University of Alberta

Hydrometeorological Factors Influencing Breakup Ice Jam Occurrence at Fort McMurray, Alberta

by

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ABSTRACT

River ice jams are commonly observed on the Athabasca River in the vicinity of Fort McMurray, Alberta. These natural events have been responsible for serious flood damages at the city of Fort McMurray. No method is currently in use to predict the occurrence or severity of ice jams at this site. A meteorological and hydraulic database was compiled in this research in order to investigate which factors influence the nature and rate of river ice breakup at Fort McMurray. These factors were first studied separately with simple threshold models. The results demonstrated that ice jams formation at Fort McMurray is very complex since none of the factors investigated individually provided any information on the occurrence of ice jams at the studied site. Linear and multiple linear regression models were also studied. Promising results were obtained when multiple factors were used to predict breakup flood levels.

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ADDT	accumulated degree-days of thaw up to the breakup date;
Adj R^2	adjusted coefficient of determination;
h_i	river ice thickness prior to breakup;
H_F	highest water level during freeze-up;
H_{Fo}	pre freeze-up water level;
H_{Bo}	water level prior to breakup;
H_B	maximum water level measured during breakup at the Water Survey of Canada gauge below Fort McMurray;
$H_{B,\ Clearwater}$	maximum water level measured during breakup at the Clearwater River confluence;
m	slope of the data to be corrected,
m_A	slope of the data to keep;
n	number of independent variables in the multiple regression model;
p	number of observations;
P	measured precipitation to be corrected;
P_A	adjusted precipitation;
$\Delta H/t\Delta$	fairly steady increase in water level prior to breakup;
S	accumulated daily average solar radiation flux received from the date degree-days of thaw accumulation started up to the breakup date;
S_4	accumulated daily average solar radiation flux received in the 4 days prior to breakup;
SWE	snow water equivalent;
R^2	coefficient of determination;
t_B	breakup date in Julian days;
T_{10}	degree-days accumulated in the 10 days prior to the breakup date;
T_{max}	number of days with maximum temperatures greater than 0°C prior to breakup calculated from the ADDT starting date.

CHAPTER 1 INTRODUCTION

During winter, Canadian rivers are covered with ice. This natural phenomenon can cause important damages during ice jam events. An ice jam occurs when the passage of the river ice floes is obstructed by natural or man made obstacles, which in many cases cause the water level to rise beyond open water flood elevations. Rive ice jams may result in damages such as flooding, destruction of bridges, and other river structures. Prowse and Ommanney (1990) estimated an average annual cost of ice jams damage in Canada of $22 million (1988 dollars) over a 10 year period.

1.1 DEFINITION OF THE PROBLEM

The occurrences of river ice jams have been documented on the Athabasca River at Fort McMurray, Alberta for more than 100 years. The latest severe ice jam occurred in 1997, which resulted in several million dollars in flood damage at the city (Hicks *et al.*, 2000b). Figures 1.1 and 1.2 show the disastrous flooding during the 1997 event. The 1997 flooding is comparable in magnitude to the high water level observed during the 1977 ice jam.

To date, no scientific method is available to predict the potential occurrence or severity of ice jams at Fort McMurray. Ice jams can form very suddenly, and thus threaten not only property, but lives as well. The following quotation from H.J. Moberly as referred to in Blench and Associates Ltd. (1964), describes the severity of an ice jam at Fort McMurray in 1875:

> "In less than an hour the water rose fifty-seven feet, flooding the whole flat and mowing down trees, some three feet in diameter, like grass."

Although no humans perished in this event, this is not always the case. Prowse and Ommanney (1990) reported 33 lives lost during river ice jam events in Canada. The need for an ice jam forecasting model is very important. Such a model would help the City of Fort McMurray in implementing their emergency preparedness program, and could help save lives during severe ice jam events.

1.2 STUDY AREA

The Athabasca River has its source in the mountains of Jasper National Park and flows northeast in the province of Alberta to Lake Athabasca (see Figure 1.3). The reach of interest for this study is the Athabasca River in the vicinity of Fort McMurray located at the Clearwater River confluence. Figure 1.4 graphically presents the studied reach. Approximately 6 km downstream of the MacEwan Bridge, Water Survey Canada (WSC) operates an annual gauge on the Athabasca River (station 07DA001). The drainage basin area above the WSC gauge is in the order of 131 000 km^2 when the Clearwater River basin is included (Environment Canada, 1999). The mean annual discharge at the WSC gauge below Fort McMurray is 661 m^3/s (Environment Canada, 1999). The mountain snowmelt and rainfall produce the annual peak discharge. The Clearwater River Basin contributes very little to flood events since its discharge is low and not synchronized with the runoff from the Athabasca River basin (Andres and Doyle, 1984).

A series of rapids characterize the Athabasca River for approximately 140 km upstream of Fort McMurray. In this region, the river channel is entrenched, has a bed slope of about 0.0010, and a top width averaging around 450 m (Andres and Doyle, 1984). Figure 1.5 shows the Athabasca River upstream of Fort McMurray. A distinct change in the geomorphology of the Athabasca River occurs at Fort McMurray. The channel slope reduces to around 0.00014 (Kellerhals *et al.* 1972). The channel width increases significantly, and numerous bars and islands are present. Figure 1.6 presents a photo looking downstream along the Athabasca River at Fort McMurray. The abrupt change of the Athabasca River channel slope at Fort McMurray is graphically presented in Figure 1.7.

The mean annual daily maximum and minimum temperatures in Fort McMurray are respectively 6.3 and –5.9°C (Environment Canada, 1998). The mean annual precipitation during the period of 1944 to 1990 was 465 mm. Only 22% of this mean annual precipitation occurred between November and March. The formation of an ice cover on the Athabasca River occurs between late October to mid-November. The river will remain ice covered generally until late April, but very occasionally, the ice stays in to May (Environment Canada, 1999).

1.3 PREVIOUS STUDIES

The first attempt to predict the likelihood of ice jam occurrence at Fort McMurray was documented by Doyle (1987). Two meteorological variables, measured at Fort McMurray, were used to predict the discharge of the Athabasca River at breakup with a linear model: the degree-days of thaw (based on mean daily air temperature above 0°C) and the hours of bright sunshine accumulated in the 4 days prior to breakup. Doyle (1987) also investigated the maximum breakup water level at the WSC gauge. The predicted discharge at breakup and the accumulated hours of bright sunshine in the 4 days prior to breakup were used in three forecasting models of the maximum water level: one linear and two non-linear. The best relationship between the model and actual maximum water level was obtained with a non-linear model, which had a standard error of estimate of 0.90 m.

Doyle (1987) also investigated the timing of breakup with the accumulated degree-days of thaw and the accumulated bright sunshine for different periods of time. No forecasting model of the breakup date was established with the results obtained by Doyle (1987). The timing and severity of breakup were also studied in the context of the characteristics of the antecedent upper atmospheric global pattern and flow. However, not enough details were available to make any conclusive interpretations.

Andres (1988) investigated river ice breakup by predicting the generation of open water on the Athabasca River between the confluence of the Pembina River and Fort McMurray (around 550 km). A numerical model was developed by describing the process from which a solid ice cover deteriorates to the point that the ice is unstable and breakup occurs. Andres's numerical model was developed with daily air temperature, solar radiation, discharge, maximum winter ice thickness, first day of steady discharge increase and last day of accumulated snow on the ice cover. The variables, which influence the results the most were the ones used to initialize the model. These variables are the maximum winter ice thickness, the last day with a snow cover on the ice, and the first day of the steady increase in water level. Calibration of the model was performed for spring 1986 during which breakup occurred on the same day from the confluence of the Pembina River to Fort McMurray. Andres (1988) did not clearly identify how to use his model when breakup in the studied reach does not occur on the same day. Dynamic events like the formation and release of ice jams, which are important events that influence breakup, were not included in the model.

1.4 AVAILABLE DATA

Meteorological and hydraulic data were considered in this study in order to investigate their influences on the likelihood of ice jam occurrence at Fort McMurray, Alberta. The meteorological factors investigated were the air temperature, the solar radiation, and the basin snow water equivalent (SWE) in late winter. The hydraulic data considered were the ice thickness, and variables related to the water level during river ice freeze-up and breakup, such as the maximum freeze-up water level and the maximum breakup water level.

The historical hydrometeorological record was first established starting from the 1973 breakup. Since an ice jam occurred at Fort McMurray during the 1972 breakup, the meteorological data were studied starting from the 1972 breakup since it was believed that this information would be fruitful compared to the time that it would take to process the data. Meanwhile, the hydraulic data were investigated from the 1973 breakup because the information regarding the 1972 ice jam was only found at the end of this research and these data are very labor-intensive to process. The historical hydrometeorological record has information gathered up to the 2001 breakup.

The historical hourly air temperatures measured at the Fort McMurray Airport from 1972 to 2001 were provided by Environment Canada. The University of Alberta meteorological station (UA meteorological station) located near the Fort McMurray Airport also provided the 2001 air temperatures. The 2001 record was used to establish a complete data record with the available Environment Canada and UA information.

Solar radiation data were provided by Golder Associates from their Aurora station located approximately 55 km north of Fort McMurray for the years of 1988, 1989, and 1995 to 2001, as well as by the UA meteorological station from October 2000 to June 2001. Hours of bright sunshine were also considered in this study to provide a longer historical record by converting the hours of bright sunshine to solar radiation. Alberta Environment provided the hours of bright sunshine measured at the Fort McMurray Airport from November 1st, 1971 to March 31st, 1996. Hours of bright sunshine were also measured at the UA meteorological station from April 22nd to April 27th, 2001.

Alberta Environment provided the SWE for the years of 1972 to 2001. Only the SWE data from the snow stations in the Athabasca River drainage basin upstream of Fort McMurray were included in this investigation since these would be likely to influence the discharge at the studied site during snowmelt runoff events.

The maximum water levels during breakup and the breakup dates at Fort McMurray were documented by various agencies over the years with the earliest breakup event documented in 1875. Details on the documentation of historical breakup events are given in Chapter 2. WSC provided the freeze-up water level at the gauge below Fort McMurray associated with the 1973 to 2001 breakup years. Breakup water levels at the

WSC gauge below Fort McMurray were mainly provided by WSC, but some years were documented by Doyle (1987).

1.5 RESEARCH OBJECTIVES

The first objective of this research was to establish a comprehensive database of hydrometeorological data pertinent to river ice breakup. Chapter 2 describes all of the steps carried out to establish over 20 years of meteorological data (air temperature, solar radiation, and SWE), while Chapter 3 presents the hydraulic variables investigated during this study (ice thickness, and factors related to freeze-up and breakup water level).

The next step was to identify which hydrometeorological variables influence the nature and rate of breakup at Fort McMurray, and to determine if the hydrometeorological database can be used to forecast the likelihood of ice jam occurrence in any given year. To achieve this objective, all of the variables were first investigated separately with simple threshold models. An attempt was then made to identify the relationship between a dependent variable, which represents a desirable element to forecast, to one or several independent variables which represent(s) measurable hydrometeorological variables that are considered to be contributing factors in terms of ice jam occurrence. This process was achieved by using linear regressions and multiple linear regressions. These results are presented in Chapter 4.

The final objective of this thesis was to establish a monitoring protocol necessary to develop reliable forecasting models at Fort McMurray, which is discussed in the conclusions and recommendations presented in Chapter 5.

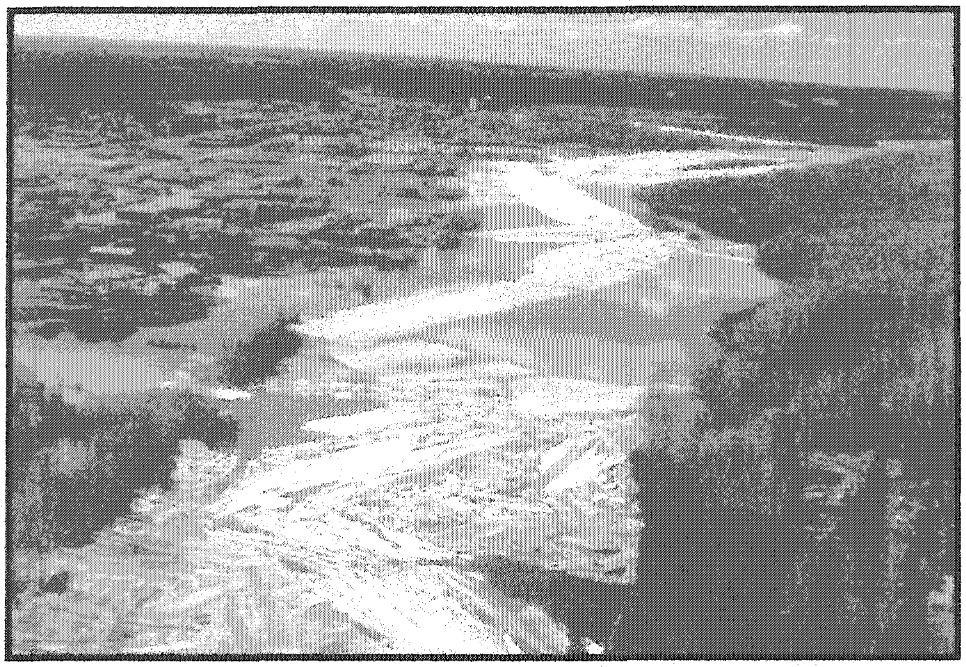

Figure 1.1 Ice jam flooding at Fort McMurray, Alberta, 1997.

Figure 1.2 Ice jam flooding at Fort McMurray, Alberta, 1997.

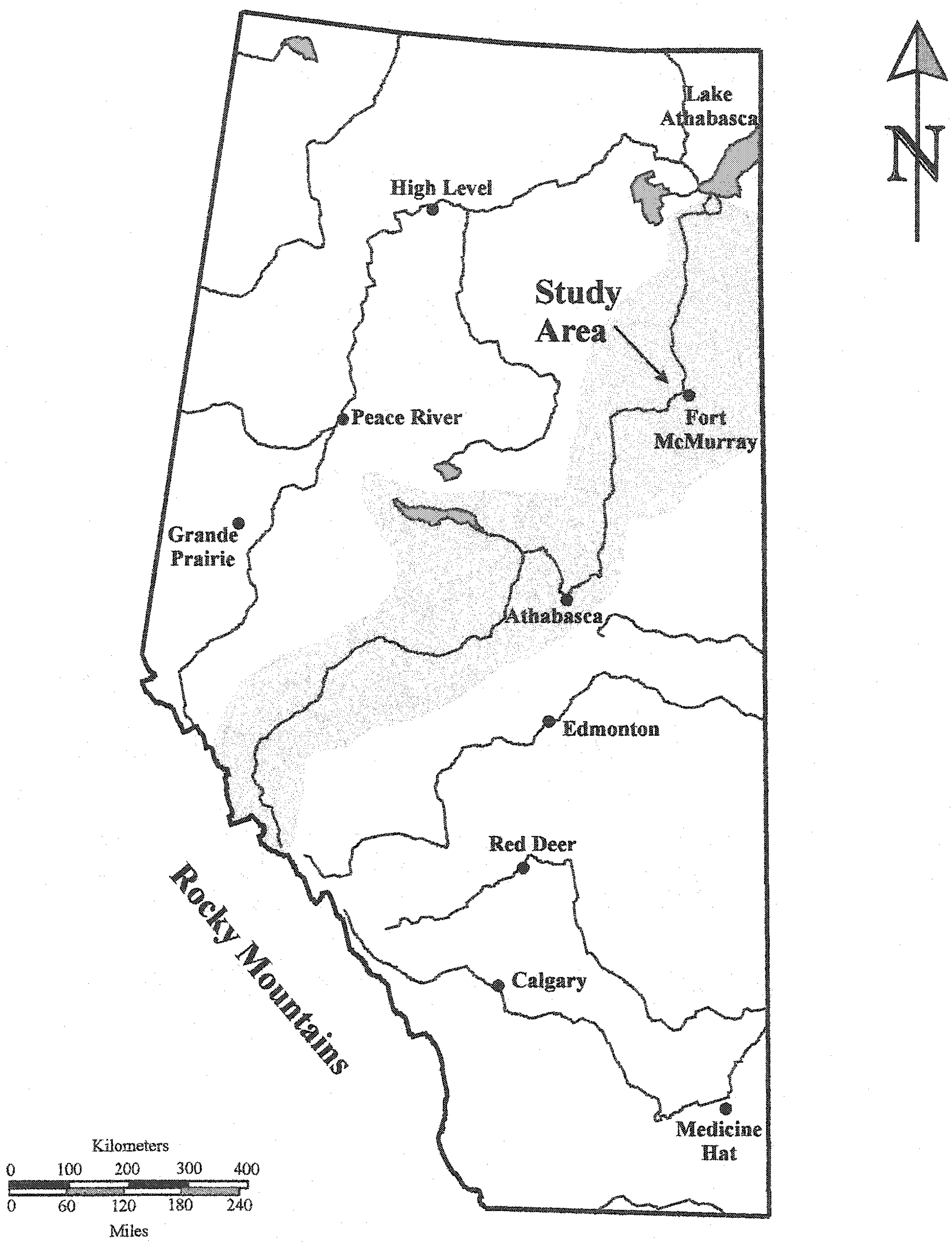

Figure 1.3 Drainage basin of the Athabasca River.

