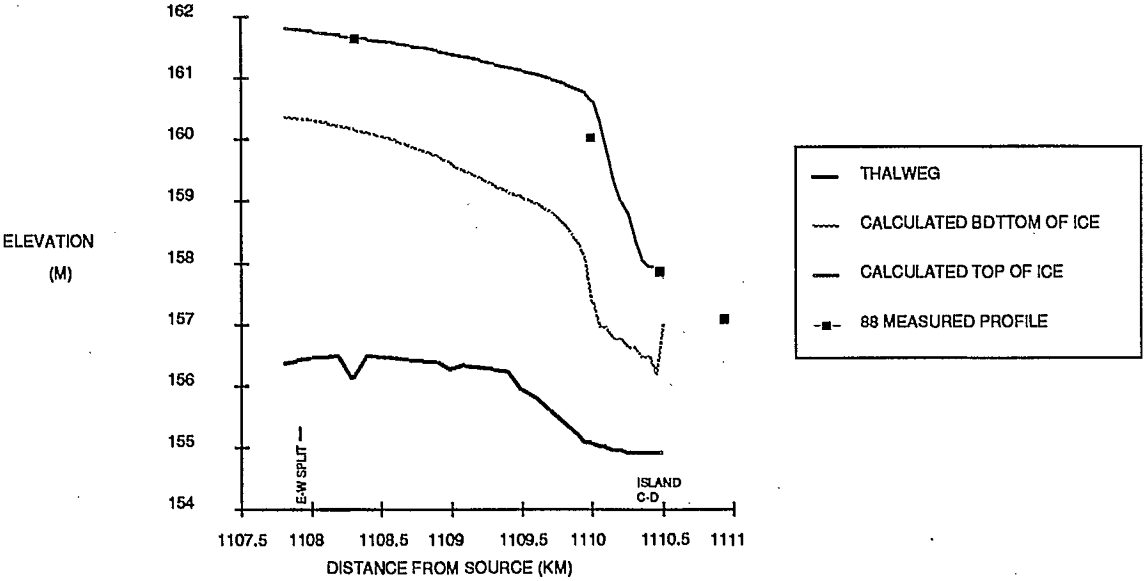


Figure G3. Comparison of numerical model output with field data, East Channel, 1988.

G.4 Ice jam rating curves for the East Channel

Using the ice jam model, a rating curve was developed for the East-West Channel split for discharges in the main channel upstream of the split from 200 to 1400 m^3/s. This was done for a jam with its toe at Island CD, the normal occurrence, with the pack extending well past the split. The calculations indicated the pack at the split would be fully-developed. The rating curve is given in Figure 32.

Serious flooding occurs when the toe of the East Channel jam sets up at the mouth. The model was therefore also applied to this situation and a rating curve developed for a point opposite Island A (km 1113). Figure 36 gives a typical calculated profile through such a jam for a discharge of 1000 m^3/s. From the figure it is evident the pack thins just upstream of the toe. This is because of the very large waterway area, and resultant low hydraulic gradient and pack forces, in this region. The rating curve for the East Channel at Island A is given in Figure 35.

An interesting feature occurred when the model was applied to a jam with its toe set between Island CD and the mouth of the East Channel. No matter what location was tried it was found that the toe was unstable in this region. It was only at either the mouth or Island CD that both the 'geotechnical' stability and erosion velocity criteria could be met. This suggests that only jams with the toe at the mouth or at Island CD can exist and, indeed, no instances of a jam forming with its toe between Island CD and the mouth could be found in the available historical data. This provides further indirect evidence of the model's validity.

G.5 Ice jam rating curve for the West Channel mouth

Ice in the West Channel tends to flow out onto the lake. There is therefore no defined toe. However the water level profiles taken along the jam at this location in 1988 (given in Figure C22) indicated that under these circumstances there is a constant slope in the West Channel near the West Channel split. This suggests the jam in this area may be close to fully developed.

A rating curve was therefore developed for the West Channel just upstream of the split of the West Channel, assuming the pack is fully-developed at this location. The result is shown as the upper curve in Figure 37. The analysis was calibrated using data from 1987 and 1988. As noted in Section 5.6, the high water levels at this location in 1985 are consistent with this rating curve. The 1985 observations indicated a slight modification was required to allow for overbank flow, as discussed in Section 5.6. The modified curve is the lower curve in Figure 37.

APPENDIX H

ASSESSMENT OF HAY RIVER SPRING DISCHARGES

APPENDIX H

ASSESSMENT OF HAY RIVER SPRING DISCHARGES

H.1 Introduction

The annual discharge variation in the Hay River is considerable. Due to the long cold winter and lack of onstream storage, discharge in the Hay River at Hay River decreases over winter to a mean seven-day low flow in March of 1.8 m^3/s (GNWT/IWD, 1984). This is followed by a rapid rise in discharge during the spring thaw to an annual mean flood of 743 m^3/s. It is this rapid discharge increase that defines when break-up will occur. A somewhat unusual feature of the Hay River at Hay River is that the **annual peak** discharge normally coincides with the break-up period. These features mean that prediction of the peak spring discharge. and timing of the rapid rise in discharge, are two of the major parameters controlling the timing and severity of break-up in Hay River.

