A NUMERICAL MODELLING
ANALYSIS OF ICE-JAM FLOODING
ON THE PEACE/SLAVE RIVER,
PEACE-ATHABASCA DELTA

TASK F.2 - ICE STUDIES

PEACE-ATHABASCA DELTA
TECHNICAL STUDIES

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PREFACE

This publication reports the method and findings of one component of the Peace-Athabasca Delta Technical Studies. The Technical Studies comprised a three year program of research initiated to “understand available options and select the most suitable remediation strategy for restoring the role of water in the delta”. The program was established in April 1993 through a Memorandum of Understanding signed by representatives of the Governments of Canada and Alberta, British Columbia Hydro and Power Authority, the Mikisew Cree First Nation, the Athabasca Chipewyan First Nation, and the Fort Chipewyan Metis Association.

The Peace-Athabasca Delta Technical Studies were initiated through a recognized need for further research regarding the effects of Peace River flow regulation and climatic variability on the hydrological processes of the delta, particularly with regard to the spring ice-jam induced flooding of the high elevation perched basin environments. The results of such research, and further assessments of remediation options, support the development of a strategy for restoring the role of water. Future implementation of this strategy will occur through an Ecosystem Management Plan for the Peace-Athabasca Delta as a next step following completion of the Peace-Athabasca Delta Technical Studies. This plan will require rigorous development of specific ecological objectives prior to the selection or implementation of any remedial measures directed toward the general objective of restoring the role of water in the delta.

Study Perspective:
A Numerical Modelling Analysis of
Ice Jam Flooding on the Peace/Slave River,
Peace-Athabasca Delta

An understanding of the range of flow conditions and ice jam locations which could result in significant flooding of the delta from the Peace/Slave River system is required to determine the potential for such flooding under current conditions, and to aid in the design of remediation strategies as required.

The backwater elevation generated as a result of ice jamming on the Peace River was calculated (or “modelled”) for different ice jam scenarios. Each scenario involved an ice jam at a different, but typical, location on the Peace River and varying Peace River flow rates. The elevation of the backwater was calculated for each scenario and compared with the bank elevation at the location of the ice jam. In this way, the flow required to generate overbank flooding for the various scenarios was determined, providing a good estimation of the magnitude of flow required to create large scale overbank flooding for the area in general.
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SUMMARY

The Peace-Athabasca Delta Technical Study, P-ADJAM, stemmed from the concerns raised regarding the long term trying trends affecting the Peace-Athabasca Delta (P-AD), one of the world’s largest freshwater deltas. A common perception during the 1970’s and 1980’s was that lower flows on the Peace River due to regulation by the W.A.C. Bennett Dam, minimized the probability of large open-water flood events capable of inundating the perched basins of the P-AD adjacent to the Peace River. Results of several companion studies using hydrometric data confirm that open-water floods have been ineffective in producing high-elevation floods along the Peace River adjacent to the Peace-Athabasca Delta. Even the historically high flow event of 1990 did not produce a flood of sufficient magnitude to flood high-elevation portions of the delta.

Over the period of the “far-field” hydrometric record (removed from but an index of events near or within the P-AD), backwater produced during river-ice breakup has exceeded that of the 1990 open-water event on several occasions. It was breakup backwater, in 1974, that resulted in the last major documented flooding of the elevated perched basins within the P-AD. Notably, local traditional knowledge and other anecdotal information also suggested that ice jams played a role in some flood events. Unfortunately, this information is highly qualitative and while valuable, much of it awaits comprehensive ground calibration (e.g., water levels). The “near-field” instrument record (within or contiguous to the P-AD) is almost non-existent for the period when ice breakup and related ice jamming are known to occur. Furthermore, concentrated stream gauging efforts are not yet fully evolved since the significance of ice jam flooding to the P-AD has only just been brought to the forefront by recent hydrological studies. In addition, stream gauging during dynamic ice conditions is very difficult, as is measurement site access in the P-AD. Quantitative data is necessary for the effective management of the water-related resources of the P-AD and the appropriate design and implementation of remedial measures such as control structure deployments or flow re-regulation. As such, modelling the backwater associated with ice jam flooding becomes a valuable tool.

In a joint Northern River Basin/Peace-Athabasca Delta Technical Study investigating the hydro-meteorological controls exerted on the discharge and ice regime of the Peace River and their role in the evolution of break-up ice jamming, the following was concluded: i) From the point of regulation, higher flows at freeze-up result in a higher freeze-up stage, an effect known to influence the timing and severity of break-up. In the lower portions of the Peace River, however, flow regulation seems to have produced minor changes in factors, such as ice thickness and strength, that could potentially affect the severity of breakup and related ice-jam flooding; ii) Temporal analysis of the aforementioned factors also detected a weak climate signal suggesting that since approximately the mid-1970’s the period of ice cover may have become slightly warmer and the pre-breakup melt period may have become more intense and/or more protracted; iii) Flow contributions from the point of regulation are higher, on average, at the time of breakup near the P-AD in the post-regulation period than prior to regulation (a common perception was that reduced flows due to regulation were responsible for the decline in severe ice jams); iv) The major ice-jam floods that occurred in the 1960’s prior to regulation and in the early 1970’s after regulation have been associated with large runoff events from downstream tributaries.

A major conclusion of the P-ADJAM study is commensurate with the above findings. Specifically, there appears to be a requirement for flows in the Peace River near the P-AD to exceed 2500 m$^3$/s so as to permit ice jam backwater to enter the P-AD via several small to
medium-sized tributaries. Moreover, evidence suggests that macro-scale flooding, such as that experienced in 1963, 65, 72, 74, may require flows in excess of 5000 m³/s. Such circumstances are characterized by extensive overland flow beyond the simple filling of the hydraulically well-connected channels and lakes in the P-AD. The aforementioned flow requirements apply to the circumstances presented by lodgments immediately adjacent to the P-AD (e.g., Moose Island, Rocky Point). An extremely large (long) jam, for example - in place near the Scow Channel outfall on the Slave River, could generate considerable over-bank water levels as far back as the Claire River mouth for flows as low as 2500 m³/s (notwithstanding limiting conditions for upstream ice supply and flow fragmentation by tributary channels along the ice jam profile).

A second major result of this study is based on a first-order analysis of the conveyance capacity of the Claire River tributary under the influence of ice jamming on the Peace/Slave River. Notwithstanding the scenario of flood-plain flow, the conveyance capacity of this channel is relatively insignificant to the water balance of the large, well connected lakes of the P-AD. At a localized scale, however, its role, in concert with secondary ice jamming, may become significant for the wetlands adjacent to its banks. This finding is particularly meaningful in light of the recent restoration of the Claire River mouth and the possibility of deploying small-scale artificial ice structures on similar tributaries to promote localized flooding.

The P-ADJAM study results point to a number of recommendations which may be instructive for the effective management of the water-related resources of the P-AD: i) Stream gauging (water stage) should be conducted during the critical periods of ice breakup and ice jamming, along the Peace/Slave Rivers and on important P-AD tributaries. These efforts would provide critical verification data for ice jam simulation research, the design of remedial measures and for hydrological investigations. In addition, information derived from local traditional knowledge and oral/written history should be actively calibrated; ii) Ice jam modelling results should be coupled with hydraulic flow models able to deal rigorously with flood-plain flow. There is also a need for additional topographic surveys which would better describe the near-channel bank geometry along and inland from the Peace/Slave Rivers; iii) The hydrologic and hydraulic role of the P-AD tributaries should be investigated further to assess the possibility of secondary ice jamming within the P-AD and to refine future flow modelling of its channel and lake system; iv) Further development of in-situ structural remedial measures, should consider the deployment of small-scale artificial ice structures in selected P-AD tributaries thereby assisting in the generation of localized flooding (promote secondary ice jam flooding); v) Remedial measures involving the re-regulation of the Peace River should evolve from multi-disciplinary study including further ice jam, hydraulic, geomorphologic and hydrologic modelling. The timing and delivery of these efforts might well be commensurate with the expectation of high snow melt yields from the main stem tributaries below the W.A.C. Bennett facility; vi) Further study is recommended to provide a comparison of available numerical ice jam models. Such study should include a comprehensive summary of the required input parameters, their physical basis and verification case studies illustrating their influence. Such a task could be undertaken by members of the Canadian Geophysical Union - Hydrology Section - Committee on River Ice Processes and the Environment.
1. INTRODUCTION

This report is the result of work conducted for the Peace-Athabasca Delta Technical Studies (P-ADTS) and the National Hydrology Research Institute (NHRI). The project evolved from a concern expressed by the P-ADTS regarding a long term drying trend that has affected the Peace-Athabasca Delta, one of the world's largest freshwater deltas. Flooding is critical to the ecosystem health of river-delta environments, particularly to perched-ponds and lakes that are vertically separated from the open-water flow system. Unfortunately, the P-AD has not experienced a major flood since 1974. As a result, significant drying has occurred in the higher-elevation portions of the P-AD landscape. This is believed to have lead to significant changes in, for example, the vegetation regime and the related small-mammal habitat. The P-ADTS is currently completing a companion study of the significance of drying/flooding to the vegetation regime of the P-AD.

Beginning in 1968, the Peace River became regulated with the construction of the W.A.C. Bennett Dam in its headwater reaches within the province of British Columbia. Initial filling of the dam caused major reductions in water levels within the P-AD and resulted in the construction of rock-filled weirs in an attempt to restore levels to pre-regulation conditions. Unfortunately, this has only been successful for the large lake and channel systems directly connected by the main flow system of the Athabasca, Peace and Slave rivers. Drying has continued in the higher elevation perched basins because of the lack of large over-bank floods.

A common perception during the late 1970's and 1980's was that lower flows on the Peace River resulting from regulation precluded the generation of flood levels that would inundate the perched basins, especially in the northern areas of the P-AD near the Peace River. There were numerous anecdotal references within the P-AD literature and opinions expressed by local inhabitants, however, that ice jams also played a role in some flood events. Prowse and Lalonde (1996) showed for the first time that ice jams play a significant role in flooding the P-AD, especially the critical productivity zones which are perched or isolated from the main flow network. Until the completion of the joint Northern River Basin Study (NRBS)/P-ADTS study examining hydro-meteorological conditions controlling ice jam floods (Prowse et al. 1996), no comprehensive analysis had been conducted to examine the influence of regulation and climate variation on ice break-up severity and ice jam formation. In concert with the aforementioned NRBS study, the objective of the P-ADTS-P-ADJAM is to examine the range of hydraulic conditions and ice-jam lodgment scenarios which could result in significant flooding of the P-AD from the Peace/Slave River. Secondly, as a companion analysis to the NRBS work, discussion is provided on the role of historical flow variations and ice conditions on the consequences of ice jam formation. Thirdly, the role of tributary inflow in relation to main-stem ice jamming on the Peace/Slave River is examined.

The main body of this report is divided into five major sections: 1) a general site description and overview of the hydrology and flood history of the P-AD and its major contiguous river reaches; 2) a brief review of the physical nature of ice jamming and the value of numerical modelling, thence a detailed description of the numerical ice jam model ICEJAM and its application to the Peace/Slave River; 3) a presentation of the modelling scenarios and the ICEJAM simulation results; 4) a discussion of the hydraulic and ice cover influences on ice-jam severity, including the effects of variations in the discharge regime. The role of P-AD tributary
inflow is introduced and discussed; 5) some final conclusions and recommendations for future work.