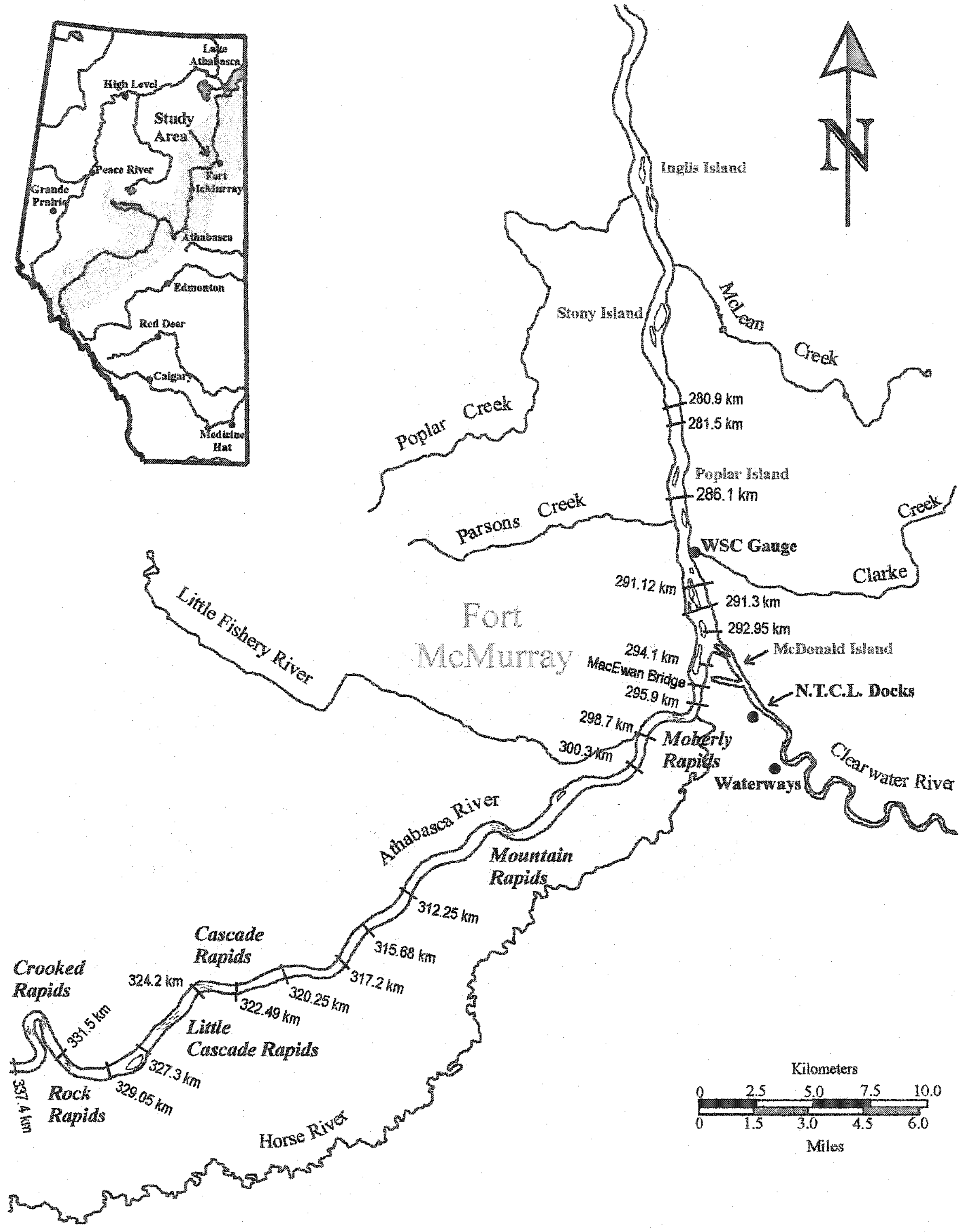

Figure 1.4 Study area.

Figure 1.5 Athabasca River upstream of Fort McMurray.

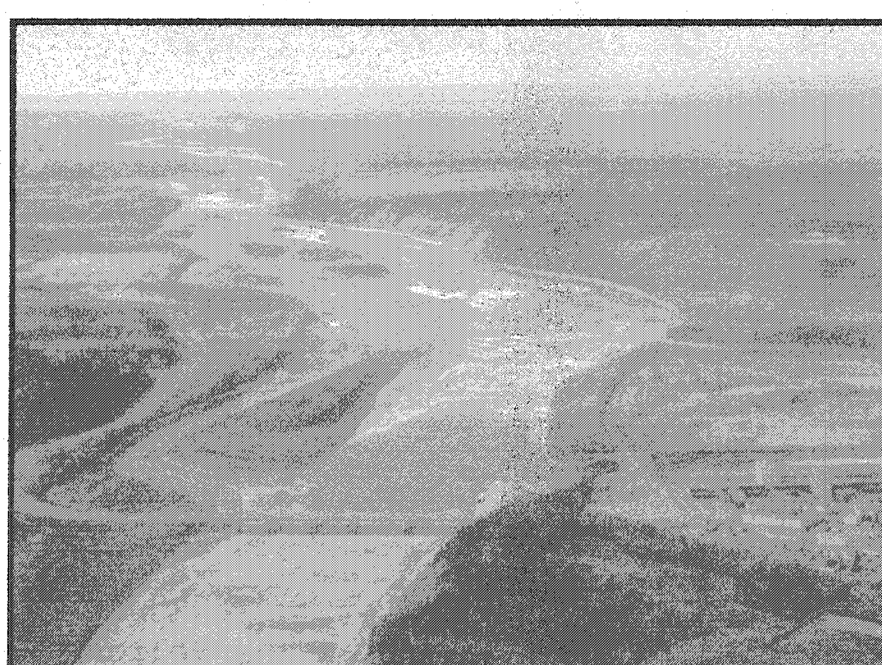

Figure 1.6 Downstream view of the Athabasca River at Fort McMurray.

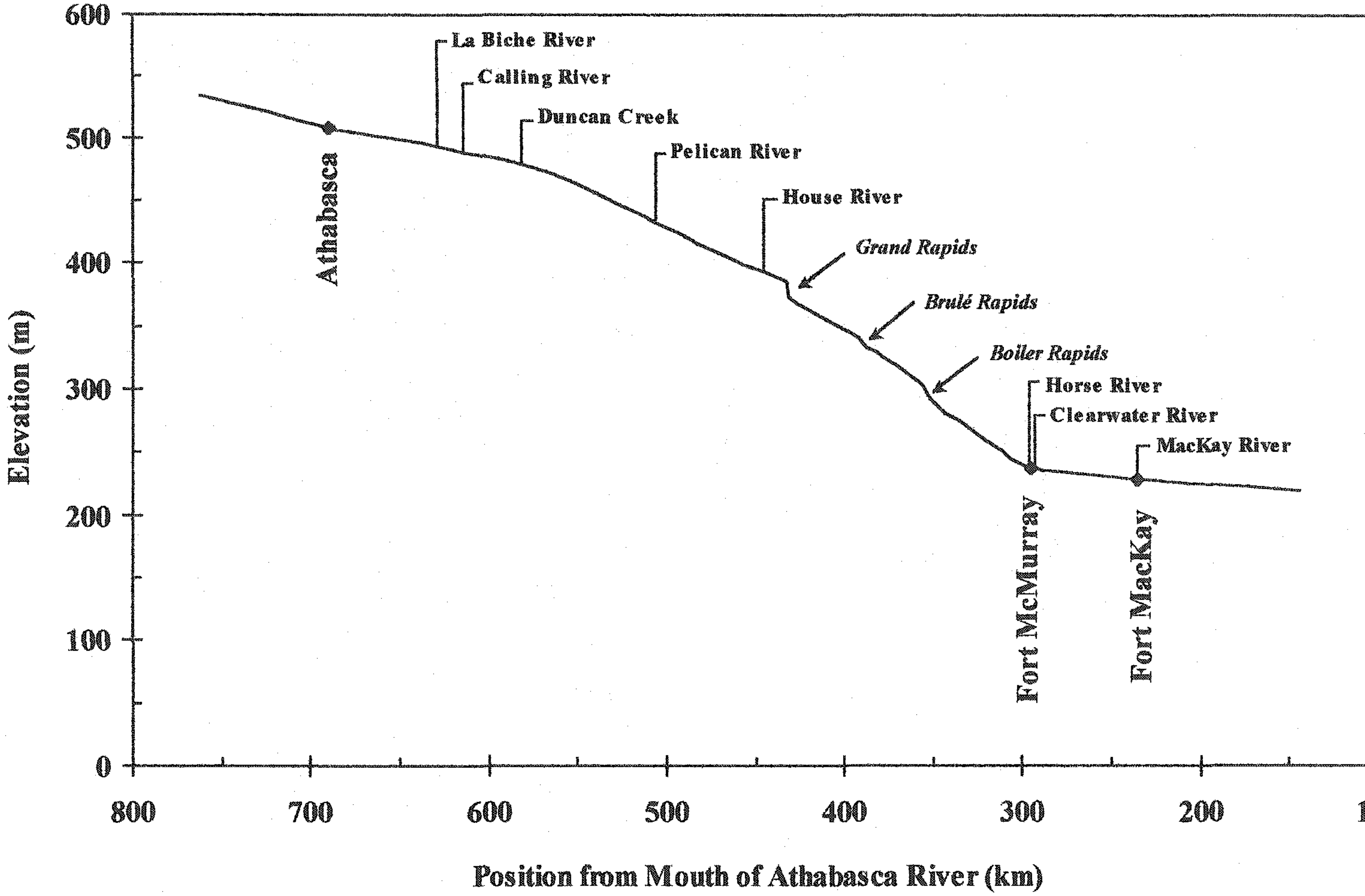

Figure 1.7 **Athabasca River longitudinal profile from Athabasca to Fort MacKay (after Kellerhals *et al.* 1972 and adjusted from Hicks *et al.* 2000a). Note: vertical exaggeration.**

CHAPTER 2 BREAKUP HISTORY AT FORT McMURRAY

This chapter gives an overview of the breakup history documented on the Athabasca River in the vicinity of Fort McMurray. First, a general description of breakup will be presented. A list of all the ice jam investigations performed over the years will then be discussed, followed by a brief summary of available breakup observations. Relevant information provided by WSC will also be presented. Finally, a summary of all the river ice breakup information gathered in this section is presented.

2.1 BREAKUP PROCESS AND DOCUMENTATION OF ICE JAMS ON THE ATHABASCA RIVER AT FORT McMURRAY

As mentioned previously, this section will first provide a general description of the river ice breakup process on the Athabasca River in the vicinity of Fort McMurray. A summary of historical documented breakup events on the Athabasca River near Fort McMurray will then be presented. Finally, a brief summary of important observations gathered from the documented spring breakup will be given.

2.1.1 General Breakup Description

River ice breakup can be classified as thermal or dynamic (Davar *et al.*, 1996). A thermal breakup generally occurs when the snow accumulation is small which likely implies a small spring runoff. In this situation, the river ice will melt significantly in place, reducing its strength. Small ice runs and low water level will generally be observed during a thermal breakup (Gerard and Flato, 1988). An ice run is observed when the river ice has been fractured and the ice sheets are moving downstream. On the other hand, a dynamic breakup is characterized with little river ice decay and significant spring runoff, which will likely lift and break the ice cover. River ice jams are generally observed when breakup is mainly governed by dynamic events.

The first indication of river ice breakup on the Athabasca River upstream of Fort McMurray is the thermal deterioration of the ice cover, which is observed by the formation of open leads that increase in size as melting proceeds. Generally, the open leads are first observed at the rapids. Figure 2.1 shows the Crooked Rapids located approximately 40 km upstream of Fort McMurray (see Figure 1.4 for location) on April 24^{th}, 2002 and Figure 2.2 presents the Crooked Rapids on April 26^{th}, 2002. It can be observed in Figures 2.1 and 2.2 that the size of the open lead at the Crooked Rapids has significantly increased in 2 days.

The next step of the breakup process is the fracture of ice sheets, which is likely caused by the weakening of the ice cover due to thermal deterioration and flexure due to the increase in discharge. After the ice sheets are fractured, they will flow downstream until they reach an obstacle such as competent ice. This obstacle can create an ice accumulation (i.e. ice jam). Figures 2.3 and 2.4 show the 2002 ice jam on the Athabasca River approximately 5 km upstream of the MacEwan Bridge (see Figure 1.4 for location). Ice jams are likely released with a significant increase in discharge or thermal deterioration of the ice.

The breakup process described previously is generally observed for approximately 140 km upstream of Fort McMurray where numerous rapids are present. As mentioned previously, this reach of the Athabasca River is very steep, which may explain why breakup is generally governed by dynamic events. Ice jams upstream of Fort McMurray are very common. It is believed that the snowmelt and the thermal deterioration of the ice cover affect the formation and release of ice jam. If an ice jam is released upstream of town, the water wave generated by this event has the potential to fracture the intact ice cover and to carry it downstream until the ice run is stalled by natural or man-made structures. Fort McMurray has high potential for ice jam formation since the river bed slope reduction decreases the velocity of the ice run, which increases the potential of the ice run to be obstructed by the many islands located in this region. If an ice jam forms downstream of the Clearwater River confluence (see Figure 1.4 for location), the increase in water level caused by the ice accumulation will raise the water level along the Clearwater River causing flooding in this area. Figures 1.1 and 1.2 show flooding along the Clearwater River caused by an ice jam on the Athabasca River during the 1997 river ice breakup.