H.2 Long-range peak discharge forecast

To provide an early indication of whether there may be flooding in Hay River in a given year, a relation was sought between the peak spring discharge, the average snowfall over the basin in the previous winter, and an index of the antecedent moisture in the catchment. As described in Section 5.1, the basin average snowfall was taken as a weighted-average of the accumulated snowfall at Fort Nelson, Fort Vermilion and Hay River. For those years before AES began to record snowmelt as such, precipitation that occurred with the mean daily temperautre below 0°C was assumed to be snow. The andecedent moisture index was taken as the mean October discharge of the previous year. The data is given in Table 2. The serial correlation in the October discharges is noteworthy.

The relation between these three variables is shown in Figure H.1. While there is considerable scatter, there is no clear influence of antecedent moisture. Hence a simple upper bound was drawn, excluding 1985, as discussed in Section 5.1.

UMA (1979) reached the same conclusion with regard to antecedent moisture. They investigated the relation between snowmelt runoff volume and the variables basin-average winter snowfall (October through April),

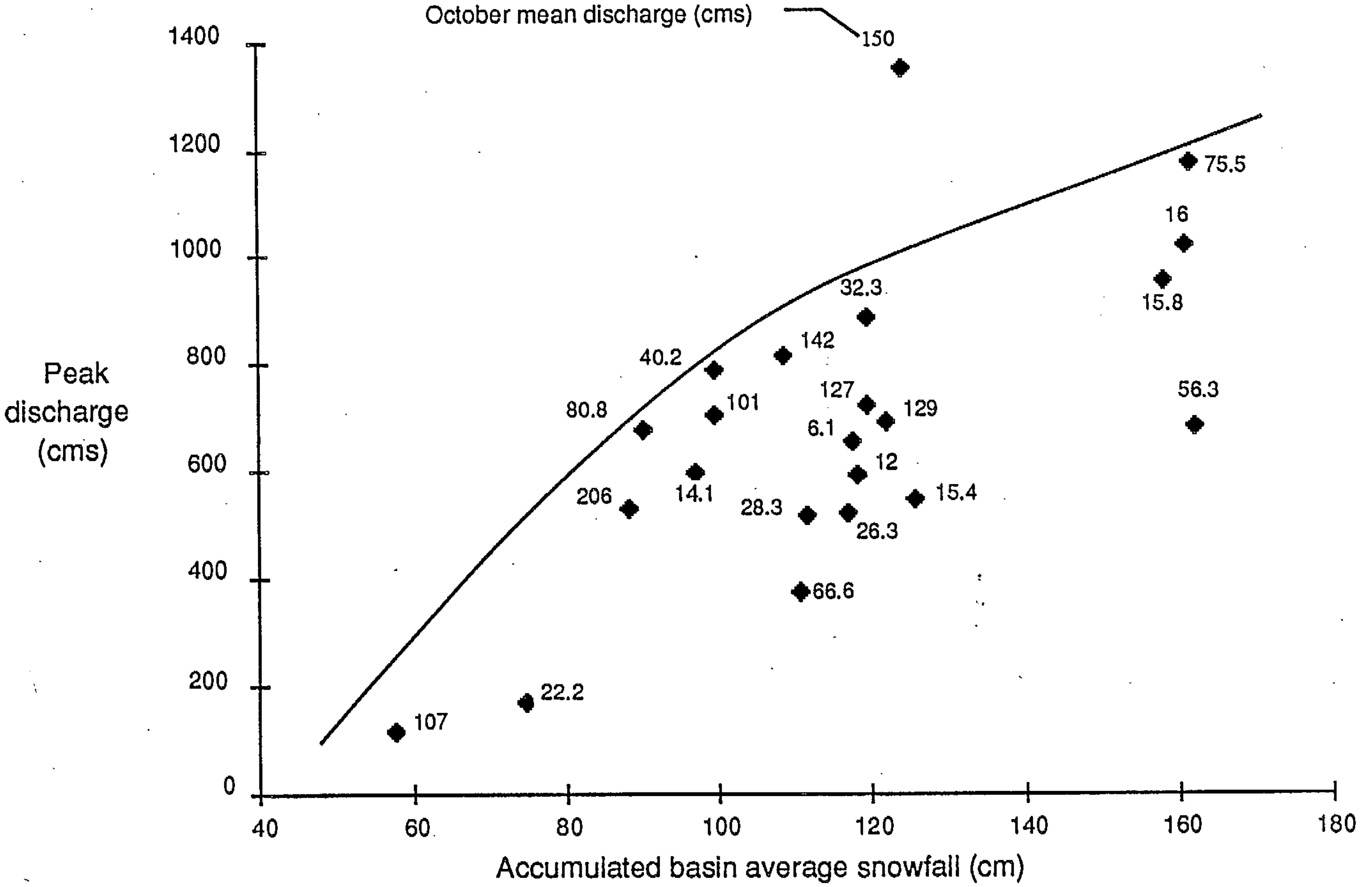


Figure H.1 Relation between peak spring discharge at Hay River and winter snowfall and antecedent moisture.

basin-average winter snowfall (October through April), basin-average fall rainfall (August through October), mean maximum April temperature and mean maximum March temperature using multiple regression. Based on the 14 years of record available at the time, the only significant correlation was between peak discharge and winter snowfall. Beyond this, the model developed by UMA (1979) is not appropriate for the present purposes.