2. BACKGROUND

2.1 Hydrology

2.1.1 Peace River

The Peace River originates in the alpine regions of northeastern British Columbia (Figure 2.1). Many of these alpine basins are glacial fed and ultimately feed into the large Williston Reservoir behind the W.A.C. Bennett dam. Immediately below the dam, in the foothills, the basin is mostly forest and has little capacity for basin storage. The channel is predominantly straight with occasional islands and minor gravel bars, and is approximately 450-500 m in width.

The Smoky River, the main tributary to the Peace, enters a short distance upstream of the town of Peace River. It drains the front ranges of the Rocky Mountains and has an area of approximately 50,300 km² representing 27% of the Peace River basin at this point. From the confluence of the Smoky River, the river trends northward, switching to the north east in the vicinity of Fort Vermilion. This reach of the Peace River primarily drains the Peace River Lowlands although the headwaters of some tributaries extend onto the Alberta Plateau. The river widens from approximately 500 m at Peace River to around 650 m at Fort Vermilion.

No major tributary contributions occur between the town of Peace River and Fort Vermilion. The contributing area along this reach of the river represents only 16.5% of the basin area at Fort Vermilion and only 12.5% of the basin area at Peace Point. In terms of the non-regulated basin area, this section represents 24% and 16.5% at Fort Vermilion and Peace Point respectively. The basin is dominated by forested terrain with intermittent muskeg.

From Fort Vermillion to Peace Point the river, which is in the vicinity of the upstream boundary of the P-AD, is in distinct contrast to the upper reaches. The landscape of the lower Peace River valley is no more than 20-25 m deep, incised into the old lake bed of Glacial Lake McConnell. As the river cut into these lacustrine deposits it wandered away from its preglacial course in several places and subsequently began to cut into bedrock. These locations coincide with the small waterfalls and rapids that exist along this reach (e.g., Vermillion Chutes, Boyer Rapids). The channel downstream of the Vermillion Chutes increases dramatically in width, exceeding 1500 m at some locations. Further downstream the channel narrows (approximately 700 m at Peace Point).

The only significant tributary draining into the Peace River below Fort Vermilion is the Wabasca River which drains the southern portions of the Birch Mountains and surrounding plains. This basin has an area of approximately 35,800 km² representing 51% of the drainage between Fort Vermilion and Peace Point and 12% of the entire basin at Peace Point. The overall drainage area between Fort Vermilion and Peace Point accounts for 24% of the entire Peace River basin and 31% of the unregulated basin area at Peace Point. Unlike the upper areas of the Peace River catchment, this portion of the basin is dominated by a forested muskeg terrain.
After some 1100 km, the Peace River finally reaches the northern edge of the P-AD. Total drainage area to this point is 293,000 km². Here the Peace River is characterized by an irregular meandering channel pattern with occasional islands (some very large) and bar complexes. The channel course, after progressing roughly east-southeast from Peace Point to Rocky Point, diverges sharply to the NW under the influence of substantial Canadian Shield bedrock extending north and somewhat west from Lake Athabasca.

2.1.2 Peace-Athabasca Delta

The Peace-Athabasca Delta is formed by the Peace, Athabasca and Birch Rivers at the western end of Lake Athabasca in the province of Alberta (Figure 2.1). Delta development began following recession of the Laurentide Ice Sheet (Late Wisconsinan), with these rivers draining into a much larger Lake Athabasca. Initially, the Peace Delta had a rapid rate of growth, but as levees attained sufficient height, most of the flow and sediment were carried directly to the Slave River; thus, the Peace River Delta can be considered inactive (Bayrock and Root 1973). In contrast, the Athabasca and Birch River deltas are still actively depositing sediment.

As the P-AD continued to grow, many water bodies became separated from Lake Athabasca. Three large shallow lakes (Figure 2.1 inset; Claire, Mamawi and Baril; <1 to 3 m deep) currently occupy a large proportion of the 3900 km² delta area, and are connected to Lake Athabasca and other small basins by a myriad of active and inactive channels. The P-AD and Lake Athabasca are connected to the northward-flowing Peace and Slave rivers by three major channels, Rivière des Rochers, Revillon Coupé, and Chenal des Quatre Fourche (Figure 2.1 inset). Although flow is normally northward, it can reverse when the Peace River is higher than the level of Lake Athabasca. Discharge in these channels is proportional to the difference in water levels of the lake systems and the Peace River; reversing flows in the P-AD are not uncommon. Water levels experience a peak on the Peace and Athabasca rivers during the spring breakup period (late April-early May) and a few weeks later (June) during a period of sustained high flow produced by runoff from the Rocky Mountain headwaters. It is during these two periods that high water levels on the Peace River can obstruct the northward flow of water. As a result, lake-water levels are typically highest in the P-AD and on Lake Athabasca during the spring and summer, but then recede during fall and winter when the outflow to the Slave River is greater than inflow to the P-AD.

Depending on the elevation of lake and river water levels, water can also feed into the adjacent landscape, and fill the shallow perched basins. Topographic relief seldom exceeds 1m above the surface of the major Delta lakes, except for the levees and islands of Canadian Shield located primarily in the north-east. Perched basins have been classified according to the degree of their connection with the lake and channel flow system as open-drainage, restricted-drainage, and isolated (Peace-Athabasca Delta Project Group 1973). These classifications roughly correspond to the general mapping of drainage types noted on Figure 2.1 (inset), i.e., open, restricted and severely restricted drainage (Jacques 1989, Prowse and Demuth 1996).

In the case of isolated perched basins (severely restricted drainage), water can only enter the basin through over-bank flooding, and water-level decreases are almost exclusively controlled by evapotranspiration. It is estimated that the P-AD region is characterized by an average annual water deficit of 80 mm (Prowse and Lalonde 1996). Groundwater flow through the levees is considered negligible (Nielsen 1972), therefore, periodic flooding of these perched basins is
essential for their survival. When full, such basins account for over 19,000 km of shoreline within the delta (Townsend 1984). Moreover, the vertical range of most delta plant communities along such shoreline is quite small and as a result, minor changes in water level can lead to dramatic changes in the abundance of emergent and submergent aquatic vegetation. Correspondingly, relatively small water-level changes will necessitate large flood-water volumes given the topographic and bathometric characteristics of these basins and the P-AD in general (e.g., P-ADTS 1996a).

2.2 Flood History

2.2.1 Peace River Flow Regime

In general, the effects of flow regulation for a large cold region river are manifested as a marked flattening of the annual hydrograph, with much of the summer flows being stored and released during the winter period. The relative influence of this regulation on downstream locations is complicated by two primary factors: a) climatic variability and its effect on the flow regime, both upstream and downstream of the dam, and b) the large contributing area downstream of the regulating structure.

Filling of the Williston Lake behind the W.A.C. Bennett Dam in 1968 marked the beginning of lower than average flows on the Peace River. During the four years, 1968-1971, there was a net storage behind the dam of $41 \times 10^9$ m$^3$ of water (Muzik 1985). As a result, Peace River flows were reduced by as much as 5600 m$^3$ s$^{-1}$ and associated water levels by as much as 3 to 4 m. Over this filling period water levels on the connected system of lakes and channels in the P-AD were greatly reduced, while lower peak flows on the Peace River were believed to eliminate the potential for flooding of higher perched-lake environments (Peace-Athabasca Delta Project Group 1973). In response to the ecological impacts to the Delta, fixed crest weirs were constructed on two major channels which, during the open-water period, serve to direct water northward from the Delta (e.g., Prowse et al. 1995, Figure 2.1 inset). Although the control structures served to restore water levels at lower elevations of the Delta (Aitken and Sapach, 1994), perched basins along the Peace River and at higher elevations in the Delta have continued to dry. As of the initiation of the $P-ADJAM$ investigation, these basins have not been flooded since 1974. Impacts of this persistent drying trend are discussed by Thorpe (1986) and Townsend (1975, 1984).

Past analysis of flood peaks, has focused primarily on water levels recorded in the main Delta lakes and channels (e.g., Aitken and Sapach 1994; Muzik 1985). Such analysis is relevant to assessing the flooding probability of open-drainage/restricted-drainage basins, but not of high-elevation isolated basins, particularly near the Peace River. Alternately, to examine the pre-/post-regulation and open-water/ice related flooding regime in detail, Prowse et al. (1996) focused on the discharge regime and water levels recorded on the Peace River at Peace Point (Water Survey of Canada gauge 07KC001). This is the closest (approximately 70 km upstream of the main Delta area) hydrometric station to the P-AD with a pre-regulation record. These data, including analysis by Prowse et al. (1996), became the basis for conceptualizing the flow regime scenarios and boundary conditions applied in the $PAD-JAM$ investigation. Records from Peace Point may be used to provide a general index of ice breakup severity and hence expected ice-jam severity. This is considered a reasonable assumption given that the river reach near Peace Point is similar in character to most of the Peace River near the Peace River Delta. As such, for given changes in
the Peace River flow regime, a perspective on the relative magnitudes of open-water and ice-induced flooding is discussed next.

2.2.2 Open-Water and Ice-Related Flood Peaks

There have been major changes in mean and peak flows near the Peace-Athabasca Delta. Prowse et al. (1996) discuss the mean, maximum and minimum monthly flows recorded at Peace Point for the pre- and post-regulation periods (unfortunately, the pre-regulation record extends back only to 1959/60). The pre-regulation peak-monthly flows typically occurred in June ranging from a low of 5,950 m$^3$ s$^{-1}$ to a maximum of 9,790 m$^3$ s$^{-1}$ and averaged 7,482 m$^3$ s$^{-1}$. With the seasonal adjustment to flow, these figures all decreased by some 3,500 m$^3$ s$^{-1}$. This translates into a decrease of open-water levels ranging from approximately 1.75 m at the higher maximum mean-monthly flows, to 3.25 for the minimum mean-monthly flows (-2.56 m for the change in mean-monthly flows). More specifically, for annual water levels achieved under open-water flow conditions before and after regulation, peaks averaged 217.5 m for the eight-year, pre-regulation period, whereas for the post-regulation period, peaks averaged 215.4 m - a 2.1 m decline.

Notably, the post-regulation data include the largest flow event on record for the Peace River. In 1990, the Peace River discharge reached 12,600 m$^3$ s$^{-1}$, 700 m$^3$ s$^{-1}$ greater than the previous high recorded in 1964 prior to regulation. Significantly, however, even this historically-high, open-water flood failed to recharge the high-elevation perched basins. It is estimated that an open-water flow in the order of 14,000 m$^3$ s$^{-1}$ is required to over-top the Peace River banks near the Delta (i.e., at Sweetgrass Landing near the Claire River, Figure 2.1; Peace-Athabasca Delta Project Group 1973). As concluded by Prowse and Lalonde (1996), open-water floods have not been responsible for the over-bank flooding of the high-elevation perched-basin regime. The other obvious source of potential flooding is that produced by ice-jam backwater.