Blench and Associates Ltd. (1964) conducted the first study to investigate the characteristics of ice jams in the vicinity of Fort McMurray. The Provincial Planning Board of the Province of Alberta commissioned this study with the objective of planning protective measures against flooding caused by ice jams. A list of historical ice jams in Fort McMurray was documented by Blench and Associates Ltd. for the years of 1875, 1881, 1885, 1925, 1928, 1936, 1958, 1962, 1963, and 1964. This information was provided by the Hudson Bay company records, newspaper articles, and interviews with local residents. Blench and Associates Ltd. (1964) also documented a list of available breakup dates defined as the first movement of ice on the Athabasca River at Fort McMurray from 1875 to 1964.

In 1974, a long term research program was initiated by the Transportation and Surface Water Engineering Division of Alberta Research Council (ARC) to observe and document breakup in selected river reaches in Alberta (Gerard, 1975). Ice jam events on the Athabasca River in the vicinity of Fort McMurray were documented by ARC in 1977, 1978, 1979, 1984, 1986, and 1987. Yaremko (1978) presented an ice jam flood level for 1972 spring breakup during an investigation of the flood hydrology for the Athabasca and Clearwater Rivers at Fort McMurray. Alberta Environment documented an ice jam in the studied reach during the 1982 spring breakup. Unpublished records from Alberta Environment also mentioned that ice jams occurred in 1988 and 1996. The more recent ice jam on the Athabasca River near Fort McMurray was in 1997. This severe ice jam was comparable to the magnitude of the 1977 event.

2.1.2 Historical Breakup Documentation on the Athabasca River at Fort McMurray

The following section presents a brief description of the documented spring breakup on the Athabasca River near Fort McMurray. For the purpose of this research, ice jams were studied if the jam toe was located in the vicinity of Fort McMurray between the Golf Course, approximately 4 km upstream of MacEwan Bridge, and downstream of the Clearwater River confluence where ice jams produced significant backwater effects on the Clearwater River. Only the ice jams in the studied reach are graphically presented in the following section, if the information was available. The other jam events are still presented in order to have a better understanding of breakup on the Athabasca River near Fort McMurray.

The 1875 Ice Jam

The 1875 event caused the biggest flood ever documented in Fort McMurray. Winhold and Bothe (1993) classify this flood as a 1 in 350 year event. The following description of the 1875 ice jam was provided by Blench and Associates Ltd. (1964). Original references of the previous source are listed below to help clarify some information.

The 1874-1875 winter was very cold with deep snow (Moberly and Cameron, 1929). A heavy snowfall on April 2^{nd} or 3^{rd} followed by a sudden rise in temperature was believed to have initiated breakup. The Hudson's Bay Co. archives contradict this somewhat, noting that no considerable snowmelt or degradation of the river ice had been noticed prior to breakup, and that the weather was still very cold.

The following description of the 1875 flood was extracted from a copy of the letter from Henry J. Moberly dated April 25^{th}, 1875 from the archives of Hudson's Bay Co.

"On the 20 Instant about 2 hours after daylight, the river suddenly gave signs of breaking up and in half an hour from that time the water had risen about 60 feet, and the whole place was flooded – the water and ice passing with fearful rapidity and carrying off everything before them. We had just time to escape to the hill, in our immediate vicinity, with the families, bedding and a little Provisions and Ammunition, and to throw up stairs the Furs and most of the valuable property, when the water was already rushing through the Fort. From the time the river first gave signs of starting hardly half and hour elapsed before there was 5 feet of water in the highest building in the Fort, and the Interpreter's house was carried bodily away and dashed to pieces in the Woods; the Workshop and Men's houses have been almost destroyed."

Blench and Associates Ltd. (1964) documented that the establishment of the Hudson's Bay Co. post was located on the right bank of the Athabasca River near the west end of Franklin Avenue. This information was provided by a long-time resident of the area. Figure 2.5 illustrates this location. Blench and Associates Ltd. (1964) investigated this site and concluded that the probable maximum water elevation was not greater then 253.0 m (830 ft) and not lower than 251.5 m (825 ft), which suggests that the water level increase would have been in the order of 12.2 m (40 ft) instead of 18.3 m (60 ft) as mentioned by Henry J. Moberly in the letter dated April 25th, 1875. Moberly and Cameron (1929) stated the ice was pushed 3.2 km (2 miles) up the Clearwater River when the ice run struck the turn in the stream at the post. From this description, the location of the jam toe was determined to likely be at the entrance of the Snye and that the authors' reference to the Clearwater River was in fact the Snye (see Figure 2.5). For clarification, the toe of an ice jam is located at the downstream end of the jam while the jam head is at the upstream end.

During the 1875 event, the water level remained high for 5 or 6 days after the initial jam occurred (Hudson's Bay Co. archives). It should also be mentioned that Moberly and Cameron (1929) stated the flood occurred on April 2nd or 3rd while the

Hudson's Bay Co. report from Moberly gives the date as April 20th. Since breakup was not clearly identified in Moberly and Cameron's (1929) description, and different interpretations can be concluded from that statement, April 20th was used as the breakup date for this research.

To be consistent with other reports that refer to Blench and Associates Ltd. (1964), the maximum water level observed during breakup 1875 was taken as 253.0 m at the entrance of the Snye. Yaremko (1978) transposed the maximum water level of 253.0 m to the Clearwater River confluence by reducing the value by 1.0 m. This reasoning comes from the fact that the 1977 ice jam profile presented in Doyle (1977), shows a 1.0 m drop in the water level from the MacEwan Bridge to the Clearwater River confluence.

The 1881 Flood

The Hudson's Bay Co. archives, as referred to in Blench and Associates Ltd. (1964), provided the following information regarding the 1881 breakup. On the morning of April 21st, 1881, the ice started to run downstream. The river jammed that same day between the McDonald Island and the little island opposite to the Hudson's Bay Co. post pushing the water into the Snye causing a flood in that area. The water level started to fall 3 days after the initial jam occurred, but it took 10 days before the Athabasca River was running almost free of ice. Blench and Associates Ltd. (1964) concluded from the Hudson's Bay Co. archives that the maximum water level would have been only a few feet below the ground at the post. Yaremko (1978) determined from the original Hudson's Bay Co. archives that the water level would have been less than 250 m and estimated the high water level to be 249.0 m at the Clearwater River confluence by again reducing the maximum water level by 1.0 m.

The 1885 Ice Jam Event

The following information was provided from the Hudson's Bay Co. archives as referred to in Blench and Associates Ltd. (1964). In the early morning of April 9th, 1885, the Athabasca River broke up and by mid-day the river was jammed. The Clearwater River was overflowing its banks on April 10th. The toe of the jam on April 19th appeared to be at the Clearwater River confluence, which was completely blocked up with the ice of the Athabasca River. Blench and Associates Ltd. (1964) concluded from the Hudson's Bay Co. archives that the maximum water elevation during this event was at least 249.0 m (817 ft). Yaremko (1978) documented a maximum water level of 249.1 m at the Hudson's Bay Co. post and once again, reduced the high water elevation by 1.0 m to transpose the level to the Clearwater River confluence.

The 1925 Breakup

The only information available regarding this event is the maximum water elevation obtained from the Northern Alberta Railways Co. as referred to in Blench and Associates Ltd. (1964). The high water level was established to be 247.4 m (811.7 ft) at Waterways along the Clearwater River. This level was documented on a plan of the railway at Waterways provided by Northern Alberta Railways Co. The Waterways location, identified in Figure 2.5, is approximately 6.4 km upstream of the Clearwater River confluence.

The 1928 Flood

The Northern Alberta Railways Co. as referred to in Blench and Associates Ltd. (1964), provided the maximum water elevation of 248.6 m (815.6 ft), which was documented on the same drawing mentioned in the previous section (i.e. at Waterways).

The 1936 Ice Jam

According to the Northern Alberta Railways Co. as referred to in Blench and Associates Ltd. (1964), the maximum water elevation at Waterways was 250.1 m during the 1936 flood. Residents of Fort McMurray also pointed out some high water elevations during the Blench and Associates Ltd. (1964) investigation. The high water mark on the inside wall of the Northern Transportation Co. Ltd. (N.T.C.L.) docks was estimated to be between 249.9 and 250.2 m (819.8 and 820.8 ft). Figure 2.5 shows the location of the N.T.C.L. docks. The maximum water elevation in the kitchen of a house located on the north side of Franklin Avenue near Peter Pond school was established around 249.8 ± 0.2 m (819.5 ± 0.5 ft). The Hudson's Bay Co. Ltd. publication, as referred to in Blench and Associates Ltd. (1964), indicated that breakup was initiated around 19:00 h on April 21st. Blench and Associates Ltd. (1964) documented that one source said that the water receded in the afternoon of April 22nd while another source indicated that the 'Prairie area' was flooded for about 10 days.

The 1958 Breakup

The Department of Northern Affairs and the National Resources, Water Resources Branch, as referred to in Blench and Associates Ltd. (1964), provided a gauge height of 7.9 m (26 ft) at the WSC gauge near Clarke Creek on the Athabasca River (Figure 2.5). This measurement represents an elevation of 244.9 m at the gauge. No flood damage was reported for the 1958 event (Blench and Associates Ltd., 1964).

The 1962 Flood

High water marks were used by the Department of Northern Affairs and National Resources, as referred to in Blench and Associates Ltd. (1964), to identify the maximum water elevation during the 1962 ice jam. This elevation was established at 246.2 m (807.74 ft), but no location was given.

The 1963 Ice Jam

The following information was provided from Blench and Associates Ltd. (1964). The Department of Northern Affairs and the National Resources, Water Resources established a maximum water elevation of 247.5 m (812.13 ft) from high water marks. With the help of pictures and other information, Blench and Associates Ltd. (1964) identified the location of the jam toe to be across the Athabasca River just downstream of the Snye. A resident stated that the water level increased rapidly after the first wave had propagated at a rate around 8.9 m/s (20 mi/hr) along the Snye.

The 1964 Flood

Blench and Associates Ltd. (1964) provided the information regarding the 1964 breakup in the vicinity of Fort McMurray. The 1963-1964 winter was classified as mild with a small snow pack. The river ice breakup on the Athabasca River at Fort McMurray occurred around 23:00 h on April 24th, and was accompanied by a rapid rise in the water level of approximately 1.2 m (4 ft). After a few hours, the Athabasca River was ice-free but had meanwhile pushed the broken ice up the Snye where it came to a rest at the northeast side of the Clearwater River. On the night of April 28th, the ice on the Clearwater River went out. The Snye was still solidly blocked with broken ice on April 30th. Blench and Associates Ltd. (1964) reported this event as the 1964 flood although he did not document any high water elevation or flood damage.

Construction of the Snye Dike, 1966

Blench and Associates Ltd. (1964) recommended that a dike should be constructed at the entrance of the Snye (see Figure 2.5). They believed that ice jams likely formed just downstream of the Snye since the water coming from the ice runs on the Athabasca River would drain into the Snye reducing the ice momentum. Blench and Associates Ltd. (1964) also believed that if a dike were build at the Snye, the location of severe ice jam toes would be moved downstream of the Clearwater River confluence which would reduce the maximum water levels at Fort McMurray by slightly more than 0.9 m (3 ft). In 1966, a dike was constructed at the entrance of the Snye (Winhold and Bothe, 1993).

The 1972 Ice Jam

Maartman (1974) reported a maximum water level of 245.3 m (804.7 ft) at the Snye dike during the 1972 ice jam. Yaremko (1978) also referred to the same elevation and assumed it was likely measured at the MacEwan Bridge. He then transposed the maximum water level to the Clearwater River confluence by reducing the value by 1.0 m.

The 1974 Breakup

Yaremko (1974) provided the information regarding the 1974 breakup. The winter ice thickness on the Athabasca River downstream of Fort McMurray was less then the average seasonal maximum of 0.9 m, varying from 0.5 to 0.8 m. Yaremko (1974) documented evidence of previous ice runs and small jams that they believed were formed during freeze-up at a few areas. Open leads were documented at the end of March in rapids areas.

The conditions one day prior to breakup at Fort McMurray were: "most of the 20 mile reach upstream of Crooked Rapids had opened up; downstream of Crooked Rapids to Fort McMurray, the river was still closed, but had braided and intermittent open water leads throughout" (Yaremko, 1974). Downstream of Fort McMurray to Inglis Island (around 24 km downstream of MacEwan Bridge), the ice cover was intact and the river snow was saturated with water. Open water was observed around the many islands downstream of Fort McMurray.

Breakup on the Athabasca River at Fort McMurray occurred at 8:02 h on April 20th. Yaremko (1974) believes that the rapid increase of the water level caused by the incoming ice run resulted from the release of an ice jam a few miles upstream of town. No visual observations of an ice jam or ice shear walls were documented upstream of town. Yaremko (1974) estimated the speed of the wave produced by the jam release to be approximately 3.1 m/s (7 mi/hr); it was breaking the intact ice as it moved downstream. No jam was reported on the Athabasca River in the vicinity of Fort McMurray; however, during the first two hours after breakup at Fort McMurray some ice from the Athabasca River was pushed approximately 0.8 km (0.5 miles) upstream into the Clearwater River. At that time, the ice on the Clearwater River was solid and stable. Over the next 24 hours, the water level variations on the Athabasca River pushed more ice into the Clearwater River, blocking the water passage. Yaremko (1974) believes that the Athabasca River ice that pushed into the Clearwater River was responsible for the flooding at Fort McMurray and Waterways. The high water mark observed on the ground at the MacEwan Bridge was 247.2 m (811 ft) during this event while the maximum water level along the Clearwater River was reported at 246.7 m (809.4 ft).

The 1977 Breakup and Ice Jams on the Athabasca River

The following information regarding the 1977 breakup was provided by Doyle (1977). He reported that: "the 1976-77 winter temperatures for November through March were 5 °C warmer than the average -14.6 °C, and the precipitation during these five winter months was only 64 percent of the normal 106 mm". Extremely mild temperatures were observed one week prior to breakup at Fort McMurray, resulting in the average daily air temperatures being well above zero.

Doyle (1977) documented that breakup on the Athabasca River at Athabasca occurred around noon on April 12th. The WSC gauge below Fort McMurray recorded a discharge of 1300 m^3/s prior to breakup at Fort McMurray, which had been increasing slowly for several days until the gauge malfunctioned on April 14th. The previous discharge reading may likely be inaccurate since the WSC gauge does not provide reliable discharge record during breakup. The river ice condition prior to breakup at Fort McMurray was described as: "ice cover in the vicinity of MacEwan Bridge at Fort McMurray was intact throughout the night of 13-14 April, with the water level at the staff gauge on the bridge steady at elevation 242 m" (Doyle, 1977). On the morning of breakup day at Fort McMurray, a total of 7.5 mm of rain had fallen in Fort McMurray from a moderate steady rainfall that began the previous night.

Breakup at Fort McMurray occurred on the morning of April 14th. A flood wave of approximately 5 m in height had passed the MacEwan Bridge at 6:50 h, initiating breakup. An eyewitness estimated its velocity to be around 5 to 6 m/s. Doyle (1977) presumed that this wave was created by the release of an ice jam located in the vicinity of Crooked Rapids, since it had little attenuation when it reached Fort McMurray and ice shear walls estimated to be as high as 8 m were observed upstream of Little Cascade Rapids. This previous statement from Doyle (1977) is unlikely since Hicks (2002) measured attenuation from 4.3 m at the remote monitoring station G140 to 1.5 m at station G135 (see Figure 1.4 for locations). On the morning of April 14th, the ice run arrested forming an ice jam, with its toe located at the upstream end of Poplar Island against the fractured ice cover. Figure 2.6 shows this location of the jam toe, and the head of the jam 14 km upstream of the MacEwan Bridge. During the ice run, the Athabasca River ice was pushed approximately 3 km upstream into the Clearwater River. On April 15th, the original ice toe failed, releasing ice and leaving the subsequent ice toe among the islands downstream of the Clearwater River confluence (see Figure 2.6). The remainder of the ice jam stayed in place until April 22nd.