H.3 Real-time peak discharge forecasts

A simple precipitation-runoff model was developed to provide a preliminary assessment of the viability of real-time forecasts of the peak discharge at Hay River using presently available meteorological information.

For this purpose, the catchment was divided into three sub-basins, for each of which one of the existing meteorological stations at Fort Nelson, Fort Vermilion or Hay River could be considered representative. The division was based on Thiessen polygons.

The daily snowmelt in each sub-basin was estimated using the relation (Viessman et al, 1977)

$$M_i = (3.4 + 0.012\ P_i)\ T_i + 1.3$$

where M_i is the water equivalent of the melt (mm), P_i the rainfall (mm), and T_i the mean daily temperature (°C) on day i. The runoff coefficient required to match the measured peak discharges was about 0.04. Such a low runoff coefficient is unusual, but not unheard of, and is not incompatible with the nature of the Hay River catchment. It is very much lower than that required to match the total snowmelt and runoff volumes (see Appendix I).

This runoff was simply routed to Hay River using lag times determined by calibration between the calculated and measured hydrograph. The values for each sub-basin are given in Table H1. As the intent of the algorithm was to predict the peak discharge, no account was taken of the recession.

Table H1: Sub-basin characteristics used for simple Hay River precipitation-runoff algorithm

Representative meteorological station	Sub-basin area (km^2)	Lag time (days)
Fort Nelson	16,354	10
Fort Vermilion	26,936	6
Hay River	4,810	2

Comparison of the output of this algorithm with measured hydrographs indicated that the rapid rise in discharge at Hay River could not be simulated. To attempt to improve the agreement the algorithm was modified so that no snowmelt runoff was generated in the sub-basins until 40°C days of thaw had accumulated, ostensibly to allow for pack ripening. The melt in this period was then released uniformly over 5 days after the accumulated thaw degree days had reached 55. This extra delay was an attempt to improve the timing of the runoff. All three numbers were simply selected by judgement.

Figure H2 shows that even with these modifications the rapid rise in spring 1974 - an 'event' year - could not be simulated. On the other hand the simulation for 1975, shown in Figure H3, is not unreasonable. Nor is the simulation of the rate of rise unreasonable in 1985 - another event year - as shown in Figure H4. In this year the problem is the very poor prediction of the peak discharge. This is further evidence to support the contention by Wedel (1988), discussed further in Appendix I, that available meteorological data does not accurately reflect events of that spring.