In early hydrologic assessments of the Peace-Athabasca, the role of ice jams in flooding perched-basins was mentioned periodically. With large-scale drying of the Delta beginning in the 1970's, however, attention was focused, almost exclusively, on open-water conditions and engineering structures (weirs) for restoring water levels within the large lake system. Following the failure of the aforementioned 1990 open-water event to flood the perched basins, the focus shifted to the role of ice jams.

Using the aforementioned gauge record for Peace Point, Prowse et al. (1996) extracted peak-instantaneous, water level data for spring breakup directly from original hydrometric chart recordings for the period, 1962-1992. The data represent the peak water levels measured during the breakup periods (as a result of the effects of a breakup front moving past the site or backwater from downstream ice jamming). In relation to the open-water rating curve for the Peace Point station, Prowse et al. (1996) show that peak breakup water levels for seven breakup years exceed that produced by the 1990 open-water event - some by as much as 2 m. Furthermore, these levels were produced by Peace River spring flows of a 1/3 to a 1/2 that which produced the 1990 open-water event. Data from the Peace Point hydrometric station, suggest this occurred on a biennial basis in the 1960's prior to regulation (1968) of the Peace River, but only three times since. While this data cannot be directly related to the P-AD area, they do illustrate that much higher water stage is produced by ice-induced backwater and at much lower flows.

Despite the value of the Peace Point hydrometric station in terms of defining the flow regime for the Peace River near the P-AD, the lack of long-term systematic visual and instrument
observations along the Peace/Slave Rivers and within the P-AD have made local historical knowledge a crucial component of this and other P-ADTS studies. Moreover, while Peace Point observations serve as a valuable severity index, the delineation of ice jam sites for the P-ADJAM study has relied almost entirely upon historical knowledge.

2.2.3 Historical Knowledge

Because of the significance of flooding to the Peace-Athabasca Delta, there have been attempts to construct flood histories from local residents and historical archives (e.g., Peterson, 1992; 1995; Thomson, 1993; Thorpe, 1986). The lack of true elevation data meant that such analyses had to rely on simple magnitude classifications of the various disparate data. The summary by Peterson (1995) notes that ice jams have been a critical factor in flooding of the P-AD and account for over 70% of the highest magnitude floods. Summer floods have been less common and less effective, the 1990 event again cited as having produced the highest water level recorded since the 1930's but being of insufficient magnitude to flood the high-elevation perched-basins of the delta. This report also notes that since 1803 there have been at least 13 years of major ice jam floods on the Peace River, the most recent including 1958, 1962, 1965 and 1974 (Peterson, 1995). An earlier report by Peterson (1992), acknowledged that some confusion existed in local accounts about the actual year of the "1962" flood which was also reported as 1961 and 1963. Subsequent archival research (Giroux 1995, personal communication) has uncovered early correspondence regarding an aerial surveillance of the flood conducted as part of a forestry impact assessment (Jackson 1963). This document confirms that 1963 was a major ice-jam flood year. Similarly, Giroux (1995, personal communication) discovered documentation describing a bank-full flood produced by an ice jam on the Peace River near the P-AD in 1972 (e.g., Smith 1972). Peterson (1992) assigns a "zero" magnitude to this year.

Aside from corroborating the occurrence of most of the major floods observed at the Peace Point hydrometric station and validating its use as an indicator of ice jam flood events that affect the P-AD, such information was of great value to the P-ADJAM study, permitting the identification of several critical ice jam lodgment sites. River geometry, interpretation of unpublished correspondence (Jackson 1963, Orange 1965, Smith 1972), flood history data by Peterson (1992, 1995) and anecdotal information suggested the following lodgment sites (Figures 2.1, 3.2):

- 2 km downstream of the Scow Channel outfall on the Slave River, characterized by split flow around large island with numerous rock islands spanning the channel.

- Junction of the Peace and Slave Rivers at the mouth of the Riviere des Rocher characterized by extensive shallows with sand bar complexes spanning the channel and sudden widening of channel.

- Rocky Point just downstream of the Chenal des Quatre Fourches mouth, characterized by a 180° change in direction, rock islands and evidence of strong ice pushes on the right bank at the turn.
• Moose Island west bifurcation downstream of Carlson’s Landing, characterized by a sudden change in channel direction, split flow and a large shoaling area emanating from the left bank of the north (main) channel.

3. NUMERICAL ICE JAM MODELLING

In this section, details of the ice jam analysis are discussed. Following a general overview of the value of the numerical modelling exercise (section 3.1) and the physical nature of breakup ice jams (section 3.2), a description of the ICEJAM numerical ice jam model is presented (section 3.3). Details of the model input data, including channel surveys conducted during 1994 and 1995 are provided in section 3.4.

3.1 The Value of Numerical Ice Jam Modelling

In remote, frontier areas such as the P-AD, the quantitative measurement of ice conditions and related hydraulic effects is often very difficult. As such, it may become practical and economic to simulate such conditions with the aid of a model. Such a situation certainly presents itself for the P-AD given the dearth of near-field hydrometric and ice-related data associated with historical ice jam flooding.

There are many types of “models” used in ice engineering and research (e.g., see Ashton 1986). In general, analytical models represent formulations that describe or simulate, by empirical means or a set of physically-based relationships, the outcome of a process affected by certain physical variables which we may or may not have knowledge of. Numerical models are simply analytical models whose formulations have been subject to a routine that permits efficient computation in space and in time. A simple analytical model may be applied by performing hand-calculations to generate results for single-case scenarios in space and time or establish upper/lower bounds. Numerical models have the ability to represent processes more continuously in space and/or time and derive utility from being able to compute extreme conditions beyond what has already been documented by direct observation.

In general, the accuracy of modelling results is commensurate with the quality of the input data. For ice jam backwater modelling, this involves representative spatial data describing the river bathometry and, if possible, direct or inferred evidence of ice jam parameters for the specific site or event of interest (e.g., ice jam roughness). There is utility, however, in modelling a process from a relative standpoint for situations where absolute results can not be realized. Following the progression of a process in time and/or space by fixing certain input parameters and allowing others to fluctuate between a set of bounds defined by previous experience or hypothetical considerations, may allow instructive sensitivity analysis and provide insight into model errors. Moreover, a further refinement of the model’s founding analytical relationships may be realized.

In summary, the P-ADJAM investigation has combined a number of the modelling elements discussed above to simulate ice jam backwater for a frontier river site where no direct, near-field instrument observations of ice jam impacts have been made. Before describing the details of the modelling undertaken, a brief overview of the physical nature of breakup ice jamming on rivers is provided.
3.2 The Physical Nature of River Ice Jams

In general, ice jamming entails a significant increase in hydraulic resistance and a reduction in the flow conveyance of a river reach and as a result, the dramatic increase of water levels upstream of the ice jam toe. The formation of an ice jam involves the congestion of ice floes. For a breakup ice jam, ice flows derived from breakup processes upstream (e.g., Beltaos 1990, Demuth and Prowse 1991), accumulate at an obstruction; usually against a relatively intact winter ice cover or at a “bridging” site where channel geometry, hydraulic conditions and ice floe properties limit the local ice transport capacity relative to the incoming ice discharge.

Ice arriving at the upstream edge of the accumulation may remain on the surface or become entrained in the flow beneath the accumulation, to either be deposited and become part of the accumulation or re-emerge downstream of it. Should the incoming floes not submerge, then the formation of a “surface” jam occurs. Jams that thicken by deposition are generally characterized by increasing thickness in the downstream direction. As a jam progresses upstream its weight and the flow shear forces applied to it increase. Forces develop between the constituent ice floes giving rise to frictional resistance at the channel boundaries. Should the external forces grow large enough the accumulation will collapse or “shove” and thence thicken until it is once again just able to withstand the applied stresses.

The severity of ice jamming is usually in direct relation to the breakup severity; dynamic or mechanical breakups produce the largest ice jam floods and thermal breakups the most ineffective jams. Breakup severity is a function of the hydro-meteorological conditions preceding the period when the cover is finally dislodged from its "over-wintering" position. Breakup is usually classified into two types: thermal or over-mature, and dynamic or pre-mature (the latter also often referred to as mechanical). Mature breakups are similar to those that occur on a lake where the forces exerted by water flow are at a minimum. The hydro-meteorological conditions that produce a mature breakup on a river include low spring runoff, usually the result of a small winter snowpack or protracted melt, and extensive decay of ice thickness and strength. Ultimately, the remnant ice cover is so thermally weakened it can be dislodged by discharge comparable to the low-flow winter period. Quite an opposite set of hydro-meteorological conditions characterize dynamic breakup events. They usually include the generation of a large spring flood-wave produced by the rapid melt of a large winter snowpack, for example. Such conditions offer little possibility for the thermal decay of the river ice cover and the advancing flood-wave must push into a reasonably competent ice cover.

Once breakup is initiated, large forces resulting from the hydraulic conditions precipitated by the failure of ice jam accumulations upstream are often required for breakup ice jamming to progress in a “serial” fashion downstream. Alternately, if downstream flow increases and related forces are relatively small, a more discontinuous, non-sequential (“non-serial”) ice jamming sequence tends to be observed. A more detailed discussion of ice jam processes is not within the scope of this report, however, interested readers are referred to Ashton (1986), Beltaos (1983) and Beltaos (1995).
3.3 ICEJAM Numerical Ice Jam Model

3.3.1 General Description

The ICEJAM model (Flato and Gerard 1986; Flato 1988) couples the analysis of steady, one-dimensional gradually varied flow in open channels with the calculation of the longitudinal variation in ice jam thickness. The idealized configuration and an ice jam is illustrated in Figure 3.1 where it is seen that the ice jam is comprised of three main sections: an upstream transition; an equilibrium section; and a downstream transition. In the transition regions the ice jam thickness varies, while in the equilibrium section the flow is approximately uniform and the jam thickness is approximately constant. The maximum water depth and ice thickness are located within this equilibrium portion of the jam. Not all ice jams are long enough to develop an equilibrium section. However, the ICEJAM model is capable of calculating the longitudinal configuration of an ice jam whether or not an equilibrium section is achieved.

3.3.2 Equations Modelled

Details of the ICEJAM model are presented by Flato (1988). The analysis is based on the ordinary differential equation describing the longitudinal thickness variation in a cohesionless “wide” channel jam, as formulated by Uzuner and Kennedy (1976):

\[ h_i \frac{dh_i}{dx} = ah_i^2 + bh_i + c \]  

where:

\[ a = \frac{-C_o}{K_x B} \]  

\[ b = \frac{\rho_i g S}{2K_x \gamma_o} \]  

and,

\[ c = \frac{\tau}{2K_x \gamma_o} \]

in which:

- \( h_i \) is the thickness of the ice accumulation;
- \( C_o \) is normally equal to \( \tan \phi \), where \( \phi \) is the internal friction of the accumulation;

\[ 1 \] The P-ADTS P-ADJAM Terms-of-Reference had originally indicated that the RIVJAM numerical ice jam model would be utilized for this investigation. Upon consideration of the numerous model iterations required by RIVJAM for solution closure (related to specifying the toe condition) and the number of model variables that made up both the sensitivity analysis and the simulation scenarios, an alternate model, ICEJAM, was selected. There was an opportunity to briefly compare the output of the two models. Details are provided in section 5.4.3.
$K_x$ is the ratio of the longitudinal stress that can be sustained by the jam to the vertical confining stress;

$B$ is the accumulation width;

$\rho_i$ is the density of ice;

$g$ is the acceleration due to gravity (9.81 m/s$^2$);

$S$ is the slope of the energy grade line;

$\tau$ is the shear stress exerted by the flow on the bottom of the accumulation;

$x$ is the river distance measure in the downstream direction;

$$
\gamma_e = \frac{\rho_r g}{2} (1 - \rho) \left( 1 - \frac{\rho_i}{\rho} \right)
$$

[5]

in which:

$\rho$ is the porosity of the accumulation; and

$\rho$ is the density of water.