Severe flooding occurred along the Clearwater River during the 1977 breakup. The maximum water elevation at Waterways (6.4 km upstream of the Clearwater River) was measured at 248.0 m, while a water level of 247.8 m was observed at the Clearwater school (2.6 km upstream of the confluence). At the Clearwater River confluence, high water marks indicated an elevation of 247.9 m at the Clearwater River side of McDonald Island and a value of 247.6 at the Athabasca River side of McDonald Island. The maximum water level observed at the MacEwan Bridge was 248.7 m. A high water elevation of 247.4 m was received from Alberta Environment. No location was specified for this water level.

The 1978 Breakup

Doyle and Andres (1978) documented the 1978 breakup at Fort McMurray. They reported that: the air temperature from November through March was equal to the average –14.6°C at Fort McMurray; the total precipitation during the 1977-1978 winter was equal to 72 percent of the normal 106 mm; and that low runoff in the Athabasca River drainage basin was caused by below normal snow depths at the beginning of April. An ice thickness of 0.9 m was measured downstream of MacEwan Bridge in early spring. During the week prior to breakup, a small amount of snow had fallen in Fort McMurray.

Breakup on the Athabasca River at Athabasca occurred uneventfully on April 13th and 14th. The daily discharge measured at the WSC gauge at Athabasca was estimated to be around 450 m^3/s during breakup with the water level rising less than a 1.0 m (Doyle and Andres, 1978). An ice jam 9 km long was first observed on April 15th in the vicinity of Long Rapids, 50 km upstream of MacEwan Bridge. On April 18th, the Long Rapids jam had compressed a little but no significant change was observed. The ice conditions on April 18th, one day priory to breakup at Fort McMurray, were: "in the vicinity of

Crooked Rapids, Cascade Rapids and Mountain Rapids, the ice was deteriorating with open leads increasing in number and length and joining together" and "some small patches of ice moved below the rapids, although the ice continued to be competent" (Doyle and Andres, 1978). Downstream of MacEwan Bridge, the top of ice was slushy with some water on the surface. The Clearwater River ice was still competent at this time with no sign of melting. Doyle and Andres (1978) believed that an ice jam, formed in the vicinity of Rapides du Joli Fou (approximately 165 km upstream of Fort McMurray) from which the remaining ice shear walls were observed on April 25th, was released after noon on April 18th.

On April 19th between 6:45 and 8:30 h, the water level rose by 0.3 m at the MacEwan Bridge, which caused the water to start flowing on top of the ice along the banks. The front of the Long Rapids jam was noticed at 11:00 h, 3 km upstream of Crooked Rapids where it had halted and formed an ice jam (4 km long). Running ice was observed for about 50 km upstream of the jam. Doyle and Andres (1978) estimated from the air that the difference in the water level upstream and downstream of the jam toe was 6 to 7 m. By 11:30 h, this major jam had released and was moving through Little Cascade Rapids. At 14:15 h, the ice run was observed to have stopped at Cascade Rapids. At this point, Doyle and Andres (1978) estimated a difference of around 7 m in height between the upstream and downstream water level at the jam toe. Since the ice run was observed by helicopter, this stage difference estimate was likely also based on aerial observations. The jam at Cascade Rapids was released just after 14:15 h. Doyle and Andres (1978) documented that when the front of the moving ice was located 3 km upstream of the MacEwan Bridge, the ice run seemed to have lost its force compared to when the jam was released at Cascade Rapids. The ice run reached the MacEwan Bridge at 16:40 h, which initiated breakup at Fort McMurray, and by around 20:00 h a stable ice jam had formed at the MacEwan Bridge. Figure 2.7 presents the location of the 22 km long jam.

By April 26th, the ice jam had reduced in length and was rotting in place. The high water mark at the Clearwater River confluence during this event was around 242 m, 5.6 m lower than the 1977 maximum water level. On April 26th, the Clearwater River ice went out and jammed against the Athabasca River ice causing an increase in the water level of around 1.4 m approximately 3.5 km upstream on the Clearwater River. Since the ice jam at Fort McMurray was upstream of the Clearwater River confluence, flood damages were minimal during the 1978 breakup.

The 1979 Spring Breakup

The 1979 spring breakup was documented by Doyle and Andres (1979). They reported that: the temperature at Fort McMurray from November to March was 2.2 °C colder then the average −14.6 °C; the monthly mean temperature for April was around 2 °C cooler than normal; and the November through March precipitation in the basin was around average. By the end of March, a warm trend had melted most of the snow in the area from Whitecourt to Hinton (750 to 950 km upstream of Fort McMurray). Doyle and Andres (1979) believed that the snow cover at Fort McMurray was probably close to normal and well below normal in the Whitecourt area during the snowmelt peak runoff. One week prior to breakup, a total of less than 2 mm of precipitation in the form of snow and rain was documented at Fort McMurray. The ice thickness was measured at the WSC gauge below Fort McMurray on April 3rd. The observed values ranged from 0.46 to 1.60 m (Doyle and Andres, 1979). On April 21st, just downstream of the MacEwan Bridge, ice thicknesses were measured to be ranging from 0.79 to 1.43 m during a WSC discharge measurement.

On April 20th, a series of open leads (1 to 2 km long) were observed from Boiler to Long Rapids (58 to 50 km upstream of Fort McMurray) with broken ice at the downstream end of these leads. From Crooked Rapids to MacEwan Bridge, some narrow leads (most less than 100 m long) were observed, mostly at the rapids. Small open leads were also observed downstream of both sewage outlets at Fort McMurray. Breakup on the Athabasca River at Athabasca started on April 24th. From the daily water level readings at the Athabasca WSC gauge, Doyle and Andres (1979) concluded that breakup was prolonged and no high water level occurred. On April 26th, the rapids were more open then the previous reconnaissance on April 20th. From 15 km upstream of Pelican Portage to Grand Rapids (around 240 to 132 km upstream of MacEwan Bridge), the ice cover was generally intact with some open leads, with the exception of Stony Rapids (around 210 km upstream of Fort McMurray) and Grand Rapids, which were open. Grand Rapids was open for 4 km downstream at which point an ice jam was observed. Brule and Long Rapids were completely open while Boiler and Middle Rapids were significantly open.

At 10:05 h on April 28th, an ice run was documented 8.5 km upstream of Mountain Rapids. The ice run was halted approximately 4 km downstream of Mountain Rapids where an ice jam was starting to form around 11:45 h. By noon, the total length of the jam was approximately 8 km. At 15:00 h, the jam toe had moved downstream by 1.5 km and the jam head was now located around 5 km downstream of Cascade Rapids. Upstream of the jam head, there was an ice run approximately 15 km long. At 19:00 h, the head of the jam was observed 3 km downstream of Cascade Rapids. By then, the ice run upstream of Crooked Rapids had reduced in density. It was also noticed that the ice downstream of the unstable jam toe had released for a short distance.

In the afternoon of April 28th, an accelerated rise and rapid fluctuation of the water level was observed at the MacEwan Bridge (Doyle and Andres, 1979). At 19:57 h, the ice cover at the MacEwan Bridge started to move without any increase of the water level. Around 20:00 h, the ice jam at Mountain Rapids failed. The ice run rushed through the bridge approximately 20 minutes after the initial ice movement at the bridge was observed. The run lasted until 22:35 h when no movement was reported at the MacEwan Bridge. The water level on the Clearwater River started to gradually increase after the ice stopped moving. The next morning, the toe of a major jam was observed at an island 16 km downstream of the MacEwan Bridge. The jam head was at this time approximately 2 km downstream of Mountain Rapids. Figure 2.8 graphically presents the location of the jam.

During the 1979 ice jam event, the maximum water level measured at the MacEwan Bridge was 247.5 m on April 29th. Just upstream of the Clearwater River confluence on the Athabasca River, the high water mark was observed at 246.9 m also on April 29th. The difference in the maximum water level observed on April 29th at the MacEwan Bridge and the Clearwater River confluence is 0.6 m, which is smaller than the 1.0 m value used by Yaremko (1978) to transpose the maximum water level at the MacEwan Bridge to the Clearwater River confluence. The maximum water level on the Clearwater River just upstream of the confluence was measured at 246.5 m. High water levels were also observed at the Grimshaw Trucking terminal, approximately 3 km upstream of the confluence, and at the WSC gauge at Draper, 17 km upstream of the confluence. The maximum water elevations measured at these locations were 246.8 m and 246.9 m.

Around 00:45 h on May 4th, the jam failed removing the ice for a few km on the Clearwater River. Breakup occurred between May 7th and 10th on the Clearwater River with no significant effect on the water level at Fort McMurray.

The 1979 breakup resulted in flooding along the Clearwater River. Doyle and Andres (1979) compared the high water level of the 1978 ice jam with previous events as followed: "peak water levels within the jam were about 1 m less than those in the 1977 jam and 0.5 m less than those of the 1978".

The 1982 Breakup on the Athabasca River

The following information was provided by Rickert and Quazi (1982). The pre-breakup conditions on March 9th and 10th were: the accumulated precipitation from November was 78 percent of the normal conditions; the average temperature was 1.4 °C above normal; and the ice cover was solid from Crooked Rapids to Fort McMurray. By March 26th, a total of 32 cm of snow was observed on the ground. The ice cover was solid on the Athabasca and Clearwater River on March 26th. An important snowfall event occurred at the end of March leaving a total of 52 cm of snow still on the ground on April 5th. Open leads were first observed in the rapids on April 14th. It was observed on April 16th that the leads in the rapid areas were growing in size and that the ice around the leads was slightly broken. On April 19th, an increase of 7.5 mm of precipitation from April 15th was measured, the accumulated precipitation for the winter was 93 percent of the normal value, and the snow on the ground was only 15 cm. By April 21st, the snow cover had reduced to 6 cm. Breakup on the Athabasca River at Athabasca occurred on April 24th. From April 19th to April 25th, the water level of the Athabasca River at Athabasca increased by 1.2 m. Rickert and Quazi (1982) also documented that the accumulated snow precipitation for the 1981-1982 winter was above normal in the drainage basin.

Rickert and Quazi (1982) documented that there were signs that a temporary ice jam had formed downstream of Cascade Rapids prior to April 26th. In the morning of April 26th, the toe of an important ice run was observed from the air at Long Rapids, around 50 km upstream of MacEwan Bridge, with the head of the run reaching beyond Grand Rapids, approximately 132 km upstream of the bridge. From the toe of the ice run to downstream of Cascade Rapids, the Athabasca River was free of moving ice. A weakly consolidated ice cover was observed just downstream of Cascade Rapids extending down to a point just upstream of Mountain Rapids. A competent ice cover was still in place just upstream of Mountain Rapids past MacEwan Bridge. The ice run met the consolidated ice immediately downstream of Cascade Rapids around noon. The run jammed twice before reaching the very competent ice cover just upstream of Mountain Rapids. A jam also developed through the Mountain Rapids between 13:30 and 15:04 h. From the observed shear walls, Rickert and Quazi (1982) believed that the ice run temporarily stopped before it reached the MacEwan Bridge at 16:40 h. Jamming also took place through the MacEwan Bridge and just upstream of the Clearwater River confluence for about 3.5 hours. The jam released around 20:30 h. The maximum breakup water level on April 26th at the MacEwan Bridge was 246.8 m and the value at the Clearwater River confluence was 242.2 m. An open channel was only observed on the night of April 29th at the Clearwater River confluence. No flooding occurred along the Clearwater River during the 1982 spring breakup.

The 1983 River Ice Breakup

Andres and Rickert (1984) provided the documentation on the 1983 breakup on the Athabasca River. They reported that: the mean monthly winter temperature from November through March was 1.2 °C warmer then normal; and the total accumulated precipitation of the five winter months was 82.8 mm which is 26 percent lower then normal conditions. On January 19th, WSC measured ice thicknesses varying from 0.4 to 1.3 m at the WSC gauge below Fort McMurray. The average ice thickness at that time was 0.72 m. Ice thickness measurements were also obtained on March 12th at the same location. The average ice thickness was 0.68 m with values ranging from 0.4 to 1.1 m. Andres and Rickert (1984) documented that this difference was insignificant and that frazil ice was probably the cause of greater ice thickness in January. The city of Fort McMurray also measured ice thickness in the vicinity of the town mainly at the Clearwater River confluence. On April 15th, the city measured an average ice thickness of 0.92 m suggesting a thicker ice cover than at the WSC gauge on the Athabasca River below Fort McMurray (Andres and Rickert, 1984).

On the April 8th, an intact ice cover was observed from 165 to 132 km upstream of MacEwan Bridge except for open leads near Rapides du Joli Fou (approximately 165 km upstream of MacEwan Bridge) and downstream of Grande Rapids (around 132 km upstream of the bridges in Fort McMurray). Open leads were also observed at Long Rapids (50 km upstream of Fort McMurray) and downstream of Crooked Rapids. The ice on the Athabasca River downstream of Fort McMurray was intact with no significant melting. On April 16th, an important ice movement was observed downstream of the House River (around 148 km upstream of MacEwan Bridge) to Grand Rapids with accumulated ice at the downstream ends of the open leads. It was also documented that the open leads observed on April 8th from Grand Rapids to Fort McMurray had enlarged and some water was flowing on top of the ice cover at the downstream end of the open areas, except for the reach just downstream of Crooked Rapids where no significant changes were observed. At this time, no melting or deterioration of the ice cover was seen on the Clearwater River.

Local observers reported that breakup on the Athabasca River at Athabasca was initiated on April 18th (Andres and Rickert, 1984). From the WSC gauge records at Athabasca (station 07BE001), Andres and Rickert (1984) suggested that a jam might have formed in the vicinity of Athabasca during the 1983 breakup. The location of the town of Athabasca is graphically presented in Figure 1.3.

The first sign of breakup in the rapids upstream of Fort McMurray was documented on April 18th when an ice jam was observed at Crooked Rapids by personnel of the City of Fort McMurray (Andres and Rickert, 1984). The total length of the jam was 6 km. At this time, all the ice from Rapides du Joli Fou to Crooked Rapids had moved downstream. The water wave associated with this event caused the water level at the WSC gauge below Fort McMurray to rise around 0.44 m (without breaking the ice cover). On April 19th, a 6 km long ice jam was observed approximately 250 km upstream of MacEwan Bridge, around 14 km upstream of Upper Wells. Meanwhile, an intact ice cover was documented between Upper Wells and Rapides du Joli Fou. Andres and Rickert (1984) believe that this jam and the intact ice cover melted without significantly affecting the ice jam at Crooked Rapids.

On April 21st, the ice downstream of the jam toe at Crooked Rapids moved 4 km downstream where it jammed against the intact ice cover. At this time, melting of the ice cover upstream of Fort McMurray was significant. A small ice run was also documented on the Clearwater River at the end of the day on April 21st, which produced a high water level of 242.3 m along the Clearwater River at N.T.C.L. Docks, approximately 3.2 km upstream of the confluence. A maximum water level of 242.0 m was also observed on April 21st at the MacEwan Bridge during the 1983 breakup. On April 22nd, the jam at Crooked Rapids collapsed, and a section of well deteriorated ice cover between the MacEwan Bridge and the Clearwater River confluence moved downstream. The Clearwater River ice at the confluence had moved downstream on April 22nd, producing a maximum water level of 239.5 m at the WSC gauge below Fort McMurray. It took 3 days before the breakup front of the Crooked Rapids jam reached Moberly Rapids on the morning of April 25th. By 7:00 pm, spring breakup at Fort McMurray was finished.