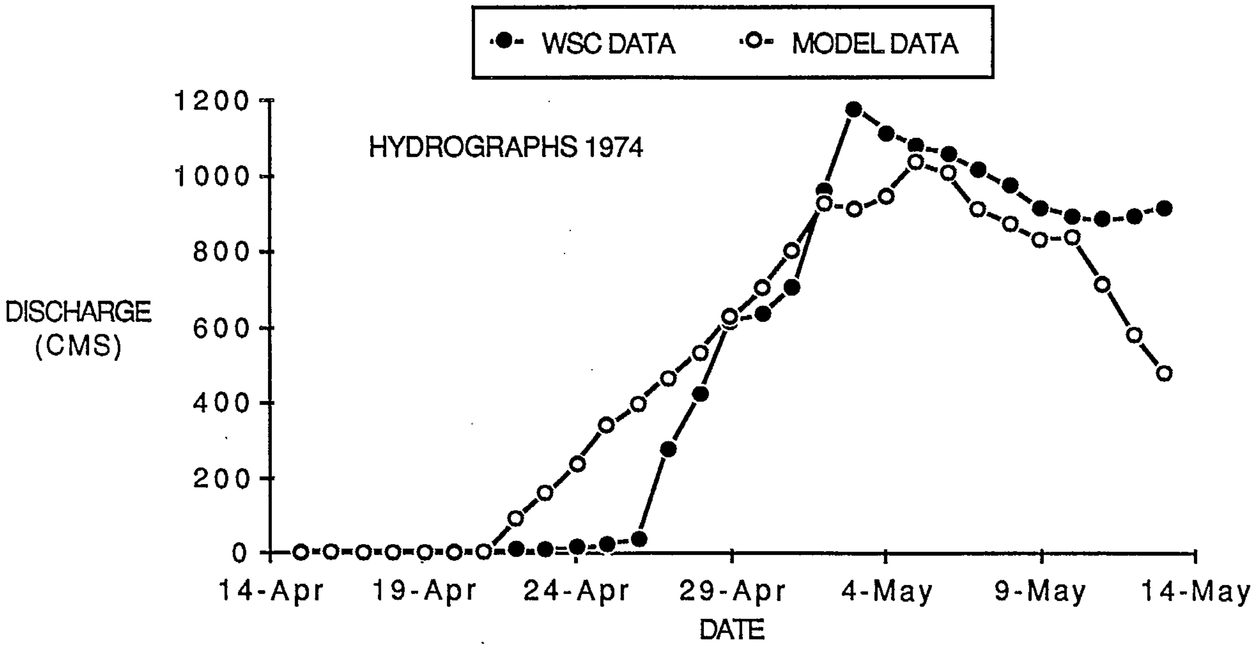


Figure H2 Calculated and (WSC) measured spring hydrograph, Hay River at Hay River, 1974

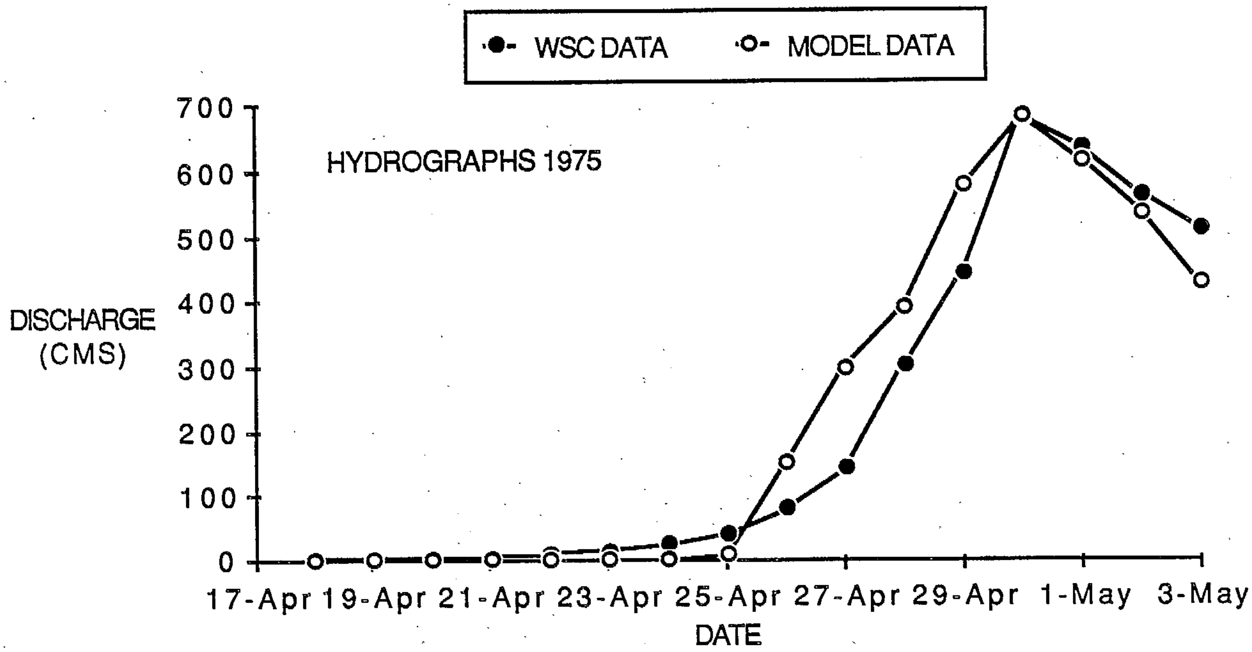


Figure H3. Calculated and (WSC) measured spring hydrograph, Hay River at Hay River, 1975.