Because it is difficult to extract $C_o$ and $\rho$ separately from field measurements, a combined parameter is defined:

$$
\mu = C_o (1 - \rho)
$$

[6]

where $\mu$ is often described as an “internal friction-porosity” parameter.

The shear stress exerted by the flow on the underside of the ice jam is quantified in the ICEJAM model using:

$$
\tau = \gamma R_i S
$$

[7]

where:

$\gamma$ is the specific weight of water ($= \rho g$); and

$R_i$ is the hydraulic radius of the ice affected portion of the flow.

In a wide channel, $R_i$ is approximately equal to $y_t$ (the flow depth from the underside of the jam to the plane of zero stress). In the ICEJAM model, this is approximated by:

$$
y_t = \gamma \left( \frac{k}{k_i} \right)^{\frac{1}{4}}
$$

[8]

where:

$y_t$ is the depth of flow beneath the jam;

$k_i$ is the equivalent roughness height of the underside of the ice jam;

$k$ is the composite roughness (for the combined effects of the ice and bed).

The composite roughness is determined using the Sabeneev equation:

$$
k = \left( \frac{k_i^4 + k_b^4}{2} \right)^{\frac{1}{4}}
$$

[9]
3.3.3 Boundary Conditions

Two boundary conditions are required to close the solution. As in all gradually varied flow analyses, a water level boundary condition must be specified. Assuming a sub-critical flow, as is usually the case, this would be a downstream water level, $H_o$, as illustrated in Figure 3.1. It is important to note that, because the accumulation normally thickens substantially in the vicinity of the toe and equation [1] no longer applies, this downstream boundary condition can only be used if the toe configuration is known. In the ICEJAM model, the toe configuration is determined by assuming that the thickness at this point is governed by an "erosion velocity" which is the maximum velocity the accumulation at the toe can withstand before individual floes are swept downstream. This "floating toe" configuration is based on a user specified erosion velocity and an assumption that the bed will not scour. Although this must be considered a significant limitation of the model, it is important to note that the alternative model, RIVJAM (Beltaos and Wong 1986, 1991; Beltaos 1993) is also limited by the inapplicability of the jam stability equation in the vicinity of the toe. In the RIVJAM model, the thickness of the accumulation at the toe is an input parameter.

The second boundary condition is the upstream ice thickness. The ice thickness at the head of a jam is usually assumed to be governed by hydraulic stability of incoming ice floes, with incoming floes either juxtaposing upstream or under-turning and joining the accumulation. In the ICEJAM model this upstream boundary condition is specified by the user. In this case, a value of 1.0 m was used (approximating a juxtaposed ice cover at the upstream end of the jam) and a sensitivity analysis was conducted to confirm that the model results were not sensitive to this parameter.

The solution is an iterative one, in which the initial ice jam configuration is estimated and a gradually varied flow profile analysis progresses in the upstream direction. Equation [1] is then solved by stepping from the head of the jam to the toe, using the water surface profile just calculated. This new ice thickness configuration is then used to compute a new gradually varied flow profile and the process is repeated until the solution converges.

3.4 Numerical Ice Jam Model Input

3.4.1 Channel Geometry

Figure 3.2 illustrates the modelled reach, which extends from Sweetgrass Landing to a point 2 km downstream of the mouth of the Scow Channel (approximately 23 km downstream of Rocky Point), a total length of 52 km, in term of distance measured along the channel centreline. The geometric data available on the Peace/Slave River in the study reach consisted of 16 cross sections surveyed in September 16 - 24, 1994 (Environment Canada 1995a, b) and September 26 - October 3, 1995 (Carter 1996) between Sweetgrass Landing and a point 2 km downstream of where the Scow Channel returns flow to the Slave River.

To develop a geometric database compatible with the ICEJAM model a stationing system was established. The furthest downstream cross section, below the mouth of the Scow Channel, was arbitrarily assigned a station value of 10000 m. The stations of the remaining cross sections were determined by measuring the distance along the channel centre-line on 1:250,000 scale National Topographic Survey maps, proceeding in the upstream direction. The cross section names, as
designated at the time of survey, and their corresponding stations are shown in Table 3.1 along with some key locations along the modelled reach.

Table 3.1 Station distances for key sites along the Peace/Slave River

<table>
<thead>
<tr>
<th>Location</th>
<th>Station (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRX004 ‡</td>
<td>10000</td>
</tr>
<tr>
<td>SRX020</td>
<td>11600</td>
</tr>
<tr>
<td>Mouth of the Scow Channel Outfall</td>
<td>12000</td>
</tr>
<tr>
<td>SRX010</td>
<td>15000</td>
</tr>
<tr>
<td>Riviere des Rochers</td>
<td>19100</td>
</tr>
<tr>
<td>PRX001</td>
<td>19500</td>
</tr>
<tr>
<td>PRX010</td>
<td>24500</td>
</tr>
<tr>
<td>PRX020</td>
<td>28300</td>
</tr>
<tr>
<td>PRX032 ‡ (Rocky Point)</td>
<td>35000</td>
</tr>
<tr>
<td>Chenal des Quatre Fourches</td>
<td>36000</td>
</tr>
<tr>
<td>PRX041</td>
<td>38000</td>
</tr>
<tr>
<td>PRX042</td>
<td>38800</td>
</tr>
<tr>
<td>PRX061LC (downstream edge of Moose Island)</td>
<td>45000</td>
</tr>
<tr>
<td>PRX071LC ‡ (upstream edge of Moose Island)</td>
<td>49000</td>
</tr>
<tr>
<td>PRX071MC</td>
<td>50000</td>
</tr>
<tr>
<td>PRX090 (Carlson’s Landing)</td>
<td>54000</td>
</tr>
<tr>
<td>PRX092</td>
<td>55900</td>
</tr>
<tr>
<td>PRX095</td>
<td>58000</td>
</tr>
<tr>
<td>PRX100 (Sweetgrass Landing)</td>
<td>62000</td>
</tr>
</tbody>
</table>

‡ modelled ice jam toe locations

To resolve the computed water surface profiles through the simulated ice jams, intermediate computational nodes were required between these surveyed sections. To refine the spatial discretization, interpolated cross sections were developed based on the surveyed cross sections.

There are a number of islands within the surveyed reach which could not be considered in the ice jam simulations as the currently available models are all based on a one-dimensional approximation. Many of these islands are small and could reasonably be neglected. Furthermore, most of the larger islands have a substantial channel only on one side. In these cases, the small side channels were neglected and only the main flow channel was used. The exception was the island located just upstream of the Scow Channel jam toe site, adjacent to the mouth of the Scow channel. In this case, the channels on either side of the island are approximately equal in terms of conveyance capacity. Therefore, to model an ice jam profile around this island, only one channel was modelled and the discharge was halved. The ice jam conditions determined at the upstream end of this island reach were then used as the downstream boundary conditions for continuing the simulations upstream through the main channel using the full discharge.
One significant limitation of the available survey data is the fact that the cross section geometry does not extend above the top of the channel banks. In order to conduct simulations at high discharges this geometry must be approximated. To do this the cross section were extended vertically at the extremities, neglecting flood plain conveyance altogether. This is a conservative approach, as it leads to higher water levels. In the absence of survey information for the over-bank areas, however, any assumption about flood-plain geometry would be purely speculative. The significance of this approximation to the model output is illustrated and discussed in the section describing the modelling results.

3.4.2 Channel Bed Roughness

The channel bed roughness in the modelled reach was determined by calibrating the water level profiles which were measured at the time the cross sections were surveyed. This calibration was conducted with the U.S. Corps of Engineers HEC-2 gradually varied flow analysis program. The discharge associated with each of the two water surface profiles was determined based on the measurements at the Water Survey of Canada (WSC) gauge at Peace Point (07KC001). In 1994, the average discharge over the period during which the surveys were conducted was 1120 m³/s. For the 1995 surveys, it averaged 725 m³/s. Based on the discharges and measured water surface profiles (supplemental stage data derived from measurements at the Alberta Environment gauge at Rocky Point (07KC005)), it was determined that a bed roughness, in terms of Mannings n, of 0.035 matched both profiles well. This corresponds to a roughness height, kₚ, of approximately 0.3 m. Figure 3.3 illustrates a comparison of the measured and computed water surface profiles.

3.4.3 Water Surface Profile for the Simple Ice Cover

To establish the downstream boundary condition for the ice jam analysis, it was necessary to establish the water surface profile for a simple ice cover at the various carrier discharges to be examined. Based on ice thickness data from the Peace Point site, a late winter ice thickness of 0.75 to 1.0 m was considered appropriate. No data was available to calibrate an ice cover roughness. Based on the experience of other investigators at other sites, however, it was considered that ice roughness values of 0.015 to 0.030, in terms of Mannings n, encompassed the reasonable range of possible values.

Using the calibrated bed roughness and the aforementioned ice thickness and roughness values, gradually varied flow profiles were calculated through the study reach. Figure 3.4 illustrates the effect of ice cover thickness on the computed water surface profiles for an ice cover roughness, nₑ, of 0.015. In the figure, the results for five discharges are presented, with the top line for each discharge representing the computed water surface profile for an ice cover thickness on 1.0 m, while the lower line is for an ice cover thickness of 0.75 m. From this analysis, it is clear that, over this range, thickness variations are not significant to the modelled water surface profile.

Figure 3.5 illustrates the effect of ice cover roughness on these profiles for an ice cover thickness of 1.0 m. In the figure, the top line for each discharge represents the computed water surface profile for an ice roughness of 0.030, while the bottom line is for and ice roughness of 0.015. Clearly, the computed profile is more sensitive to this parameter.

In the ice jam analysis, three ice jam toe locations were considered. The first was located just upstream of Moose Island (at station 49000 m), the second at Rocky Point (35000 m) and the third just downstream of the Scow Channel outfall (10000 m). These three sites are shown on
Figure 3.2. In the analysis of the hypothetical ice jam profiles at each of these toe sites, the computed ice affected profiles shown in Figure 3.5 were used to quantify the downstream boundary condition.