The 1984 Spring Breakup

Documentation of the 1984 breakup in the vicinity of Fort McMurray was provided by Andres and Rickert (1985a). They reported that: the mean air temperature at Fort McMurray from November to March was 3.3 °C warmer then the average -14.4 °C; and that the accumulated snow precipitation during the 1983-1984 winter was 68 percent of normal conditions in Fort McMurray. The average ice thickness measured at the WSC gauge below Fort McMurray was equal to 0.81 m on March 6th (Andres and Rickert, 1985a). The City of Fort McMurray measured an average ice thickness of 1.0 m in the vicinity of the Clearwater River confluence on March 12th. The ice thickness in this area had decreased to 0.8 m by March 26th. The ice thickness measured by the City of Fort McMurray were documented by Andres and Rickert (1985a).

The first aerial reconnaissance was done on March 29th. At this time, the ice between Grand Rapids (approximately 132 km upstream of MacEwan Bridge) and Crooked Rapids was intact except for some open leads. Melting and surface overflow were documented at Crooked Rapids and Mountain Rapids. The ice cover was intact with no significant snow cover downstream of Mountain Rapids to the Suncor plant, around 31 km downstream of MacEwan Bridge. Breakup on the Athabasca River at Athabasca occurred on April 7th. Andres and Rickert (1985a) concluded from the WSC records that breakup at Athabasca was uneventful during spring 1984. Landsat imagery on April 9th showed that the ice cover from Pelican Rapids (approximately 215 km upstream of the bridges in Fort McMurray) to Long Rapids (50 km upstream of MacEwan Bridge) was still in place except for a 10 km open section at the House River confluence (about 148 km from the bridges). Short open areas were also noticed at the numerous rapids. The next day, no ice was observed from Calling River (around 315 km from the MacEwan Bridge) to Pelican Rapids. The ice in this area had moved downstream, filling the river from Pelican Rapids to the House River confluence. Open water was also documented downstream of Brule Point (approximately 101 km upstream of MacEwan Bridge in Fort McMurray) to Middle Rapids (around 55 km upstream of MacEwan Bridge). Andres and Rickert (1985a) documented that an ice jam (8 km long, at maximum) was probably located from Middle Rapids to downstream of Long Rapids. Downstream of the jam toe, the ice cover was not continuous since open water was documented at Crooked Rapids, upstream of Little Cascade Rapids, and at Mountain Rapids. The ice cover remained intact downstream of Mountain Rapids all the way to the Suncor plant (31 km downstream of Fort McMurray) where the river was open for 20 km downstream of the plant.

The ice accumulated upstream of the House River (observed earlier with the Landsat imagery) was released before 17:00 h on April 10^{th} and the resulting ice run had reached Rock Rapids by 19:00 h. A gradual water increase of 0.12 m initiated at 17:00 h was measured at the WSC gauge downstream of Fort McMurray over a period of four hours. The House River ice run was halted just downstream of the Horse River (see Figure 1.4) when an ice jam formed at 22:40 h. Figure 2.9 graphically presents the location of the Moberly Rapids jam. The ice jam caused the water level at the MacEwan Bridge to drop 0.2 m, but no effects were measured at the WSC gauge (Andres and Rickert, 1985a). Approximately 6 m of water head had built at the jam toe before the jam was released at 00:26 h on April 11^{th}. No details were given on how the 6 m of water head was estimated in Andres and Rickert (1985a). A maximum water elevation of 244.5 m was measured at the MacEwan Bridge at 00:30 h and a value of 241.0 m was recorded at the WSC below Fort McMurray at 02:00 h (Andres and Rickert, 1985a). The breakup front had reached Suncor (approximately 31 km downstream of the bridges) by 03:00 h. From the WSC records, Andres and Rickert (1985a) believed that an ice jam had formed downstream of the gauge below Fort McMurray after 08:00 h on April 11^{th} and was gradually released after 42 hours. During the spring 1984, the Clearwater River broke up after the Athabasca River and no flooding was documented (Andres and Rickert, 1985a). Winhold and Bothe (1993) documented a maximum water elevation of 243.5 m at the Clearwater River confluence during the 1984 breakup, which was probably deducted by reducing the high water level at the MacEwan Bridge by 1.0 m as previously done by Yaremko (1978) for earlier events.

Observations of the 1985 Breakup

Andres and Rickert (1985b) provided the documentation of the 1985 spring breakup. They reported that the average air temperature for the winter of 1984-1985 was −14.3°C representing normal conditions in Fort McMurray; In fact, the months of November, December, and February were colder than normal while January and March were warmer. Andres and Rickert (1985b) documented that the total precipitation during the 1984-1985 winter was approximately 62 percent of normal at Fort McMurray. The average ice thickness near the WSC gauge below Fort McMurray was 0.72 m on April 2^{sd} and the mean ice thickness measured by the City of Fort McMurray in the vicinity of the Clearwater River confluence was equal to 1.11 m on March 20th (Andres and Rickert, 1985b).

On April 1st, open leads were observed from an aerial reconnaissance at the numerous rapids on the Athabasca River upstream of Fort McMurray. Breakup was initiated on the Athabasca River at Athabasca on April 11th when ice movements were observed at the town (Andres and Rickert, 1985b). An ice run passed the WSC gauge at Athabasca at 18:00 h on April 12th. Downstream of the running ice front, open water was documented 15 km to Duncan Creek (approximately 285 km upstream of Fort McMurray) where the head of an ice jam (13 km long) was located on April 13th. Downstream of this jam, the ice was intact with around 50% of it melted and with numerous open leads. This condition was observed downstream to around 250 km upstream of Fort McMurray where open water was documented for 22 km. The head of an 8 km long ice jam was then observed on April 13th at the mouth of Parallel Creek approximately 226 km upstream of MacEwan Bridge. An intact ice cover was observed downstream of this jam with significant open leads extending to Grande Rapids around 132 km upstream of the bridges in Fort McMurray. Downstream of Grande Rapids, open water was documented for approximately 7 km with broken ice sheets at the downstream end. Open water was also documented downstream of the Alger River confluence around 65 km upstream of MacEwan Bridge until it reached a 3 km long jam at Long Rapids approximately 50 km from the bridges in Fort McMurray. Downstream of the Long

Rapids to Little Cascade Rapids, numerous open leads were noticed. Significant leads were also observed at Mountain Rapids.

The April 14^{th} aerial reconnaissance indicated that the small ice run recorded at the Athabasca WSC gauge (around 405 km upstream of MacEwan Bridge) on April 13^{th}, had reached a 9 km long ice jam toed at Stony Rapids (approximately 210 km from the bridges in Fort McMurray). The jam had formed against an intact ice cover that extended downstream of Rapides du Joli Fou. These rapids are located around 165 km upstream of the MacEwan Bridge. Downstream of the intact ice cover previously mentioned, open water was observed extending to downstream of Brule Rapids where the head of an ice run was documented. This moving ice had reached Cascade Rapids at 10:33 h on April 14^{th}. At 11:20 h, the ice run came to a stop upstream of Mountain Rapids building a stable ice jam. The length of the jam was 18 km (Andres and Rickert, 1985b). A sudden rise in the water level at the WSC gauge below Fort McMurray was observed at 14:00 h, 2.5 hours after the formation of the Mountain Rapids jam.

On April 17^{th}, it was observed that the toe of an ice jam was located 4 km downstream of Stony Rapids. This jam had a total length of 11 km and no ice run was noticed upstream of the head. At the same time, the ice cover was still intact 6 km upstream of Rapides du Joli Fou in a sharp bend extending approximately 8 km upstream. A 5 km long ice jam was toed against the upstream end of the intact ice cover.

The ice cover upstream of the MacEwan Bridge started to breakup at 6:30 h on April 18^{th}. The Mountain Rapids jam was still in place on April 18^{th} at 8:00 h. The ice cover downstream of Mountain Rapids generated a small ice run at the MacEwan Bridge. No ice jam was observed in the vicinity of Fort McMurray during this event. The maximum water level observed at the MacEwan Bridge during the ice run was 244.5 m, while the maximum stage at the Clearwater River confluence was 243.5 m (Andres and Rickert, 1985b). It is important to mention that the Mountain Rapids ice jam melted in place sometime after April 18^{th}.

The 1986 River Ice Breakup

The following information was provided in part by Malcovish *et al.* (1988), and also by Andres (1988). Malcovish *et al.* (1988) reported that: November was the coldest month with a mean daily temperature 8.1°C below normal;. December, January and March were warmer with daily mean temperature 4.2°C, 10.0°C, and 6.1°C greater than normal; and the total precipitation from November to March was 82 percent of normal conditions. WSC measured an average ice thickness of 1.04 m near the WSC gauge below Fort McMurray on March 7th and a mean of 1.03 m upstream of the MacEwan Bridge on April 15th (Malcovish *et al.*, 1988). In early April, an average ice thickness of 1.05 m was measured by the City of Fort McMurray in the vicinity of the Clearwater River confluence (Malcovish *et al.*, 1988).

The first aerial reconnaissance on April 3rd was documented by Andres (1988). At this time, the ice cover in the rapids upstream of Fort McMurray was intact with some overflow and open leads generally observed at the rapids. Andres (1988) reported the river ice conditions on April 16th. Many open areas and long open leads were noticed on the Athabasca River from Pelican Rapids (around 215 km upstream of MacEwan Bridge) to Fort McMurray. Approximately 6 km downstream of Grand Rapids (around 132 km upstream of Fort McMurray), the head of a 4 km long ice accumulation was observed. The ice jam was halted against an intact ice cover. Around 106 km upstream of MacEwan Bridge, a deteriorated intact ice cover toed another ice accumulation. The length of this jam was only 1 km. The aerial reconnaissance on April 18th documented that an ice accumulation (5 km long) was separating the House River open reach from the Grand Rapids open section (Andres, 1988). From the WSC records at Athabasca, Andres (1988) suggested that breakup occurred on April 18th on the Athabasca River at Athabasca.

Malcovish *et al.* (1988) reported that: "aerial observations indicate that breakup of the ice cover between the town of Athabasca and the city of Fort McMurray occurred on April 19th". They also documented that: the toe of an ice run had moved through Brule Pointe (approximately 101 km upstream of MacEwan Bridge) around 10:00 h on April

19th; and the head of this ice run was observed at the MacEwan Bridge at about 21:00 h. Malcovish *et al.* (1988) believed that the ice probably stopped moving at the bridges in the early morning of April 20th. The toe of the ice jam was located around 7 km downstream of the MacEwan Bridge while the head was located approximately 3 km downstream of Mountain Rapids (9 km upstream of the MacEwan Bridges). Figure 2.10 presents the location of the ice jam. This jam was released around 16:00 h on April 24th. During the 1986 spring breakup, a maximum water level of 244.0 m was measured at the Clearwater River confluence.

The 1987 Spring Breakup

The 1987 breakup documentation was provided in part by Malcovish *et al.* (1988) and also by Winhold (1988). Malcovish *et al.* (1988) reported that: November was the coldest month during the 1986-1987 winter with a mean air temperature 5.4°C below normal; December, January, and February were warmer with mean temperatures of 8.6°C, 12.6°C, and 8.0°C higher than normal conditions; and March was close to the mean monthly air temperature. The total precipitation for the 1986-1987 winter was 18 percent greater than normal at Fort McMurray (Malcovish *et al.*, 1988). WSC measured an average ice thickness of 0.80 m near the WSC gauge below Fort McMurray on January 14th and a mean of 0.92 m upstream of the MacEwan Bridge on April 7th.

The first aerial reconnaissance was done April 6th (Winhold, 1988). At this time, the rapids upstream of Fort McMurray were mainly frozen over with some leads starting to develop in most of the rapids. The ice on April 14th, from Athabasca to Grand Rapids (around 132 km upstream of Fort McMurray), had significant deteriorated with all the rapids open. Significant border flow and open leads were also observed. From Grand Rapids to Crooked Rapids, all the rapids were also open, but a maximum open area of 2 to 3 km was observed downstream of the rapids where broken ice was accumulating downstream of the open sections. The ice appeared intact and solid downstream of Cascade Rapids. Mountain Rapids was just starting to open up while Moberly Rapids was still ice covered. In the afternoon of April 15th, three distinct ice runs were located between Grand Rapids and Cascade Rapids. Breakup on the Athabasca River at Athabasca was initiated at 14:00 h on April 15th.

On the morning of April 16th, an ice jam (around 6 to 7 km long) had formed just downstream of Cascade Rapids. A small ice run was reported at Crooked Rapids while an important run was observed upstream (Winhold, 1988). The front of the ice run arrived at the MacEwan Bridge approximately at 16:00 h on April 16th. Around 18:00 h, the ice floes stopped moving and a jam was initially formed just downstream of Poplar Island, around 11 km downstream of the MacEwan Bridge in Fort McMurray. A subsequent jam toe was located downstream of Stony Island (approximately 17 km downstream of Fort McMurray) around 20:00 h after the initial jam had released. The head of the jam was observed downstream of Mountain Rapids on April 16th. The maximum water level observed at the MacEwan Bridge during the April 16th ice run was 246.5 m while a value of 244.9 m was measured at the Clearwater River confluence that day. Again, the difference in the maximum water level at the MacEwan Bridge and at the Clearwater River confluence was only 0.6 m not 1.0 m, which Yaremko (1978) always assumed. In the afternoon of April 17th, the subsequent ice jam had released. Figure 2.11 shows the locations of the jams in the vicinity of Fort McMurray during the 1987 breakup as described in Winhold (1988). The maximum water level at the Clearwater River confluence during breakup was 245.1 m observed on April 17th. Minor flooding along the Snye and the Clearwater River was observed this year.

Observations of the 1988 Breakup

The following information was provided from a draft report by Rickert and Quazi (1989). They reported that: October and November had normal to a little below normal monthly mean temperatures; December through February were mild compare to normal; and March and April were near the monthly average temperature. The total precipitation from November to March in Fort McMurray was 91 percent of normal.

During the first reconnaissance of March 22nd, the rapids upstream of Fort McMurray were still ice covered with open leads just starting to develop. Breakup on the Athabasca River at Athabasca occurred April 10th. The April 14th observations were: an ice jam was reported upstream of the Calling River (315 km upstream of Fort McMurray); the ice was deteriorated downstream of the jam toe to Iron Point (265 km upstream of MacEwan Bridge); downstream of Iron Point to Fort McMurray, the ice cover was still solid. On April 15th, the Athabasca River was ice-free upstream of Upper Wells (approximately 213 km upstream of Fort McMurray). An ice jam (around 3 km long) was released at 13:30 h downstream of the island at Upper Wells. Downstream of this location, the ice cover was deteriorating rapidly. Many open areas and border flow were observed from Upper Wells to Mountain Rapids. Border flow occurs when water is observed along the riverbanks. Downstream of Mountain Rapids to Fort McMurray, the ice was intact with some border flow.