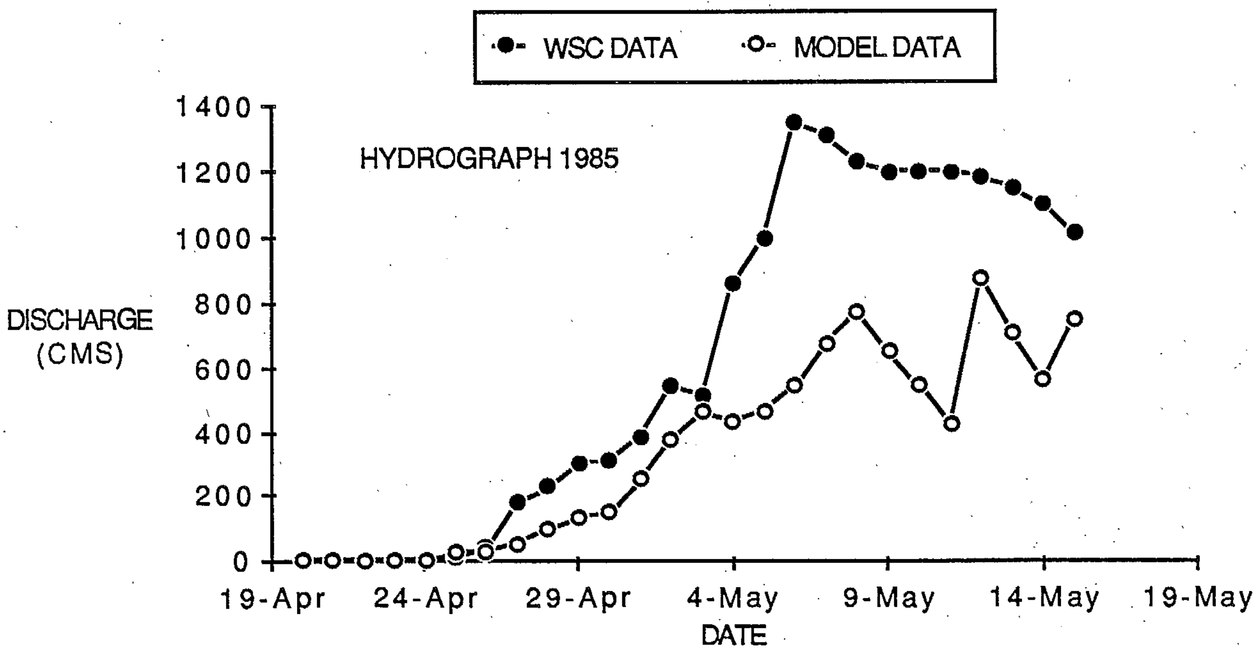


Figure H4. Calculated and (WSC) measured spring hydrograph, Hay River at Hay River, 1985.

Further evidence of this is provided by the comparison of peak discharges in the Hay River at Meander River and at Hay River given in Figure H5 and the hydrographs of Figure H6. The gauge at Meander River has a drainage area of 36,900 km^2, or the upper 77% of the catchment, and began operation in 1974. From Figure H5 it is apparent that the spring runoff from the portion of the catchment above Meander River was more-or-less normal for 1985 and 1986. This cannot be said of the situation at Hay River in these two years, when more than 60% of the peak discharge was provided by the lower 25% of the catchment. Clearly events in the Cameron Hills and Caribou Mountains can have dramatic effects on the discharge at Hay River and thereby on flooding in Hay River.