3.4.4 Ice Jam Parameters

In the absence of ice jam profiles for historic events within the study reach, it was not possible to quantify the various parameters which affect an ice jam configuration. Instead it was necessary to examine a range of potential ice jam scenarios, by considering practical ranges for the ice jam parameters. Based on the experience of other investigators at a variety of sites, the following parameter ranges were considered suitable:

- internal friction-porosity parameter, $\mu = 0.8$ to 1.6
- ice jam roughness, $k_f = 0.7$ m to 4 m
- passive pressure coefficient, $K_x = 8.3$ to 10.4

To determine the relative significance of varying these parameters, a sensitivity analysis was conducted at the Moose Island jam site, at a moderate discharge of 2500 m$^3$/s. Sixteen runs were conducted for various combinations of these parameters, as well as for the varying tail-water conditions as determined from the HEC-2 analysis discussed above. It was found that the highest water surface profiles occurred for the following combination of parameters:

$$\mu = 0.8, \ k_f = 4 \ m \ and \ K_x = 8.3$$

as might be anticipated, given the physical influence of these various parameters. Figure 3.6 illustrates typical results of this sensitivity analysis. In the Figure 3.6a, the effect of changing the ice jam roughness from $k_f = 0.7$ m to 4 m, while holding the other two parameters constant, is seen to have a significant impact on the computed ice jam profile. On the other hand, it is seen in the other two figures that the computed profile is relatively insensitive to changes in $K_x$ and $\mu$. Based on this sensitivity analysis, it was determined that $\mu = 0.8, \ k_f = 4$ m and $K_x = 8.3$ would be used as the input parameters for the ice jam simulations.

4. NUMERICAL ICE JAM SIMULATION RESULTS

In this section, a description of the hypothetical jam scenarios is provided (section 4.1). Section 4.2 presents the results of the ice jam simulations in the form of ice jam thickness and water level profiles. The profiles are supplemented with tabular data at key station distances.

4.1 Ice Jam Scenarios

Three ice jam toe locations were considered in the ice jam simulations:

- section PRX071LC at upstream edge of Moose Island (west bifurcation (49000 m);
- section PRX032 at Rocky Point (35000 m); and
- section SRX004 downstream of the Scow Channel outfall (10000 m).
These lodgment positions were considered an adequate representation of the zones of sensitivity as defined by the tributary mouths (Figures 2.1, 3.2).

Simulations were carried out for five carrier discharges (500, 1000, 2500, 5000, and 9000 m$^3$/s). These discharges adequately span the historical flow regime during ice breakup near the P-AD (e.g., Prowse et al. 1996). Two tail-water boundary conditions, $n_i = 0.015$ and 0.030 were considered (as illustrated in Figure 3.5). As previously discussed, physical evidence and model sensitivity analysis suggested the following ice jam parameters be used: $\mu = 0.8$, $k_t = 4$ m and $K_x = 8.3$.

4.2 Ice Jam Profiles and Related Water Levels

4.2.1 Ice jam toe located at the upstream edge of Moose Island (49000 m)

Figure 4.1 illustrates the ice jam profiles computed for each of the five carrier discharges, for the case when the downstream ice cover roughness was taken as $n_i = 0.015$, and Figure 4.2 presents the water surface profiles corresponding to these computed ice jam profiles. As Figure 4.2 illustrates, the computed water levels exceeded the top of bank elevation for the ice jam simulations at 5000 and 9000 m$^3$/s, and to a lesser extent at 2500 m$^3$/s. Table A.1 (see Appendix A) presents the computed water levels at the surveyed cross sections within this reach.

Figures 4.3 and 4.4 show the ice jam and water surface profiles calculated for the case where the downstream ice cover roughness was taken as $n_i = 0.030$, illustrating the sensitivity of the model results to the specified downstream water level for this site. The maximum differences are in the order of a meter for the higher discharges, with the effect felt mainly near the toe. Water levels near the upstream end of the jams were quite similar for the two downstream boundary conditions. The computed ice jam thickness values were also comparable for the two different downstream boundary conditions. Table A.2 presents the computed water levels at the surveyed cross sections for these runs.

4.2.2 Ice jam toe located at Rocky Point (35000 m)

Figure 4.5 illustrates the ice jam profiles computed for each of the lower four carrier discharges, for the case when the downstream ice cover roughness was taken as $n_i = 0.015$. No results were obtained for the carrier discharge of 9000 m$^3$/s as the degree of channel constriction caused by neglecting flood-plain geometry at this high flow resulted in a physically impossible flow scenario. The high degree of irregularity in jam thickness reflects the sparse survey data, and is not physically meaningful. Figure 4.6 presents the water surface profiles corresponding to these computed ice jam profiles. As Figure 4.6 illustrates, the computed water levels exceed the top of bank elevation for the discharges of 2500 m$^3$/s and higher. Figures 4.7 and 4.8 illustrate the ice jam and water surface profiles calculated for the case where the downstream ice cover roughness was taken as $n_i = 0.030$. As the figure illustrates, the results were not significantly different between this case and the case when the downstream ice cover roughness was taken as $n_i = 0.015$. Tables A.3 and A.4 present the computed water levels at the surveyed cross sections for these runs.
4.2.3 Ice jam toe located downstream of the Scow Channel outfall (10000 m)

As discussed earlier, the island located just upstream of the Scow Channel jam toe site, adjacent to the mouth of the Scow channel, was handled in a unique way (as compared to the handling of the other islands in the modelled reaches) as the channels on either side of the island are estimated to be approximately equal in terms of conveyance capacity. In this case, only one channel was modelled and the discharge was halved. The ice jam conditions determined at the upstream end of this island were then used as the downstream boundary conditions for continuing the simulations upstream through the main channel (using the full carrier discharge).

Figure 4.9 illustrates the ice jam profiles computed for carrier discharges of 2500 m$^3$/s and 5000 m$^3$/s, for the case when the downstream ice cover roughness was taken as $n_i = 0.015$. Again, the high degree of irregularity in jam thickness reflects the sparse survey data, and these variations are not physically meaningful. Figure 4.10 presents the water surface profiles corresponding to these computed ice jam profiles where it is seen that the computed water levels exceed the top of bank elevation for both discharges. No results were obtained for the carrier discharge of 9000 m$^3$/s, again because the degree of channel constriction caused by neglecting flood-plain geometry at this high flow results in a physically impossible flow scenario. Results were also not obtained at two of the lower carrier flows, specifically 500, 1000 m$^3$/s, as the computed profiles were even more physically unreasonable than those presented. As discussed above, this may be explained by the sparse geometry, and the resulting adverse bed slopes which do not reflect the actual geometry.

Figures 4.11 and 4.12 illustrate the ice jam and water surface profiles calculated for the case where the downstream ice cover roughness was taken as $n_i = 0.030$. Once again, the results were not significantly different from those obtained with the alternate downstream boundary condition. Tables A.5 and A.6 present the computed water levels at the surveyed cross sections for these runs.

5. DISCUSSION

In this section, the major hydraulic and ice cover influences on ice jam severity are discussed (section 5.1). In section 5.2 the water surface profiles resulting from the various ice jam scenarios simulated are related, in general, to the role of the three major tributaries which route water into the central P-AD (Chenal des Quatre Fourches, Baril River, Claire River). For the Claire River specifically, a cursory examination of its conveyance capacity under conditions of Peace/Slave River ice jamming is presented. Finally, in sections 5.3 and 5.4, aspects of model verification and model accuracy/utility are provided.

5.1 Influences on Ice Jam Severity

5.1.1 General

The influences on the occurrence and severity of breakup ice jamming are numerous. One of the major influences for a regulated, cold region river such as the Peace River, is related to higher winter flows and increased freeze-up elevations. In general, the higher a freeze-up cover, the greater the flows it can pass without breaking. Prowse et al. (1996) discussed the hydro-meteorological influences controlling breakup severity near the P-AD and, in general, applied the
analysis to ice jam severity. The present investigation considers the specific role of carrier discharge and lodgment location on the magnitude of ice jam backwater. Additional discussion relates ice jam severity to the physical properties of the ice floes making up the ice jam, influencing its roughness and mechanical strength.

5.1.2 Discharge Regime

Two runoff sources combine to generate spring flows that can exceed the freeze-up level: the upstream flow from above the point of regulation and the downstream tributary flow. Under regulated conditions, a major increase in upstream flows is unlikely at the time of breakup in the more distant reaches due to the operational transition to lower summer releases. Correspondingly, if the amount of regulated flow at the time of breakup is declining, tributary flow will have to account for this "loss" to the main-stem discharge, before having an affect on the ice cover. In a companion NRBS study to assess the origin of the spring flows that appeared to be driving breakup, Prowse et al. (1996) found that, between the pre-regulation period (1962-67) and that post-regulation (1972-1992), the average relative contribution of the flow at Hudson Hope (Peace River headwaters; Figure 2.1) has increased while the average contribution from the downstream tributaries (e.g., Smoky River; Figure 2.1) has decreased. Under the current regulated/climatic regime, therefore, the evolution of severe breakups and related ice jamming has become more dependent on tributary inflow. This is evidenced by the abnormally high spring flows in the tributaries in association with extreme ice jam events in both the pre- and post-regulation periods (e.g., 1963, 1965 and 1974). The importance of the source of flow that contributes to that necessary for the evolution of severe ice jam backwater is re-affirmed when consideration is given to flow re-regulation as a remedial measure for the P-AD (discussed later).

Regardless of the source, results presented in section 4 suggest that the combined flow needed to cause macro-scale flooding of the P-AD may generally need to be in excess of 5000 m³/s for lodgments immediately adjacent to the P-AD (e.g., Moose Island, Rocky Point). An extremely large (long) jam, for example - in place near the Scow Channel outfall on the Slave River, could generate considerable over-bank water levels as far back as the Claire River mouth for flows as low as 2500 m³/s (notwithstanding limiting conditions for ice jam stability, upstream ice supply and the possible fragmentation of flow by tributaries along the jam longitudinal profile of the backwater region).

As previously discussed, hydrometric analysis in conjunction with various historical and local-knowledge data confirms that open-water floods have been ineffective in producing high-elevation floods along the Peace River adjacent to the Peace-Athabasca Delta. Over the period of the far-field hydrometric record, backwater produced during river-ice breakup has exceeded that of the historical high 1990 open-water event (e.g., for Peace Point). Based on the available near-field instrument record for Rocky Point (gauge 07KC005) the maximum open-water stage did not exceed 210.5 m.a.s.l., some 2.4 m below bank full stage. For a location near the Rocher mouth (station distance 19100 m; gauge 07NA001), the maximum open water stage did not exceed 209.6 m.a.s.l., 0.8 m below the bank. Relative to the backwater stage simulated in the ice jam modelling scenarios for similar discharges, the open-water/ice jam induced contrast is, in general, very evident.
5.1.3 Ice Jam Physical Properties

Limiting the discussion to the influence of the ice “particles” making up the ice jam, it may be generalized that an accumulation made up of thick, competent ice floes is likely to be rougher, present more resistance to the flow and thereby cause higher backwater for a given discharge. Conversely, accumulations made up of slush, heavily deteriorated ice or smaller floes, present the flow with less resistance. This is commensurate with the fact that the resistance offered by a thermally weakened ice sheet does not favour the formation of thick ice masses, typical of equilibrium ice jams (e.g., see Beltaos 1983; 1995) that create maximum backwater levels. In the current investigation the physical significance of floe size and therefore, to a degree floe thickness and strength, is manifested in the variable $k$, as defined in section 3.