Trappers confirmed on April 17th that a heavy ice run occurred on the morning of April 16th at their cabin located 6 km upstream of Rapides du Joli Fou. Breakup at Fort McMurray occurred on April 16th, when the front of an ice run had reach the MacEwan Bridge around 16:00 h (Rickert and Quazi, 1989). The ice run pushed the Athabasca River ice into the Clearwater River for around 2 km. The ice run at Fort McMurray halted around 21:30 h when an ice jam was formed upstream of Poplar Island. The maximum water levels measured on April 16th are 244.8 m at the MacEwan Bridge, 244.5 m at the Clearwater confluence, and. 243.1 m at Waterways along the Clearwater River (around 6.4 km upstream of the Clearwater River confluence). The head of the jam was located downstream of Mountain Rapids on April 17th. The location of the ice jam is graphically presents in Figure 2.12. Rickert and Quazi (1989) documented the ice jam to be finally released in the afternoon of April 22nd and 23rd. The Clearwater River was free of ice on April 23rd. No flooding was documented for the 1988 breakup.

2.1.3 Summary of Historical Breakup Observations on the Athabasca River at Fort McMurray

An important observation provided with the historical breakup documentations was that spring breakup on the Athabasca River at Fort McMurray can be triggered by an ice run likely produced by the release of an ice jam upstream of town. This process was actually documented in several years such as 1982, 1986, and 1988. From this observation, it can be concluded that ice conditions upstream of town need to be monitored during breakup in order to advise the City of Fort McMurray of the likelihood for a severe ice jam at the town.

Severe flooding occurs at Fort McMurray when the toe of an ice jam is located downstream of the Clearwater River which produces high water levels along the Clearwater River. During a significant ice run on the Athabasca River, the ice from the Athabasca River will likely be pushed upstream into the Clearwater River. It was also noticed that the Clearwater River at the confluence may breakup before the Athabasca River when spring breakup is mainly governed by thermal effects, which was observed during the 1983 breakup.

2.2 WATER SURVEY CANADA GAUGE BELOW FORT MCMURRAY

The WSC records at the gauge on the Athabasca River below Fort McMurray (station 07DA001) provided freeze-up and breakup water levels. Ice thickness documented during winter discharge measurements in the vicinity of Fort McMurray were also obtained from WSC. The following sections will present the hydraulic parameters for the 1973 to 2001 spring breakup at the studied reach.

2.2.1 Freeze-up Water Levels

The freeze-up water level (H_F) defines the level that needs to be exceeded for the ice cover to float freely. When an ice cover is free to move downstream, it has the potential to create an ice jam if its passage becomes obstructed. The 1972 to 2000 freeze-up water levels were studied in this research. For clarification, the 1972 freeze-up information was used to study the 1973 breakup (this process applies for all the breakup years investigated). Original strip charts from the WSC on the Athabasca River below Fort McMurray were used to retrieve the freeze-up water levels for the years of 1972 to 1995. Electronic files were provided by WSC for the remaining years (1996 to 2000). Appendix A1 graphically presents the water level during the 1972 to 2000 freeze-up.

In this study, H_F was defined as the maximum water level observed during the river ice freeze-up period. In cases where the WSC gauge was malfunctioning during this period, the highest elevation measured was used as H_F. Another parameter studied was H_{Fo}, which represents the pre freeze-up water level. This value was calculated as the average water level measured during the one week period prior to the significant increase in water level which is caused by freeze-up (due to the reduction in conveyance capacity which results). If an important drop in the stage was observed just before the increase in the water level, H_{Fo} was calculated as the average level 7 days before the drop in stage. The only exception to the preceding rules is the 1982 freeze-up since only 5 days prior to a drop in the stage was available. The difference in stage from H_F and H_{Fo}, represents the increase in stage due to freeze-up (ΔH_F). Table 2.1 summaries the parameters obtained with the WSC freeze-up records.

2.2.2 Breakup Water Levels

Breakup water levels at Fort McMurray have been responsible for some serious flooding in Fort McMurray. The increase in stage cause by ice jams is generally sudden, leaving little time for evacuation. It is therefore important to study breakup water levels in order to identify if any patterns exist. The water levels during the 1973 to 1995 breakup were retrieved from the original WSC strip charts. Electronic files received from WSC provided the 1996 to 2001 information. The water levels during the 1973 to 2001 breakup are graphically presented in Appendix A2.

The following breakup parameters were studied in this research at the WSC gauge below Fort McMurray: breakup date, pre-breakup elevation (H_{Bo}), the fairly steady increase in water level prior to breakup ($\Delta H/\Delta t$), and maximum breakup water level (H_B). For this study, initiation of breakup at the WSC gauge was defined as a sudden fluctuation of water level that generally results in a significant stage increase, or when the WSC gauge starts to malfunction. The day of breakup initiation at the WSC gauge was defined as the breakup date. For some years, the day of breakup was not available from the WSC records. In this case, the breakup date at Fort McMurray was use since it generally occurs on the same day. When the gauge was malfunctioning, other sources were also used if they documented a different date than the one from the WSC records. Alberta Environment, Alberta Research Council (ARC), the Regional Municipality of Wood Buffalo (RMWB), and the University of Alberta (UA) provided the breakup dates for 1982, 1985, 1997, and 2001.

The pre-breakup elevation (H_{Bo}) was chosen as the water level at the end of a gradual increase in stage preceding breakup ($\Delta H/\Delta t$). This latter parameter is considered an indicator of the rate of snowmelt runoff preceding breakup. Figure 2.13 shows an example of $\Delta H/\Delta t$ during the 1973 spring breakup at the WSC gauge below Fort McMurray. In some instances, this stage increase was rather difficult to identify therefore the error in determining H_{Bo} was evaluated as $\pm$ 0.2 m. The maximum breakup elevation (H_B) represents the highest stage available during breakup from the WSC records. When the WSC gauge below Fort McMurray was malfunctioning, maximum water levels (H_B) were obtained by other sources if they were greater then the ones measured with the gauge. The water levels from Alberta Research Council (ARC) for the years of 1976, 1977, 1981, 1982, and 1985 as documented in Doyle (1987), were used in this research. Rickert and Quazi (1982) suggested a maximum water level for the 1982 breakup greater than the one from ARC. This value appears to be a rough estimate and was not considered reliable. In the ARC report describing 1987 spring breakup, the WSC gauge measurements were documented. The peak water level referred in this report was dismissed since the reading was omitted by WSC because the gauge was malfunctioning at the time. Table 2.2 presents H_{Bo}, $\Delta H/\Delta t$, and H_B for 1973 to 2001.

2.2.3 River Ice Thickness

Ice thickness prior to breakup gives an indication of the availability of ice to form an ice jam. In addition, the thicker the ice cover, the greater its resistance to strength deterioration due to thermal influences. Over the years, WSC had measured ice thickness while obtaining their winter discharge measurement in the vicinity of Fort McMurray. In order to get a winter discharge, holes need to be drilled in the ice cover so that the velocity probe can be lowered into the water. An average ice thickness (h_i) was calculated based on the individual value measured at each drill hole. It should be mentioned that areas with no ice (generally along the banks) were omitted from the average since they represent a very small portion of the ice cover. Appendix A3 presents the average ice thickness measurements for the winter of 1972-1973 to 2000-2001. In order to be consistent, the ice thicknesses measured by WSC were used exclusively in this research. The city of Fort McMurray also provided ice thickness measurements, but the data record was not as complete. For the 2000 breakup, WSC did not measure an ice thickness at the end of the winter (March or April), therefore the average ice thickness measured by the city of Fort McMurray was used for that year (Regional Municipality of Wood Buffalo, 2002). Table 2.3 summaries the average ice thicknesses used in this study.

2.3 SUMMARY

Table 2.4 gives a summary of the available breakup date, and maximum water elevation during breakup from 1875 to 2001. Appendix A4 gives a more detailed summary including the breakup date, H_B, and location of ice jams. Unofficial documentation was also included in Table 2.4 and Appendix A4 since the information was relevant to this study. Table 2.5 gives a brief list of the jam and no jam years available from 1972 to 2001. As mentioned previously, ice jams were studied if the jam toe was located in the vicinity of Fort McMurray between the Golf Course, approximately 4 km upstream of MacEwan Bridge, and downstream of the Clearwater River confluence where jams produced significant backwater effects on the Clearwater River. Appendix B provides electronic copies of all the data gathered in this Chapter.

Table 2.1 Water elevation prior to freeze-up (H_{Fo}), maximum stage during freeze-up (H_F), and stage increased caused by freeze-up (ΔH_F) at the WSC gauge below Fort McMurray from 1972 to 2000.

Year	H_{Fo} (m)	H_F (m)	ΔH_F (m)
1972	237.71	240.15	2.44
1973	238.22	239.52	1.30
1974	237.83	239.16	1.33
1975	237.71	239.10	1.38
1976	237.63	238.80	1.17
1977	237.82	239.09	1.26
1978	237.94 [a]	239.20 [a]	1.26 [a]
1979	237.46	238.74 [a]	1.28 [a]
1980	237.58	238.47	0.89
1981	237.24 [a]	237.84 [a]	0.60 [a]
1982	237.64	238.81	1.18
1983	237.62	238.56	0.94
1984	238.08	239.36	1.28
1985	237.63	238.87	1.24
1986	237.67	239.25	1.58
1987	237.21	238.78	1.57
1988	237.39	239.03	1.64
1989	237.65	238.92	1.27
1990	237.36	238.68	1.32
1991	237.42	238.88	1.46
1992	237.33	238.84	1.51
1993	237.47	239.07	1.59
1994	237.31	238.02	0.71
1995	237.51 [a]	239.53 [a]	2.02 [a]
1996	-	-	-
1997	237.96	238.97	1.01
1998	237.39	238.42	1.02
1999	237.11	238.43	1.32
2000	237.46	238.32	0.86

[a] WSC gauge below Fort McMurray malfunctioning

Table 2.2 Water level elevation before breakup (H_{Bo}), fairly steady increase in stage prior to breakup ($\Delta H/\Delta t$), and maximum water elevation during breakup (H_B) at the WSC gauge below Fort McMurray.

Year	H_{Bo} (m)	$\Delta H/\Delta t$ (m/day)	H_B (m)
1973	239.0	0.065	240.5
1974	239.8	0.400	241.4 [a]
1975	238.7 [a]	0.094 [a]	239.7 [a]
1976	239.0	0.131	242.4 [a b]
1977	238.9 [a]	0.123 [a]	244.2 [a b]
1978	239.0	0.037	240.6
1979	239.4	0.200	244.9 [a]
1980	238.9	0.094	240.7
1981	239.0	0.085	240.7 [a b]
1982	-		238.9 [a b]
1983	238.5	0.059	239.6
1984	238.4	0.029	240.9
1985	239.0	0.100	241.2 [a b]
1986	239.0	0.065	240.9
1987	239.1	0.083	240.7 [a]
1988	238.4 [a]	0.133 [a]	240.6 [a]
1989	238.2 [a]	0.022 [a]	238.2 [a]
1990	238.6 [a]	0.028 [a]	239.3 [a]
1991	238.7	0.172	240.1 [a]
1992	238.6	0.016	239.5
1993	238.5 [a]	0.032 [a]	238.5 [a]
1994	238.7	0.122	242.8
1995	238.7	0.176	239.0
1996	239.1	0.500	243.2
1997	-		-
1998	238.7	0.050	239.0
1999	238.0	0.045	238.5
2000	238.3	0.055	238.6
2001	-		-

[a] WSC gauge below Fort McMurray malfunctioning
[b] Water level obtained from ARC

Table 2.3 Average ice thickness (h_i) in meters measured in the vicinity of Fort McMurray at the end of the winter from 1973 to 2001.

Year	h_i (m)
1973	1.62
1974	0.61
1975	0.61
1976	0.82
1977	0.88
1978	0.88
1979	1.10
1980	0.69
1981	0.75
1982	0.65
1983	0.54
1984	0.81
1985	0.73
1986	1.05
1987	0.87
1988	0.66
1989	0.62
1990	0.63
1991	0.77
1992	0.75
1993	0.82
1994	0.68
1995	0.85
1996	0.73
1997	0.77
1998	0.58
1999	0.81
2000	0.68
2001	0.67

Table 2.4 Available breakup date, and maximum water elevation during breakup from 1875 to 2001.

Year	Breakup Date		Peak Breakup Water Levels (m)					
	Day (dd-mm)	t_B (Julian day)	G90 Intake 1	G85 Intake 2	G80 Bridges	G75 Mc I	G70 Clearwater	G55 WSC
1875	20-Apr	110			253.0		252.0	
1881	21-Apr	111			<250		249.0	
1885	09-Apr	99			249.0		248.1	
1925							247.4	
1928							248.6	
1936	21-Apr	112					250.1	
1938	27-Apr	117						
1939	21-Apr	111						
1940	25-Apr	116						
1941	14-Apr	104						
1948	01-May	122						
1949	15-Apr	105						
1950	28-Apr	118						
1953	21-Apr	111						
1954	09-May	129						
1955	17-Apr	107						
1956	20-Apr	111						
1957	before 3-May	before 123						
1958	15-Apr	105						244.9
1959	13-Apr	103						
1960	15-Apr	106						
1961	28-Apr	118						
1962	17-Apr	107					246.2	242.7
1963	20-Apr	110			247.5		247.5	244.1
1964	21-Apr	112						
1965	14-Apr	104						
1966	15-Apr	105						239.6
1967	28-Apr	118						238.8
1968	27-Apr	118						238.4
1969	14-Apr	104						239.0
1970	07-Apr	97						238.4
1971	20-Apr	110						239.0
1972	22-Apr	113			245.3		244.3	244.7
1973	18-Apr	108						240.5
1974	19-Apr	109			247.2		246.7	241.4
1975	25-Apr	115						239.7
1976	13-Apr	104						242.4
1977	14-Apr	104			248.7		247.6	244.2
1978	19-Apr	109					242.0	240.6
1979	28-Apr	118			247.5		246.9	244.9
1980	15-Apr	106						240.7
1981	10-Apr	100					244.0	240.7
1982	26-Apr	116			246.8		242.2	238.9
1983	18-Apr	108			242.0		242.3	239.6
1984	10-Apr	101			244.5		243.5	240.9
1985	18-Apr	108					243.5	241.2
1986	19-Apr	109					244.0	240.9
1987	16-Apr	106			246.5		245.1	240.7
1988	16-Apr	107			244.8		244.5	240.6
1989	22-Apr	112					243.1	238.2
1990	20-Apr	110					243.0	239.3
1991	13-Apr	103						240.1
1992	03-Apr	94					241.4	239.5
1993	19-Apr	109						238.5
1994	11-Apr	101					244.0	242.8
1995	22-Apr	112						239.0
1996	16-Apr	107					245.9	243.2
1997	20-Apr	110					247.0	
1998	09-Apr	99	243.0					239.0
1999	14-Apr	104	242.0	242.1	241.2	240.8	240.4	238.5
2000	23-Apr	114	241.9				240.6	238.6
2001	25-Apr	115	243.2	242.7	242.1		240.9	
2002								

Table 2.5 Jam, no jam, and unknown years on the Athabasca River in the vicinity of Fort McMurray from the 1972 to 2001 breakup.