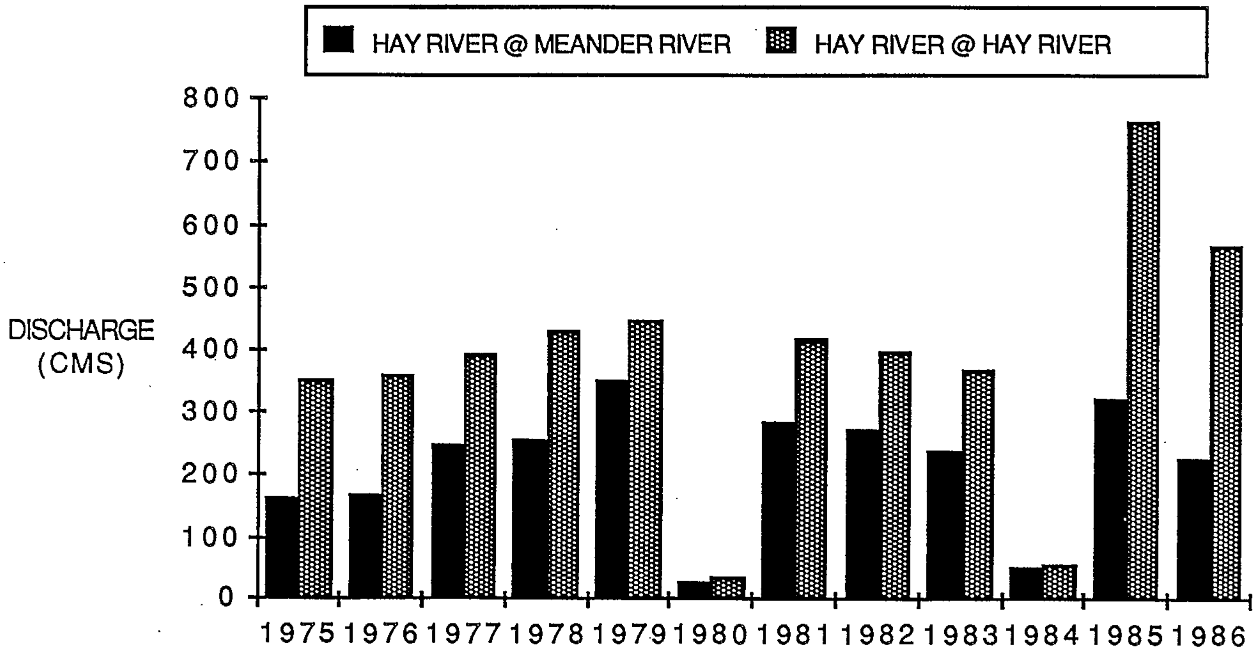
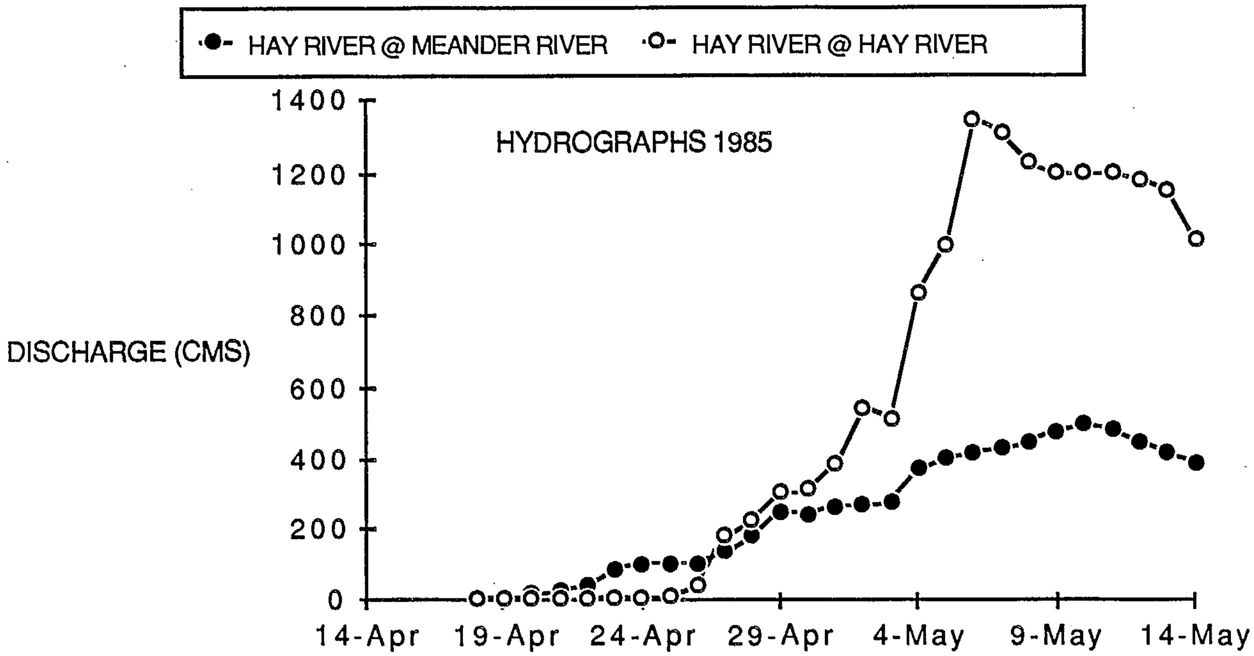


Figure H.5 Comparison of measured spring peak mean daily discharges for the Hay River at Meander River and at Hay River (from WSC data).