While Prowse et al. (1996) suggest a weak climate signal may have contributed to somewhat weaker and thinner ice in the lower reaches of the Peace River since regulation, the sensitivity analysis (section 3) indicates that such variations, as manifested in the roughness of the accumulation, are not likely to influence ice jam severity to any great extent. Changes in ice thickness (measured) and strength variations (modelled) are well within the range of inter-annual variability (e.g., for Peace Point, Prowse et al. 1996). In summary, a major control on roughness is the type of breakup that precedes ice jam formation; pre-mature breakup generally results in rough accumulations while breakup tending toward the over-mature characteristic may precede the development of jams that are smoother.

Related to the size and competence of the individual ice floe is the overall strength of the accumulation under the vertical stress imposed on it by buoyancy and the cumulative longitudinal stress resulting from flow shear and gravity. When a breakup jam first forms it likely has negligible cohesion. While ICEJAM assumes a cohesionless accumulation, there is physical evidence to suggest that some cohesion may develop (e.g., remnant shear walls after ice jam release), depending to some degree on the time available for individual ice floes to “freeze-bond” and on the porosity of the jam (controls inter-floe contact). Fortunately, for breakup ice jams, the accumulation thickness and related water levels are governed by initial hydraulic conditions. Increasing cohesion, however, may play a role in the longevity of an ice jam lodgment. Further discussion on the role played by jam porosity and related ice floe properties (size and strength) can be found in Beltaos (1983, 1995).

5.1.4 Lodgment Position

Between the pre-regulation period and that post-regulation, the average flows that initiate breakup near the P-AD (based on data from Peace Point) have increased, averaging 3050 m$^3$/s and 3418 m$^3$/s, respectively (Prowse et al. 1996). As previously discussed, this is largely due to the higher flows that are sustained throughout the winter period. Interestingly, there has been no significant change in the flow that caused peak breakup water levels (averaging 4128 m$^3$/s and 3771 m$^3$/s, respectively). This may suggest that the physical situation responsible for the creation of extreme breakup flood events is also related to the position of the lodgment. It also points to the necessity of having near-field instrument records and the possible vagaries of using far-field data as an index of distant ice conditions.

While the fragmentation of ice jam backwater towards the P-AD via over-bank flooding and tributary inflow would be expected, this eventuality is not considered in the current analysis. As such, the water level profiles presented in section 4 represent maximums for a continuous channel.
without distributing branches. Clearly, backwater generated by a lodgment near the Scow Channel outfall, for example, may not only be routed into the central P-AD via overland flow and the smaller tributaries (e.g., Claire River and Chenal des Quatre Fourches; Figure 2.1 inset), but also into the northern regions of the Delta via the larger Riviere des Rocher, for example. Water levels upstream of the Rocher mouth or Rocky Point, therefore are likely to be less than those simulated. For a jam at Rocky Point, it would be difficult to determine how much main-stem fragmentation might take place via the Chenal des Quatre Fourches, given the proximity of its mouth relative to the likely toe location where the ice accumulation may reach a substantial thickness. Interestingly, for lodgments downstream of the Rocher mouth, the overall resistance of the system to flow (main stem plus distributing branches) would be enhanced by the broad crested weirs which exist in the Riviere des Rochers and the Revillon Coupe (Figure 2.1 inset). Furthermore, their geographical situation, under certain conditions, may give rise to the promotion of secondary ice jamming.

While the number lodgment sites selected for simulation was restricted and given the limitations imposed by not considering the distribution of flow either overland or through tributaries, it could be stated that for a given discharge, the impact of lodgment position on the degree of over-bank flow will be strongly related to the relative position of tributaries which could fragment flow to the more hydraulically well-connected areas of the P-AD. Lodgments located at or upstream of Rocky Point may provide significant, but more localized, flooding to the central P-AD. Lodgment located downstream of Rocky Point would primarily impact the northern P-AD, however, given the greater size and number of well-connected distributing channels there, as compared to those in the reaches upstream of Rocky Point, the severity of the event that would cause macro-scale flooding of the entire P-AD would require circumstances for which the current modelling effort could only speculate upon (as discussed earlier). Further hydraulic modelling studies which could rigorously evaluate the impact of distributing channels and flood-plain flow with respect to ice jam lodgment position, would benefit both the interpretation of this studies findings and the future design and deployment of structural remedial measures such as artificial ice jams.

5.2 Role of Tributaries in Flooding the P-AD

5.2.1 General

As previously introduced in the discussion of lodgment position, there are numerous tributaries which, under high water conditions on the Peace/Slave River, can route flow into the P-AD. They are the Riviere des Rochers, Revillon Coupe, Chenal des Quatre Fourches, Baril River and Claire River. In general, these tributaries may contribute water into the well-connected open drainage's of the P-AD or if conditions such as flood-plain flow or secondary ice jamming exist, water may enter the more restricted environments adjacent to the tributary. As reviewed earlier, local traditional knowledge sources identified several secondary ice jam sites. Notably, one of these was on the Chenal des Quatre Fourches at a conspicuous, sharp bend in the river where the initial P-AD-TS ice dam experimentation took place (e.g., Peterson 1993).

To illustrate the role played by tributary inflow and flood-plain flow in partitioning water to the P-AD, the Peace River - Slave River flow “deficit” has been estimated for the large breakup years 1963, 65, 72, 74 (Figure 5.1). Flow on the Peace River upstream of the P-AD is determined at
Peace Point (gauge 07KC001; Figure 5.2) while that for the Slave River downstream of the P-AD is determined at Fitzgerald (gauge 07NB001; Figure 2.1). As a first approximation, it is instructive to note the extensive period for which there exists a flow deficit, i.e., where Slave River flows are less than those in the Peace River. This deficit is provided to the P-AD and Lake Athabasca through either tributary inflow and/or flood-plain flow. Simple deficit volume estimates for the 1963 breakup period (April 22-May 12), for example amount to 5.6 billion cubic metres. Further examination of a flow “fragmentation” or deficit index is underway by the authors.

Of the numerous tributaries connecting the Peace River to the P-AD, the authors thought it instructive to conduct a first-order approximation of conveyance for the Claire River, under the influence of high water simulated for Peace/Slave River ice jamming. The Claire River is the most upstream tributary of the Peace/Slave River adjacent to the P-AD. Of special significance, is the recent restoration of the disturbed Claire River channel near Sweetgrass Landing.

5.2.2 The Claire River and its Restoration

Of recent significance is the restoration of the Claire River channel near the mouth at Sweetgrass Landing (Figures 3.2, B.1). Activities related to a local sawmill operation (Swanson Lumber Company) resulted in the construction of berms over the channel near the mouth, effectively eliminating water conveyance from the Peace River to Lake Claire for all but the most extreme high water events (e.g., P-ADTS 1996). In the 1995/96 winter, approximately 1 km of channel was restored resulting in a reduction of the bed elevation near the Claire River mouth of up to 2.5 m. The disturbed and restored bed slope profiles of this portion of the Claire River are illustrated in Figure B.2 (Appendix B). Also shown is the longitudinal bed profile of the Claire River from the restoration site to its outfall into Lake Claire.

Discharges were estimated by assuming an approximate geometry for the Claire River as follows: 3.1 m bank height, 10 m top width (mean) and 3:1 side slopes (from anecdotal evidence). Uniform flow was assumed based on the surveyed bed slope, $S_o = 0.000107$ (survey data from Lavergne (1993)). It was also assumed that negligible backwater effects (from Lake Claire) are impeding the release of flow from the Peace River down the Claire River, nor are there any ice accumulations present. As such, estimates derived represent maximum possible values. The bed roughness ($n_b$) for the Claire River was unknown and could not be calibrated as there were no discharge measurements conducted during the 1993 survey of its open-water surface and bed profiles. As an alternative three values for $n_b$ were used: 0.025 - typical of excavated earth channels that are winding or slightly weathered with minimal vegetation; 0.035 - typical of excavated earth channels and natural channels that are winding and weathered with more extensive vegetation (weeds in channel or light brush on banks); 0.045 - typical of natural channels that are winding and contain pools and shoals as well as stones, weeds and brush on banks.

Generally, it is estimated that there would likely be no flow down the Claire River for Peace/Slave River ice jams at carrier discharges below 2500 m$^3$/s. Limited knowledge of Claire River geometry did not allow a complete analysis of all flows below 2500 m$^3$/s, however, the water levels for the higher flows support this general conclusion. For carrier discharges of 2500 m$^3$/s and higher, we could expect flows of approximately 8 to 25 m$^3$/s. Based on photographs and anecdotal evidence, $n_b \geq 0.035$ is likely to represent the appropriate bed roughness. It may be
concluded therefore, that the Claire River could convey approximately 10 to 17 m³/s during a major ice jam event on the Peace/Slave Rivers as modelled in this study. It should be noted, however, that at the higher flows (>>5000 m³/s) commensurate with severe ice jamming, macro-scale flooding associated with over-bank flow occurs and a more sophisticated analysis would need to be undertaken.

Valuable anecdotal data surrounding the magnitude and effect of ice jams on the Peace and Slave Rivers, were derived from observations related to the flooding and damage experienced at the Swanson Lumber Company sawmill at the Claire River. These data and other validating information are discussed in more detail in the next section.

5.3 Verification of Modelling Results

Verification of ice jam modelling results can involve a number of data sources. Direct measurements and near-field hydrometric data are most suitable for verifying model results and assist in refining the representative physical variables required by the model. As previously indicated, there is a dearth of near-field, site-specific observations to aid this investigation. Local traditional knowledge, oral history and historical documents have permitted insight into the development of model scenarios (e.g., ice jam lodgment positions) and to date, provide the basis for the limited but instructive verification efforts reported herein. Far-field hydrometric records are used to supplement the interpretation of the aforementioned information sources.

For recent ice jam flood events as reported in Jackson (1963), Orange (1965) and Smith (1972), evidence of macro-scale flooding is extensive. Most notable are the references made to the buildings at the Swanson Saw Mill at Sweetgrass Landing and at the Sweetgrass Buffalo Management Station (discussed below). Dixon (1996, personal communication) indicates that saw mill debris can be found along the entire length of the Claire River to Lake Claire. Carter (1995, personal communication) reported that log accumulations comprised of large tree stumps (roots on) exist north of Lake Claire; their large size indicating they may have been transported by flood waters into the P-AD from the Peace River. 3 sites have been documented at approximately UTM Grid Reference 6522850 m Northing, 453000 m Easting (NTS ref. 73L/13, NAD27, geocoded image Figure B.1, Appendix B). The elevation of the surrounding landscape is ≈ 211.5 m.a.s.l. An approximate date of deposition has not been determined. Information supplied by Grandjambe (1995, personal communication), points to the existence of a barge vessel in the bush south of Sweetgrass Landing. While this item has not been found to date, it would be relatively simple to determine the approximate flood elevation required to float such a vessel to its current position.