Jam	No Jam	Unknown
1972	1974	1973
1977	1983	1975
1978	1985	1976
1979	1991	1980
1982	1992	1981
1984	1993	1989
1986	1994	1990
1987	1995	
1988	1998	
1996	1999	
1997	2000	
	2001	

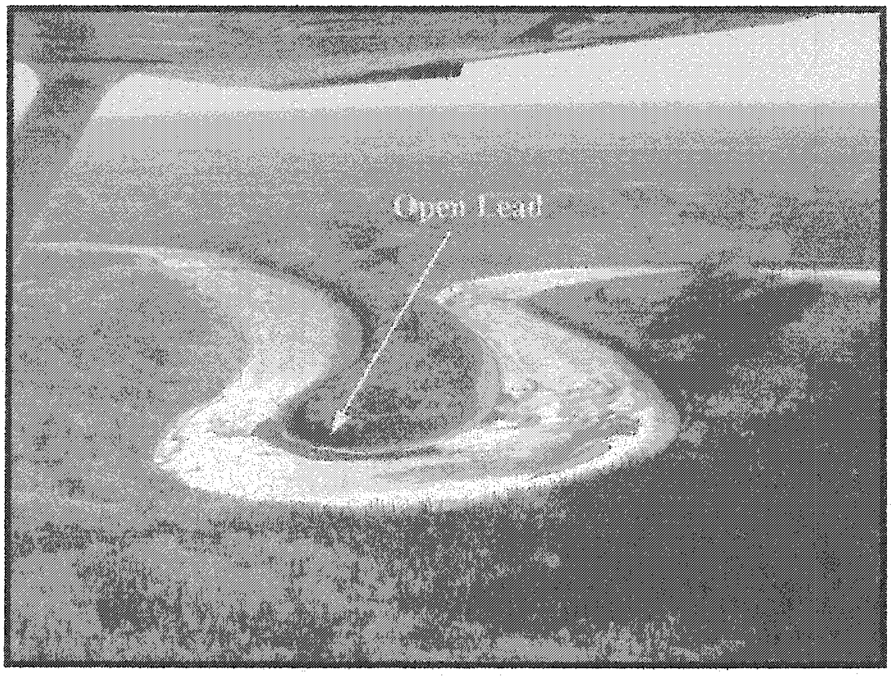

Figure 2.1 Crooked Rapids on April 24th, 2002.

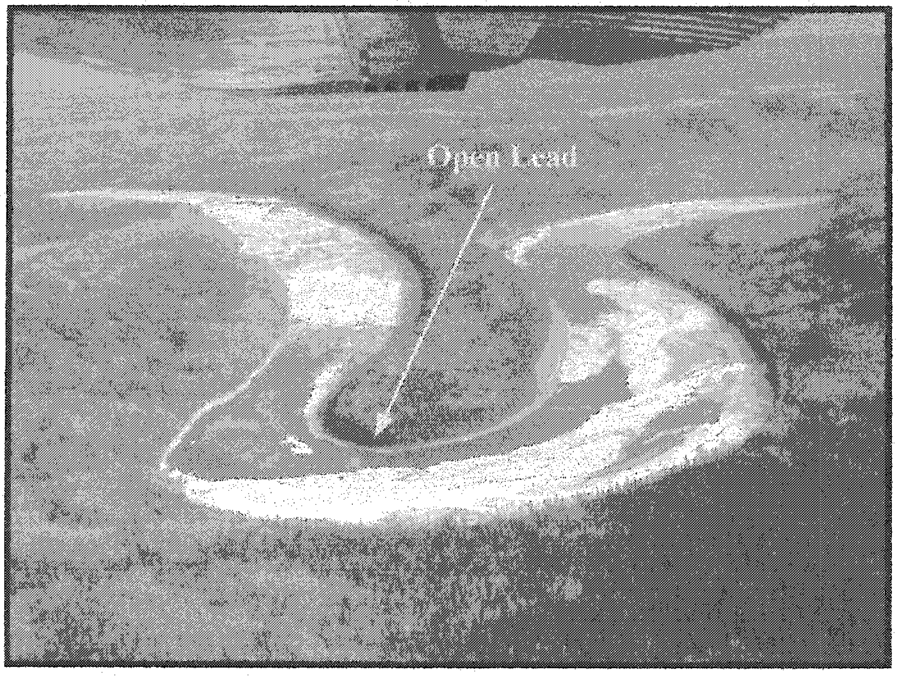

Figure 2.2 Crooked Rapids on April 26th, 2002.

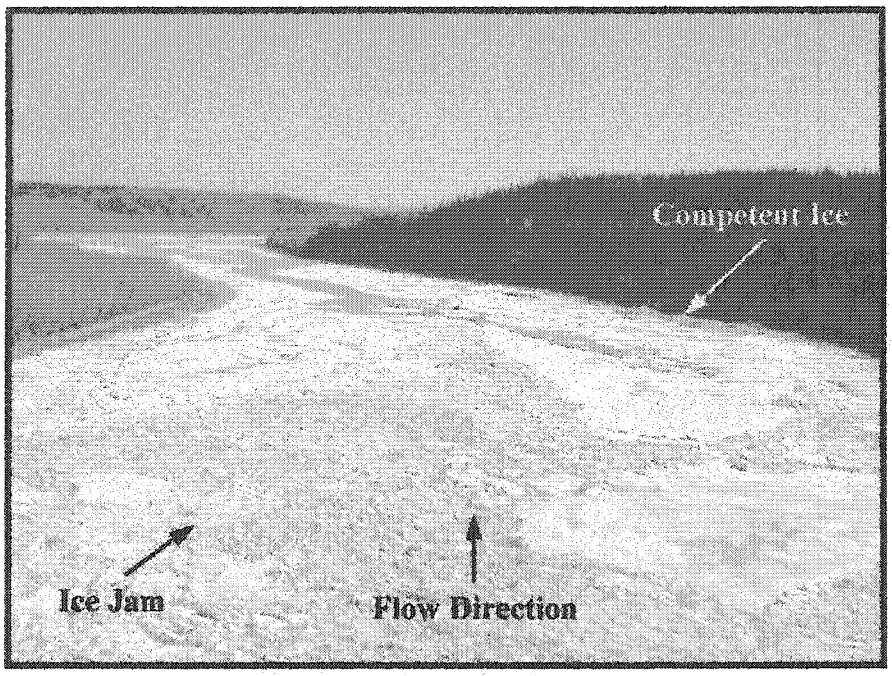

Figure 2.3 2002 ice jam on the Athabasca River 5 km upstream of MacEwan Bridge.

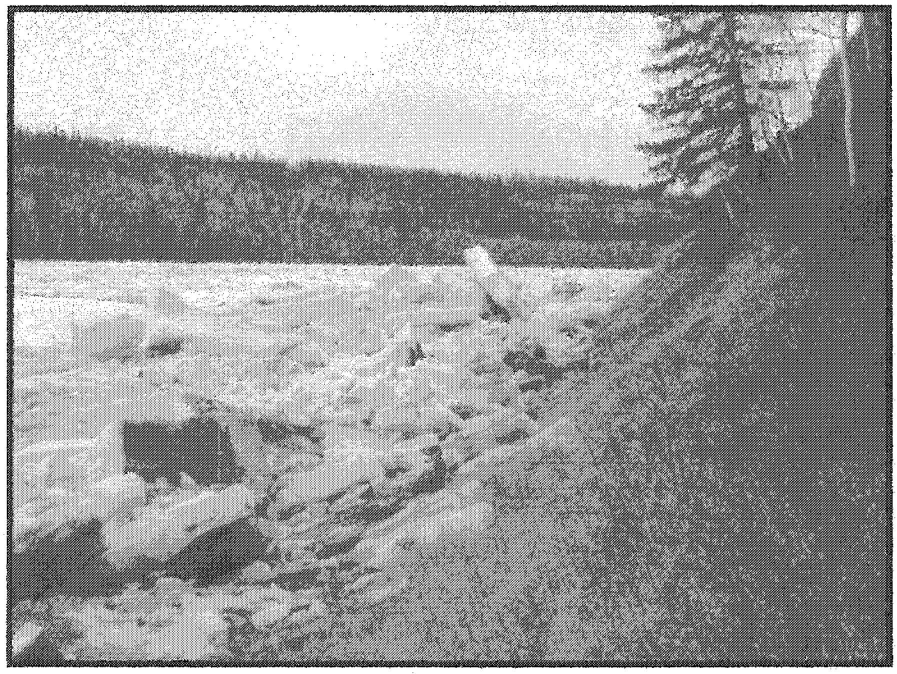

Figure 2.4 2002 ice jam on the Athabasca River 5 km upstream of MacEwan Bridge.

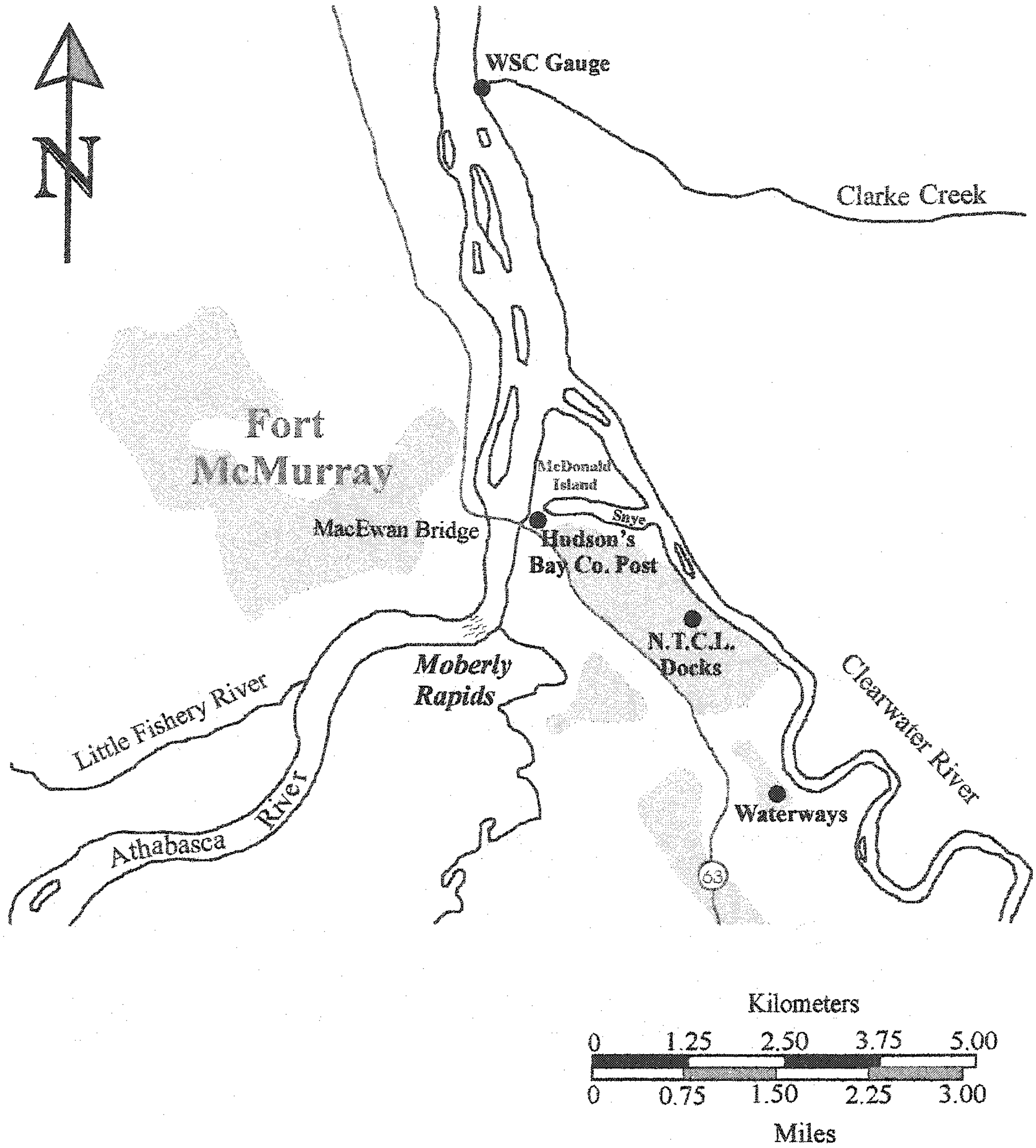

Figure 2.5 Clearwater River confluence.

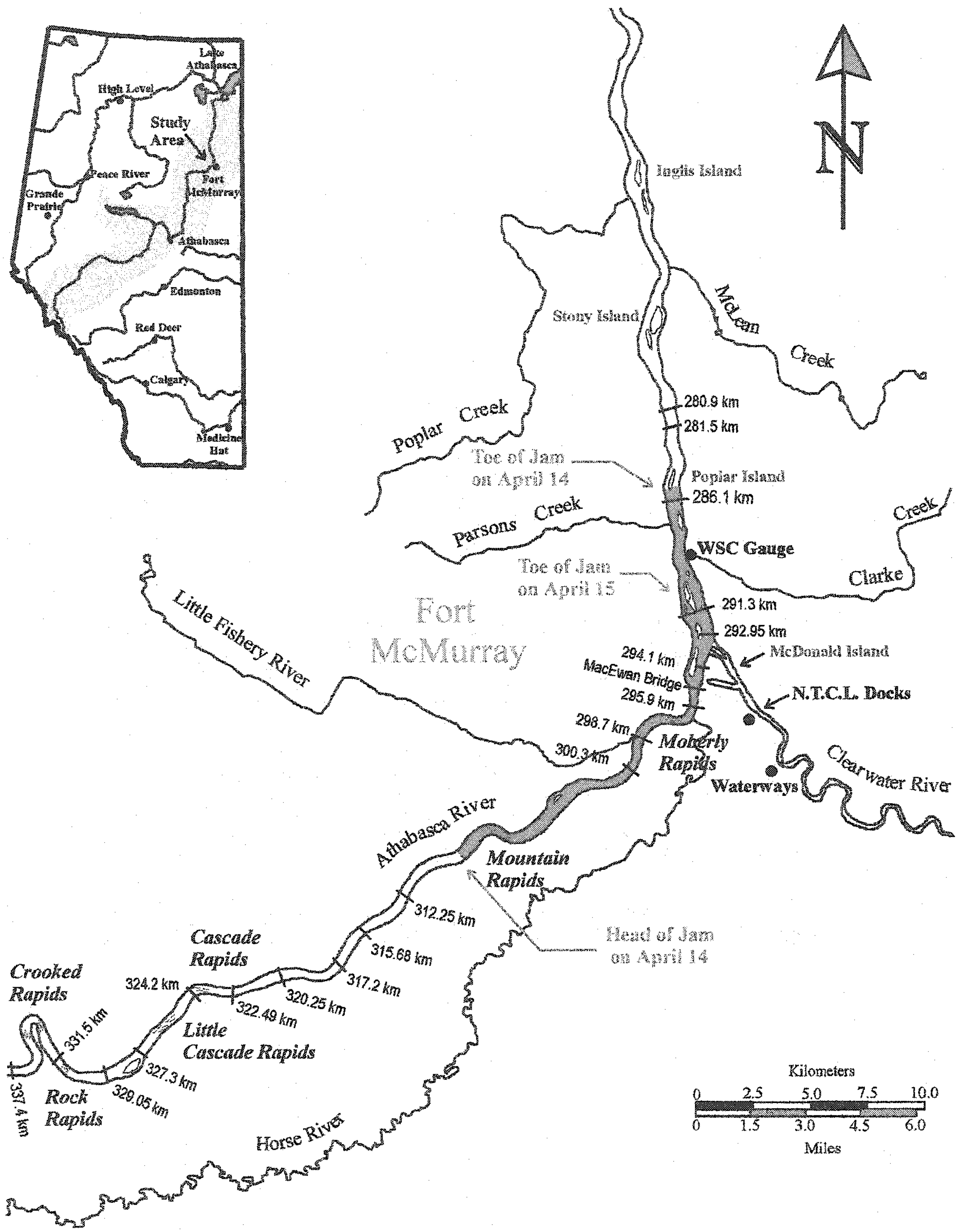

Figure 2.6 Location of the 1977 ice jams on the Athabasca River at Fort McMurray.