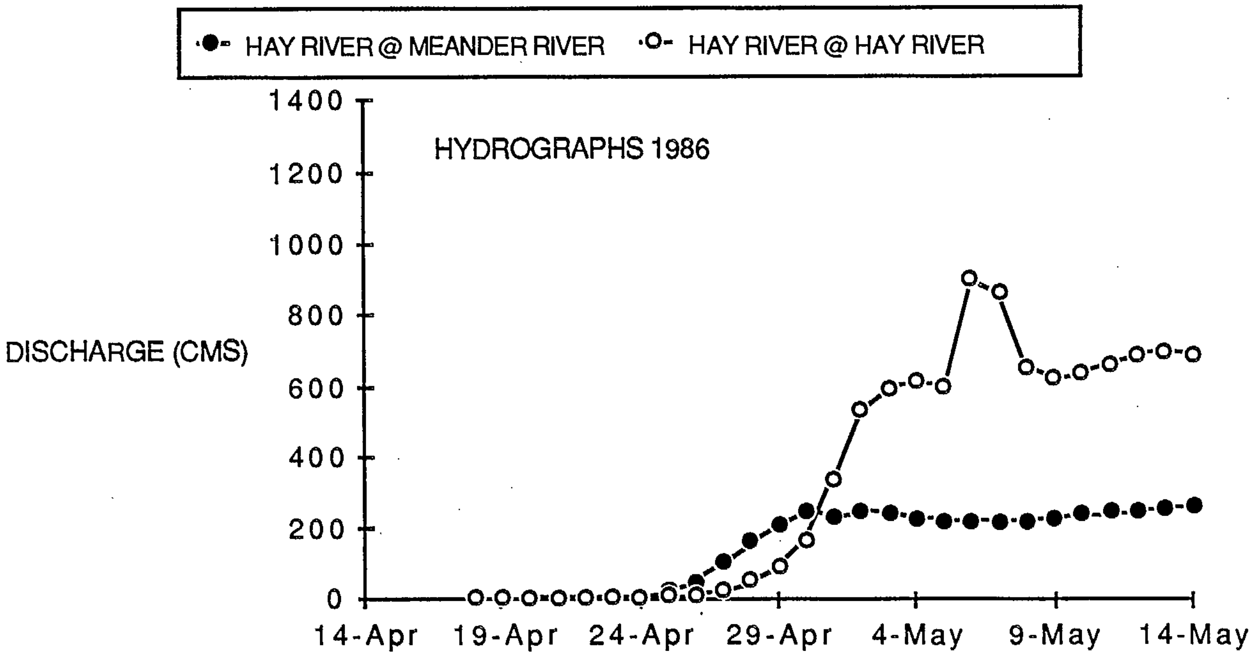
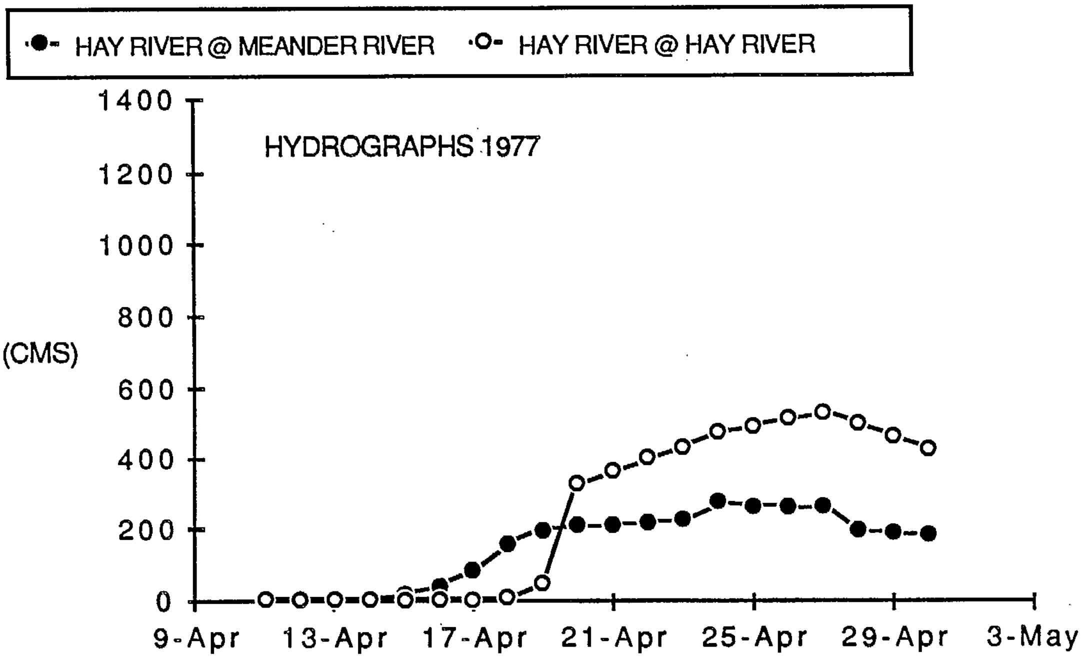


Figure H.6 Comparison of measured spring hydrographs for the Hay River at Meander River and at Hay River (a) 1985 (b) 1986 (from WSC data).

Further clues are evident in Figure H7 as to the reason for the difficulty in simulating the rate of rise at Hay River with the present algorithm. This figure compares the measured hydrographs at Meander River and at Hay River, for the years 1977 and 1982, both years of relatively mild runoff. In both years the hydrograph rise at Meander River is mild while that at Hay River is much more rapid. The intriguing feature is that during the travel time from Meander River - which appears to be about 4 days - there is **no** runoff appearing at Hay River from the lower 25% of the basin, which includes Cameron Hills and Caribou Mountains. It seems that in these years the runoff from this portion of the catchment reaches Hay River more-or-less at the same time as that from above Meander River, and it is this conflation that accounts for the rapid hydrograph rise. This effect could likely be incorporated into the algorithm by considering more sub-basins, but it seems meteorological data from this area is required to make it worthwhile. In addition, mobilization of the Steen River and Lutose Creek WSC gauges during break-up would be useful.

Despite the above limitations, it seems even a quite simple precipitation-runoff algorithm will provide reasonable estimates of the peak mean daily discharge in Hay River, providing adequate meteorological data is available. However, it is clear from the above discussion that much more attention must be paid to the lower Hay River catchment. With no meteorological stations in this area prediction of peak discharges at Hay River will be unreliable, no matter how sophisticated the runoff model.