More specific information commensurate with the modelling results are provided by the following event summaries for the 1963, 65, 72 and 74, as interpreted from historical documents (Giroux 1995, personal communication), and from historical remote sensing data (Prowse et al. 1994, personal communication):
• **1963**
  
  *Ice Jam Toe:* unknown  
  *Head:* 2 miles east of Carlson's Landing (May 1)  
  *Water Levels:*  
  Crested on April 30  
  Carlson's Landing 12 feet above normal for time of year (May 1)  
  Carlson's Landing 8 feet higher than normal for time of year (May 3)  
  Many houses (Sweetgrass Landing) off their foundations.  
  In general water is everywhere, possibility of Buffalo drowning  

• **1965**
  
  *Ice Jam Toes:* Junction Peace and Slave Rivers (Rocher mouth)  
  Carlson's Landing  
  *Head:* Sweetgrass Landing  
  *Water Levels:*  
  Ice movement commenced May 1, 09:00 (Sweetgrass Landing)  
  Crested on May 2, ~ 12:00  
  Sweetgrass Landing 20 feet above normal for time of year  
  3.5 feet of water/ice had risen on sides of buildings in centre of Swanson Lumber camp  
  3.5 feet above the general level of the mill site, (1 foot less than 1963)  

• **1972**
  
  *Ice Jam Toe:* Moose Island west bifurcation  
  *Head:* 1 mile upstream of Sweetgrass Landing  
  *Water Levels:*  
  Ice Jam occurred May 4  
  Crest May 5 - May 8  
  Swanson Lumber Company mill site inundated  
  Ten persons marooned on mill ramp (evacuated by helicopter)  
  Water backed up Sweetgrass Creek to Sweetgrass Buffalo Management Station  
  Minimal damage to Wood Buffalo National Park Buildings at Sweetgrass  

• **1974**
  
  *Ice Jam Toe:* Slave River, vicinity of Fitzgerald between Ryan Island and Cassette Rapids\(^2\)  
  *Head:* Bocquene River mouth across from Wood Buffalo National Park Station "Hay Camp"  
  *Water Levels:*  
  Large scale flooding of entire P-AD  
  Specific details not yet determined  

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\(^2\) Toe location for the 1974 event is partially corroborated by the peculiar temporal nature of the Slave-Peace River flow deficit for the period April 20-May 20, 1974 (Figure 5.1).
Figure 5.2 Illustrates the Peace River flows at Peace Point during the above breakup ice jamming events. Despite some question as to whether the Peace Point gauge was influenced by the backwater of one or more of these events, it is worthy to note the magnitude of the flow during events which quite clearly involve significant over-bank flooding due to ice jamming. Furthermore, the data is commensurate with ice jam model results which indicate that flows in the order of 5000 m$^3$/s or greater are required for the occurrence of significant flooding of the P-AD during breakup ice jamming.

5.4 Modelling Limitations and Utility

5.4.1 General

The P-ADJAM study involved the examination of an idealized ice jam, in place at several, but not all, possible lodgment locations. The modelling effort was specifically designed to examine the consequences of a jam near the P-AD and as such, was not intended to ascertain the regulation/climate variation impacts on ice jam evolution. Moreover, it should be recognized that the process of breakup initiation and ice jam formation is highly complex (e.g., Beltaos 1985, Beltaos 1990, Demuth and Prowse 1990) and that numerous in-situ conditions may complicate the representativeness of the simulations undertaken. Such complications include the evolution of multiple ice jams or the non-serial progression of ice jamming along the river reach. More specific difficulties and limitations associated with the present effort are discussed next.

5.4.2 Model Input Data

The greatest shortcoming of the current modelling effort was the lack of adequate geometric data describing the river channel. Intermediate computational nodes were required between the surveyed cross sections, therefore, additional sections were interpolated based on the existing survey data. There was a considerable degree of irregularity, however, between surveyed sections which could not be accounted for with the limited data available. For example, sections taken at bends (across a deep scour hole), introduced non-representative bed elevations into the profiles, resulting in adverse local bed slopes in some cases. Low flow scenarios could not be run in some instances because of this problem.

The sparsity of the geometry was exacerbated by the presence of islands in the reach, and the approximate way in which they had to be accommodated in this one-dimensional model (as discussed in Section 3.4.1). Furthermore, channel geometry above the top of the bank was not available to facilitate simulations at higher discharges. To circumvent this problem, each cross section was extended vertically from the top of the channel bank. This restricted channel neglects the existence of flood-plains and causes the model to predict higher water levels. In some case, this approximation resulted in an inability to model high discharges, as the degree of channel constriction resulted in physically impossible flow scenarios at these high flows. As a conservative estimate, it is probably reasonable to assume that water levels would likely not exceed the bank height by much more than the ice jam thickness.
5.4.3 Model Accuracy and Utility

Based on a limited but illustrative comparison to results obtained using RIVJAM, the original ice jam model proposed for this study (Beltaos 1993), it is estimated that 1 metre represents the approximate water level accuracy produced by these simulations. This does not include the additional error associated with the lack of over-bank survey data which, of course, cannot be quantified in the absence of that data. While the influence of ice jam parameters ($\mu$, $K_s$, and $k_i$; section 3.4.4) has been illustrated, the absence of substantive verification data for the modelled scenarios will limit further commentary on their representativeness beyond the current available literature.

A detailed comparison of the ICEJAM and RIVJAM models is beyond the scope of this report, however, it is instructive to note how they differ in-so-far as the physical characterization of the lodgment. The most substantial difference is that RIVJAM allows the simulation of a "grounded toe" and thereby also requires "seepage" through the accumulation. Grounding is a distinct possibility, especially for channels exhibiting hard-rock control. It is unlikely that grounding would occur in a sand bed river such as the Peace River, however a number of lodgment positions may be influenced by the presence of rocky islets. The toe condition is an input parameter for the RIVJAM model, and as such the model is particularly useful as a post-event analysis tool (requires ice jam thickness field data). By contrast, ICEJAM computes the toe thickness based on a maximum allowable velocity under the toe (no seepage through the accumulation). It too assumes an non-erodible bed condition. The difference in the computed water levels generated by the two models may be attributed primarily to the seepage/non-seepage flow through the accumulation. Notably, the computed ice jam thickness values were similar for the two models. Investigating the possibility of ice jam grounding/seepage and providing a more comprehensive commentary on the representativeness of the ice jam parameters used in these simulations will require field data not yet available to this study.

6. RECOMMENDATIONS FOR FUTURE WORK

Based on the results and interpretations generated in the P-ADJAM investigation the following recommendations are made such that a better understanding of the natural and anthropogenic influences on the Peace-Athabasca Delta is realized.

i) As evidenced by the current dearth of verification data, there is a clear need for pro-active stream gauging and ice observation initiatives (e.g., Beltaos et al. 1990, Petryk et al. 1996, White and Zufelt 1994). Stream gauging (water stage) should be conducted during the critical periods of ice breakup and ice jamming, along the Peace/Slave Rivers and on important P-AD tributaries. These efforts would provide critical verification data for further ice jam simulation research, the design of remedial measures and for hydrological investigations. Additional efforts should be directed towards calibrating local traditional knowledge, oral history and historical documents.

ii) Ice jam modelling results should be coupled with hydraulic flow models able to deal rigorously with tributary and flood-plain flow. Commensurate with this recommendation is the need for additional topographic surveys which would better describe the near-channel bank geometry, along and inland from the Peace/Slave Rivers.

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iii) A most instructive extension of the current analysis would be the examination of secondary ice jamming within the delta under the influence of aggressive inflow from the Peace/Slave Rivers. Improved knowledge about the role and behavior of the inflow tributaries would likely benefit future flow modelling of the P-AD as a whole (e.g., see Aitken and Sapach 1994, P-ADTS 1996c).

iv) Further development of *in-situ* structural remedial measures, should consider the deployment of small-scale artificial ice structures in selected P-AD tributaries thereby assisting in the generation of localized flooding (promote secondary ice jamming) (e.g., see Prowse and Demuth 1996).

v) Remedial measures involving the re-regulation of the Peace River alone or in combination with large-scale artificial structural alternatives should evolve from multi-disciplinary study including further ice jam, hydraulic, geomorphologic, hydrologic and eco-system investigations. A multi-agency task force should be mandated to ensure that the potential hazards, responsibilities and design of safe operating procedures, associated with the deployment of remedial measures, are clearly elucidated (e.g., British Columbia-Alberta Task Force 1992, Ferrick and Mulherin 1989, Beltoos and Krishnappen 1982).

As noted by Prowse *et al.* (1996), the timing of such study and utilization of a re-regulation strategy might well be commensurate with the expectation of high snow melt yields from the main-stem tributaries below the W.A.C. Bennett facility. Notably, the results of the current investigation suggest that the combined flow needed to cause macro-scale flooding of the P-AD may generally need to be in excess of 5000 m$^3$/s for lodgments immediately adjacent to the P-AD (e.g., Moose Island, Rocky Point) (within the limits of the ICEJAM model and the input data available and notwithstanding the spatial and temporal ice cover/hydraulic conditions necessary to initiate an ice jam). An extremely large (long) jam, for example - in place near the Scow Channel outfall, could generate considerable over-bank water levels as far back as the Claire River mouth for flows as low as 2500 m$^3$/s (notwithstanding limiting conditions for upstream ice supply and flow fragmentation by tributary channels along the ice jam profile).

vi) Further study is recommended to provide a comparison of available numerical ice jam models. Such study should include a comprehensive summary of the required input parameters; their physical basis and verification case studies illustrating their influence. Such a task could be undertaken by members of the Canadian Geophysical Union - Hydrology Section - Committee on River Ice Processes and the Environment.
7. ACKNOWLEDGMENTS

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It is hoped that the P-ADJAM Technical Study and related Peace-Athabasca Delta Technical Studies may assist in the understanding and management of a national ecological treasure.
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Figure 2.1. Peace-Athabasca Delta Study Area
Figure 3.1. Ice jam definition and longitudinal schematic.
Figure 3.2. Location of key hydrographic and modelled ice jam sites along the Peace/Slave River.
Figure 3.3. Calibration of bed roughness for measured water surface profiles ($n_b = 0.035$)
Figure 3.4. Effect of ice cover thickness (upper = 1.0 m; lower = 0.75 m) on modelled surface profile under simple ice conditions ($n_i=0.015$).
Figure 3.5. Effect of ice cover roughness (upper = 0.030; lower = 0.015) on modelled surface profile under simple ice conditions (1m thick ice cover).
Figure 3.6 Effect of varying the ice jam parameters at a discharge of 2500 m$^3$/s, Moose Island site.
Figure 4.1. Modelled ice jam profiles at Moose Island (downstream ice cover $n_i = 0.015$)
Figure 4.2 Water levels for ice jam profiles at Moose Island (downstream ice cover $n_i = 0.015$).
Figure 4.3. Modelled ice jam profiles at Moose Island (downstream ice cover $n_i = 0.030$).
Figure 4.4. Water levels for ice jam profiles at Moose Island (downstream ice cover $\eta = 0.030$).
Figure 4.5. Modelled ice jam profiles at Rocky Point (downstream ice cover $n_i = 0.015$).
Figure 4.6. Water levels for ice jam profiles at Rocky Point (downstream ice cover $n_i = 0.015$).
Figure 4.7. Modelled ice jam profiles at Rocky Point (downstream ice cover $n_i = 0.030$).
Figure 4.8. Water levels for ice jam profiles at Rocky Point (downstream ice cover $n_i = 0.030$).
Figure 4.9. Modelled ice jam profiles at Scow Channel outfall (downstream ice cover $n = 0.015$).
Figure 4.10. Water levels for ice jam profiles at Scow Channel outfall (downstream ice cover $n_i = 0.015$).
Figure 4.11. Modelled ice jam profiles at Scow Channel outfall (downstream ice cover $n_i = 0.030$).
Figure 4.12. Water levels for ice jam profiles at Scow Channel outfall (downstream ice cover $n_t = 0.030$).
Figure 5.1. Slave River (Fitzgerald) - Peace River (Peace Point) mean daily flow deficit for large breakup ice jamming events near the Peace-Athabasca Delta.
Figure 5.2. Peace River mean daily discharge at Peace Point (07KC001) for large breakup ice jamming events near the Peace-Athabasca Delta.
APPENDIX A

MODELLED STATION WATER LEVEL SUMMARY TABLES
Table A.1.  Water levels for ice jam profiles at Moose Island, 
(downstream ice cover n=0.015)

<table>
<thead>
<tr>
<th>Location</th>
<th>Station</th>
<th>Q=500 m$^3$/s</th>
<th>Q=1000 m$^3$/s</th>
<th>Q=2500 m$^3$/s</th>
<th>Q=5000 m$^3$/s</th>
<th>Q=9000 m$^3$/s</th>
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</tr>
</tbody>
</table>

* Sweetgrass Landing - mouth of the Claire River

Table A.2.  Water levels for ice jam profiles at Moose Island, 
(downstream ice cover n=0.030)

<table>
<thead>
<tr>
<th>Location</th>
<th>Station</th>
<th>Q=500 m$^3$/s</th>
<th>Q=1000 m$^3$/s</th>
<th>Q=2500 m$^3$/s</th>
<th>Q=5000 m$^3$/s</th>
<th>Q=9000 m$^3$/s</th>
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<tr>
<td>PRX071LC</td>
<td>49000</td>
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<td>208.1</td>
<td>211.3</td>
<td>214.5</td>
<td>217.9</td>
</tr>
<tr>
<td>PRX071MC</td>
<td>50000</td>
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<td>208.7</td>
<td>211.6</td>
<td>214.8</td>
<td>218.3</td>
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<tr>
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<td>219.0</td>
</tr>
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<td>208.9</td>
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<td>219.3</td>
</tr>
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<td>209.0</td>
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<td>219.6</td>
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<td>209.1</td>
<td>212.4</td>
<td>215.9</td>
<td>219.9</td>
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</tbody>
</table>

* Sweetgrass Landing - mouth of the Claire River
### Table A.3.
Water levels for ice jam profiles at Rocky Point
(downstream ice cover n\(\text{f}=0.015\))

<table>
<thead>
<tr>
<th>Location</th>
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<th>Q=500 m(^3)/s</th>
<th>Q=1000 m(^3)/s</th>
<th>Q=2500 m(^3)/s</th>
<th>Q=5000 m(^3)/s</th>
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<tr>
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<td>208.0</td>
<td>211.0</td>
<td>214.0</td>
</tr>
<tr>
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<td>208.5</td>
<td>211.6</td>
<td>214.4</td>
</tr>
<tr>
<td>PRX061LC</td>
<td>45000</td>
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<td>209.5</td>
<td>213.1</td>
<td>216.5</td>
</tr>
<tr>
<td>PRX071LC</td>
<td>49000</td>
<td>208.2</td>
<td>210.1</td>
<td>213.8</td>
<td>217.4</td>
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<tr>
<td>PRX071MC</td>
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<td>210.1</td>
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<td>210.3</td>
<td>214.1</td>
<td>217.9</td>
</tr>
<tr>
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<td>58000</td>
<td>208.4</td>
<td>210.3</td>
<td>214.2</td>
<td>218.0</td>
</tr>
<tr>
<td>PRX100(^*)</td>
<td>62000</td>
<td>208.5</td>
<td>210.4</td>
<td>214.3</td>
<td>218.2</td>
</tr>
</tbody>
</table>

* Sweetgrass Landing - mouth of the Claire River

### Table A.4.
Water levels for ice jam profiles at Rocky Point
(downstream ice cover n\(\text{f}=0.030\))

<table>
<thead>
<tr>
<th>Location</th>
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<th>Q=500 m(^3)/s</th>
<th>Q=1000 m(^3)/s</th>
<th>Q=2500 m(^3)/s</th>
<th>Q=5000 m(^3)/s</th>
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</thead>
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<td>214.3</td>
</tr>
<tr>
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<td>208.5</td>
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<td>214.6</td>
</tr>
<tr>
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<td>45000</td>
<td>207.4</td>
<td>209.5</td>
<td>213.1</td>
<td>216.6</td>
</tr>
<tr>
<td>PRX071LC</td>
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<td>208.2</td>
<td>210.8</td>
<td>213.8</td>
<td>217.5</td>
</tr>
<tr>
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<td>50000</td>
<td>208.2</td>
<td>210.2</td>
<td>213.9</td>
<td>217.6</td>
</tr>
<tr>
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<td>54000</td>
<td>208.3</td>
<td>210.3</td>
<td>214.0</td>
<td>217.8</td>
</tr>
<tr>
<td>PRX092</td>
<td>55900</td>
<td>208.4</td>
<td>210.3</td>
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<td>217.9</td>
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<tr>
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<td>208.4</td>
<td>210.3</td>
<td>214.2</td>
<td>218.1</td>
</tr>
<tr>
<td>PRX100(^*)</td>
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<td>208.5</td>
<td>210.4</td>
<td>214.3</td>
<td>218.3</td>
</tr>
</tbody>
</table>

* Sweetgrass Landing - mouth of the Claire River

Station Water Levels - Rocky Point Jams
Table A.5. Water levels for ice jam profiles near the Scow Channel outfall (downstream ice cover n_i=0.015)

<table>
<thead>
<tr>
<th>Location</th>
<th>Station</th>
<th>Computed Water Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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<tr>
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<tr>
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<td>11600</td>
<td>205.3</td>
</tr>
<tr>
<td>SRX010</td>
<td>15000</td>
<td>207.9</td>
</tr>
<tr>
<td>PRX001</td>
<td>19500</td>
<td>208.0</td>
</tr>
<tr>
<td>PRX010</td>
<td>24500</td>
<td>210.3</td>
</tr>
<tr>
<td>PRX020</td>
<td>28300</td>
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<td>211.9</td>
</tr>
<tr>
<td>PRX041</td>
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<td>212.2</td>
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<td>214.5</td>
</tr>
<tr>
<td>PRX090</td>
<td>54000</td>
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</tr>
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<td>214.7</td>
</tr>
<tr>
<td>PRX095</td>
<td>58000</td>
<td>214.8</td>
</tr>
<tr>
<td>PRX100*</td>
<td>62000</td>
<td>214.9</td>
</tr>
</tbody>
</table>

* Sweetgrass Landing - mouth of the Claire River

Table A.6. Water levels for ice jam profiles near the Scow Channel outfall (downstream ice cover n_i=0.030)

<table>
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<tr>
<th>Location</th>
<th>Station</th>
<th>Computed Water Levels</th>
</tr>
</thead>
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<td></td>
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<tr>
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<td>10000</td>
<td>206.0</td>
</tr>
<tr>
<td>SRX020</td>
<td>11600</td>
<td>206.2</td>
</tr>
<tr>
<td>SRX010</td>
<td>15000</td>
<td>207.9</td>
</tr>
<tr>
<td>PRX001</td>
<td>19500</td>
<td>208.0</td>
</tr>
<tr>
<td>PRX010</td>
<td>24500</td>
<td>214.3</td>
</tr>
<tr>
<td>PRX020</td>
<td>28300</td>
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<td>PRX032</td>
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</tr>
<tr>
<td>PRX100*</td>
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<td>214.9</td>
</tr>
</tbody>
</table>

* Sweetgrass Landing - mouth of the Claire River
APPENDIX B

CLAIRED RIVER RESTORATION PERSPECTIVE

EPILOGUE: 1996 ICE JAM EVENT
Epilogue: 1996 Ice Jam Event

The progression of ice break-up on the Peace River in 1996 advanced to the vicinity of the Peace-Athabasca Delta on April 25. Water levels at the Claire River Mouth began to rise substantially (2.5 m) between ≈ 09:00 and 21:00 MDT (Figure B.3), apparently under the influence of an ice jam near Carlson’s Landing/Moose Island (personal communication, S. Macmillan, WBNP). The backwater associated with this jam was rather transient (Figure B.3) with the jam likely having failed at 21:00 MDT. This event was quickly followed by the re-establishment of ice jamming in the vicinity of the Rocher mouth on April 26 (personal communication, S. Macmillan, WBNP). This jam remained in place for some 3 days with peak water levels at the Claire River mouth (215.25 m a.s.l.) occurring at ≈ 10:00 MDT on April 29. While gradually declining from that point on, it is evident that ice-progression influences were still being manifested at the Claire River mouth until May 03, when transient water-level fluctuations apparently ceased. Water levels dropped rapidly as the Peace/Slave River contiguous to the P-AD gradually became clear of ice.

Extensive flooding of the P-AD, including Egg Lake, occurred under the influence of the jams described above. The significance of the back-water extent can, in part, be appreciated by comparing the water levels shown in Figure B.3. with the geometry of the Claire River channel disturbance and its recent restoration (Figures B.1, B.2) Aerial photography and satellite imagery acquired during the event are currently being processed, calibrated and analyzed. Calibration of water levels will be assisted by water level records similar to that shown in Figure B.3.

Coupling the Claire River mouth record with knowledge of ice jam lodgment positions and estimates of discharge from the Peace Point gauge can provide the present study with excellent verification data. Unfortunately, on April 25, the Peace Point gauge orifice was damaged by scouring ice and was not made serviceable until May 3 (Personal communication, S. Macmillan, WBNP). At the Claire River mouth, however, high quality cross-section data is available for the Peace River. Field notes and photographic records of ice conditions at the site were also made during the above noted period. This information should allow an estimate of the mainstem discharge upstream of the ice jam sites and provide a crude but useful case history for additional model verification. Of notable significance to the understanding of the Peace River flow regime and ice breakup effects, it has been determined that the tributary basins below the W.A.C. Bennet Dam had above average snow water equivalent prior to the onset of spring breakup in 1996.
Figure B.1. The Claire River planform in relation to the Peace River and ice jam toe locations at Moose Island and Rocky Point.
Figure B.2. Longitudinal profile of the Claire River from the restoration site to its outfall into Lake Claire.

Data from P-ADTS (1996b) and Laveryne (1993)
Figure B.3. 1996 ice jam backwater near the Claire River Mouth

Preliminary data courtesy of NHRI (T. Carter/T. Prowse) and WBNP (S. Macmillan/S. Giroux)
Table B.1. Discharge on the Claire River for variable bed roughness.

<table>
<thead>
<tr>
<th>Toe Location (m)</th>
<th>n_j</th>
<th>Peace River</th>
<th>Claire River</th>
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<td>Discharge (m^3/s)</td>
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Claire River conveyance under the influence of Peace/Slave River ice jam backwater