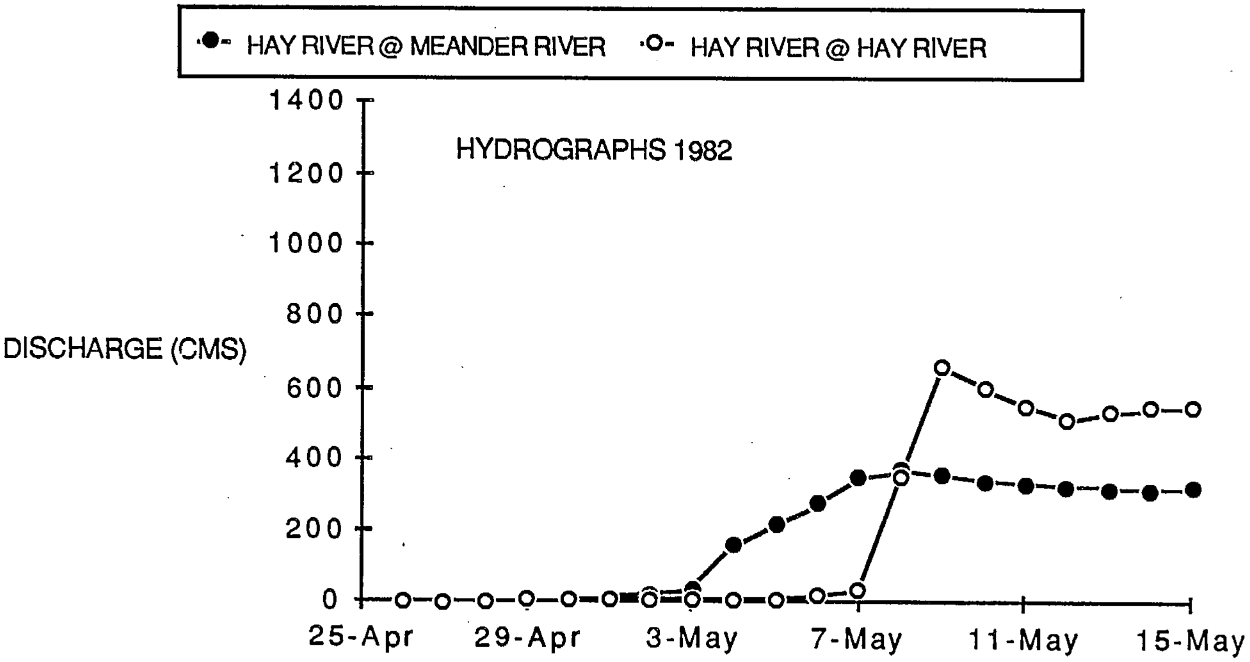


Figure H.7 Comparison of measured hydrographs for the Hay River at Meander River and Hay River (a) 1977 (b) 1982 (from WSC data)

APPENDIX I

APPRAISAL OF THE CAUSE
OF THE
1985 PEAK DISCHARGE

APPENDIX I

APPRAISAL OF THE CAUSE OF THE 1985 PEAK DISCHARGE

In Figure 30 it seems the 1985 peak discharge is an outlier. Wedel (1988) argues that rain from a severe storm in the Cameron Hills area was responsible for the disparity. As no meteorological stations exist in the Cameron Hills, and the two WSC gauges on the streams draining these hills are not operative in spring, this was deduced from general weather patterns in the area and ground photographs from Hay River showing storm clouds over the Cameron Hills. If such rain did occur, existing information suggests it is most unusual, which is consistent with the 1985 discharge showing up as an outlier. Some rain was recorded at each of the meteorological stations in the Hay River basin during the 1985 break-up, but it was not enough to explain the very high discharge.

Discussions with various people involved indicate that this conclusion is still somewhat contentious. As this is an important consideration for the study, to investigate it further a simple water balance was done for the Hay River catchment for that year. As is evident from Figure 9 the volume represented by the spring runoff hydrograph is dominated by that associated with the recession. The rising section of the hydrograph accounts for only a small percentage of the total runoff volume. Therefore a first, and in this case, conservative, estimate of runoff volume can be obtained by simply integrating under the recession limb of the hydrograph.

Some 20 years of hydrographs from the WSC gauge at Hay River were analyzed. Recession constants, K, were calculated for each snowmelt peak using

[I.1] $$Q_2 = Q_1 K^{-\Delta t}$$

where Q_2 is the discharge at time t_2, Q_1 that at time t_1, K the recession constant, and Δt the time interval $(t_2 - t_1)$. These recession constants were remarkably consistent from year to year. The average for $\Delta t = 1$ day was $K = 1.044$. Integration of Equation [I.1] gives:

[I.2] $$\forall = \frac{Q_p}{\ln K}$$

where $\forall$ is the total volume of water under the recession limb of the hydrograph, Q_p the peak discharge and K the recession constant.

The measured peak discharge in 1985 was 1,350 m^3/s. This, with $K = 1.044$, gives a total runoff volume of about 2.7 km^3. The average snowpack on the ground just prior to break-up was 10 cm of water equivalent (INAC, 1985). This represents a volume of 4.8 km^3 of water and gives a runoff coefficient of about 0.56. In the other 21 years analyzed it was typically about 0.36. This disparity in runoff coefficients suggests that a significant portion of the high discharge in 1985 was indeed something other than snowmelt. The most likely explanation is rain.