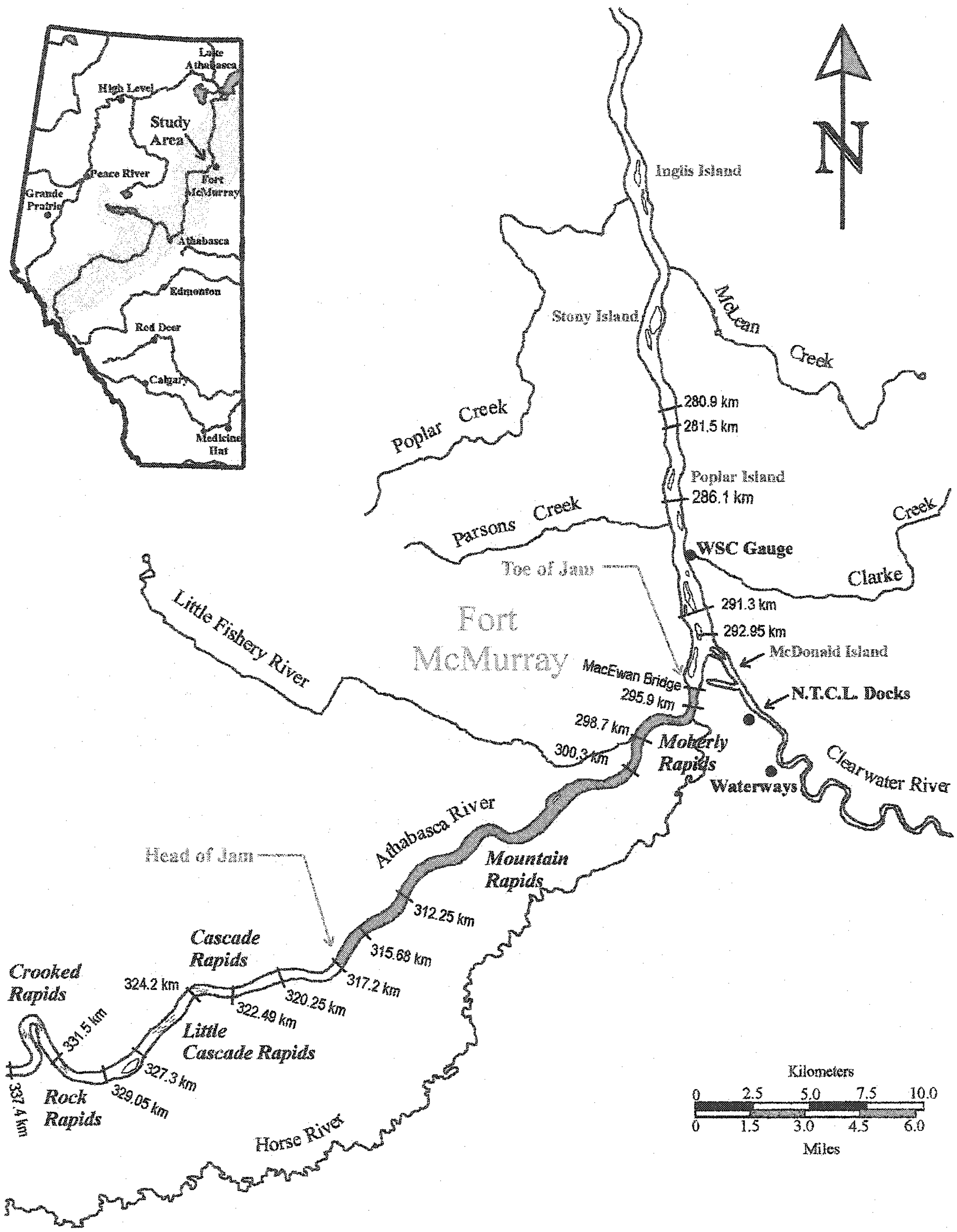

Figure 2.7 Location of the 1978 ice jam on the Athabasca River at Fort McMurray.

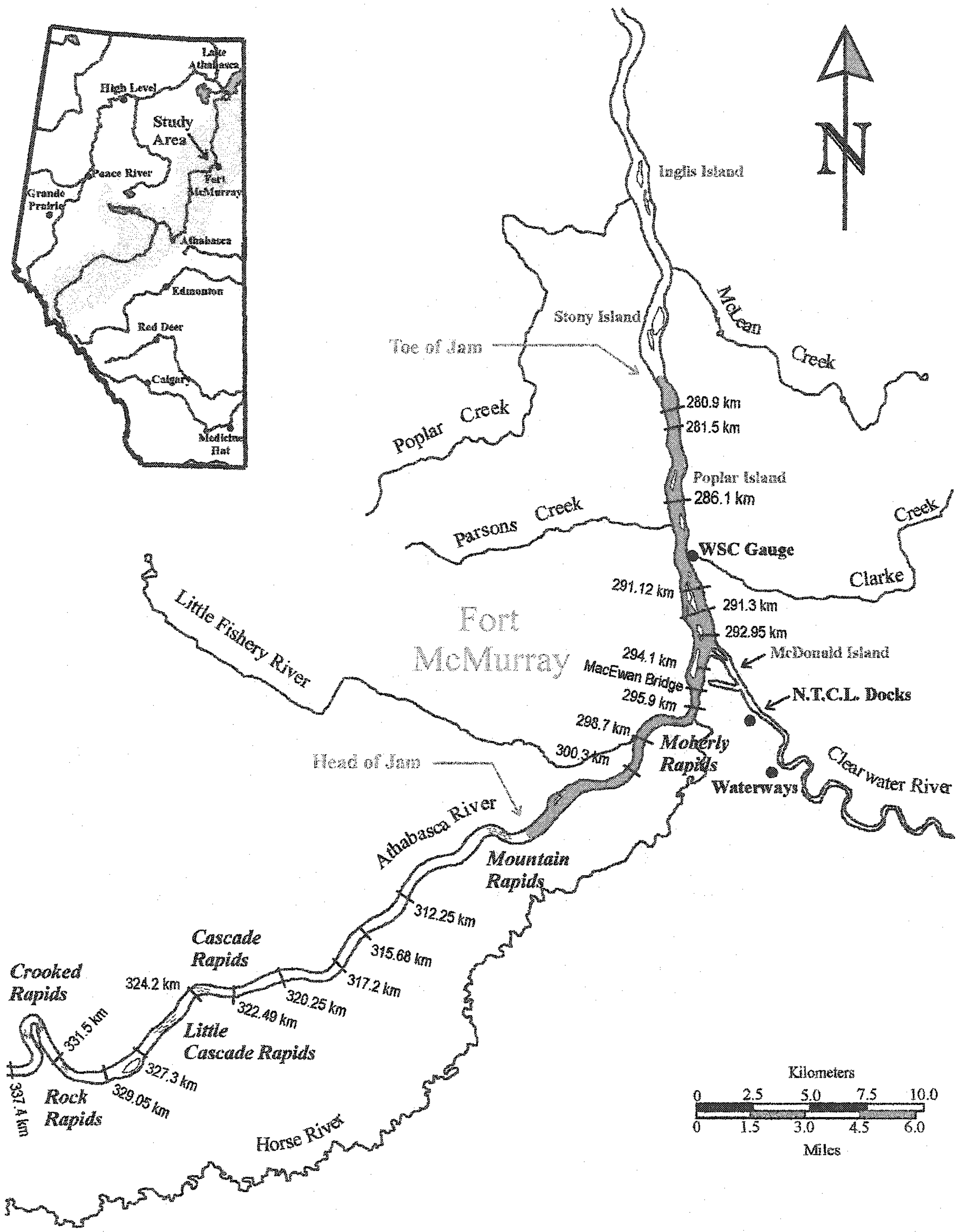

Figure 2.8 Location of the 1979 ice jam on the Athabasca River at Fort McMurray.

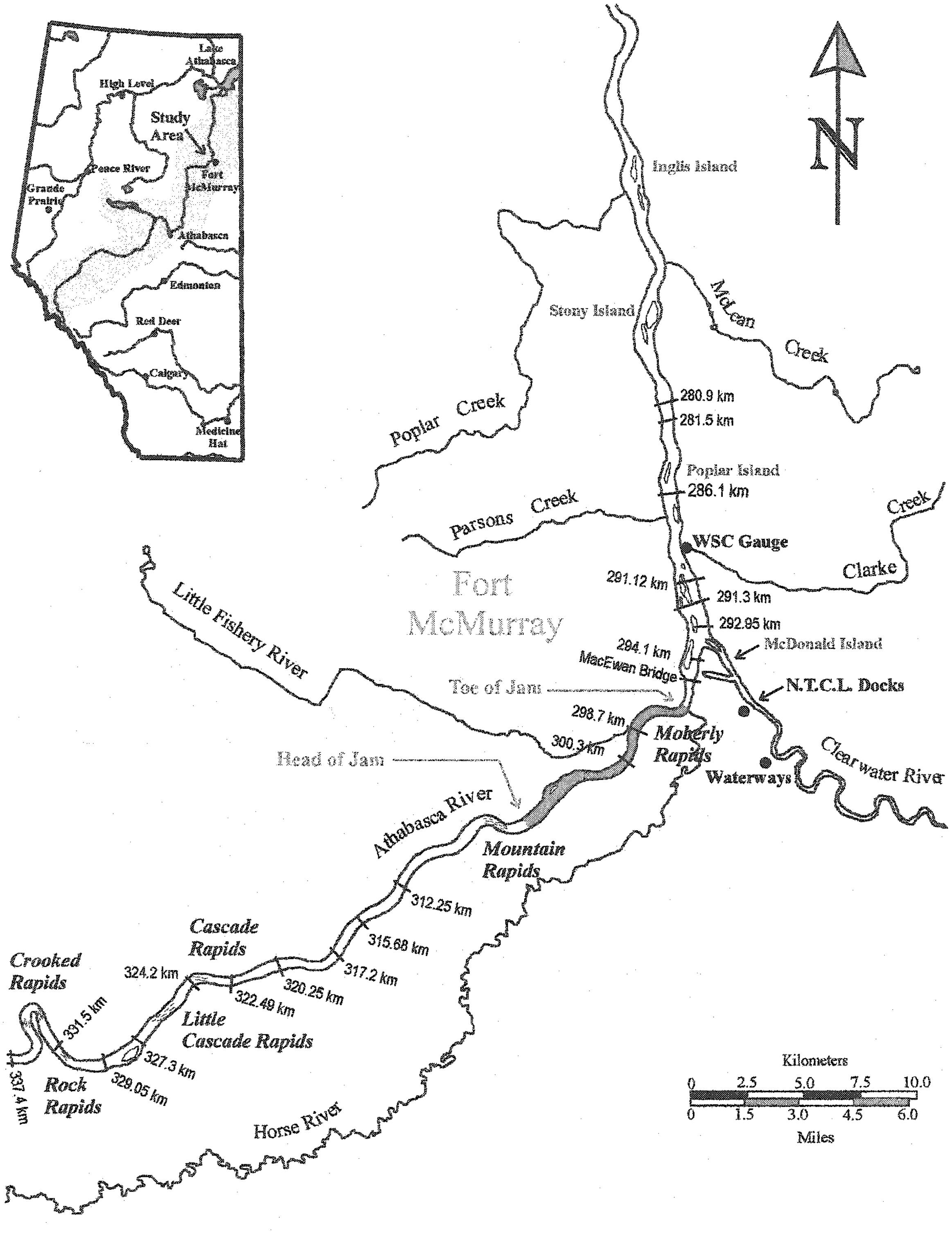

Figure 2.9 Location of the Moberly Rapids ice jam on April 10th, 1984.

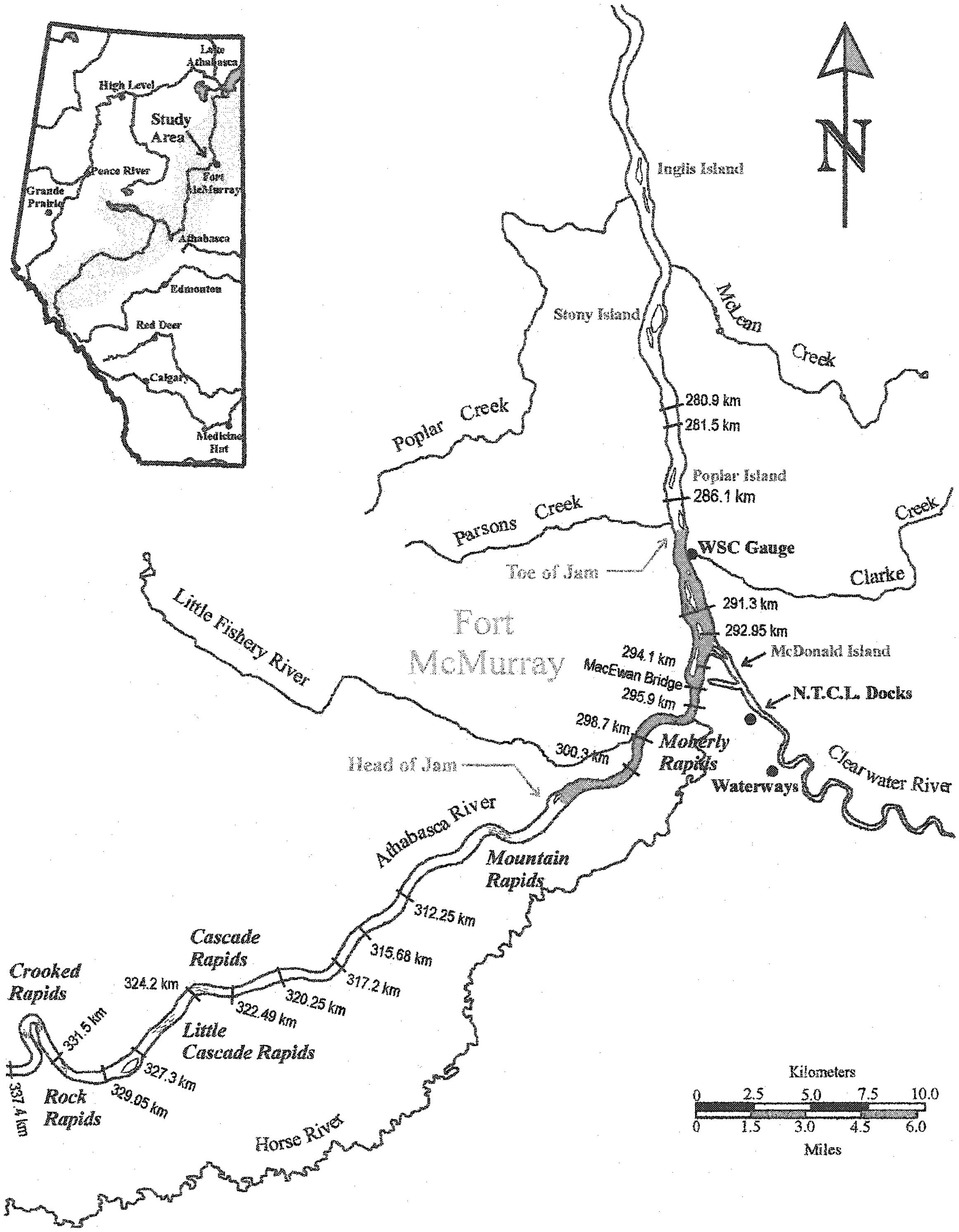

Figure 2.10 Location of the 1986 ice jam on the Athabasca River at Fort McMurray.

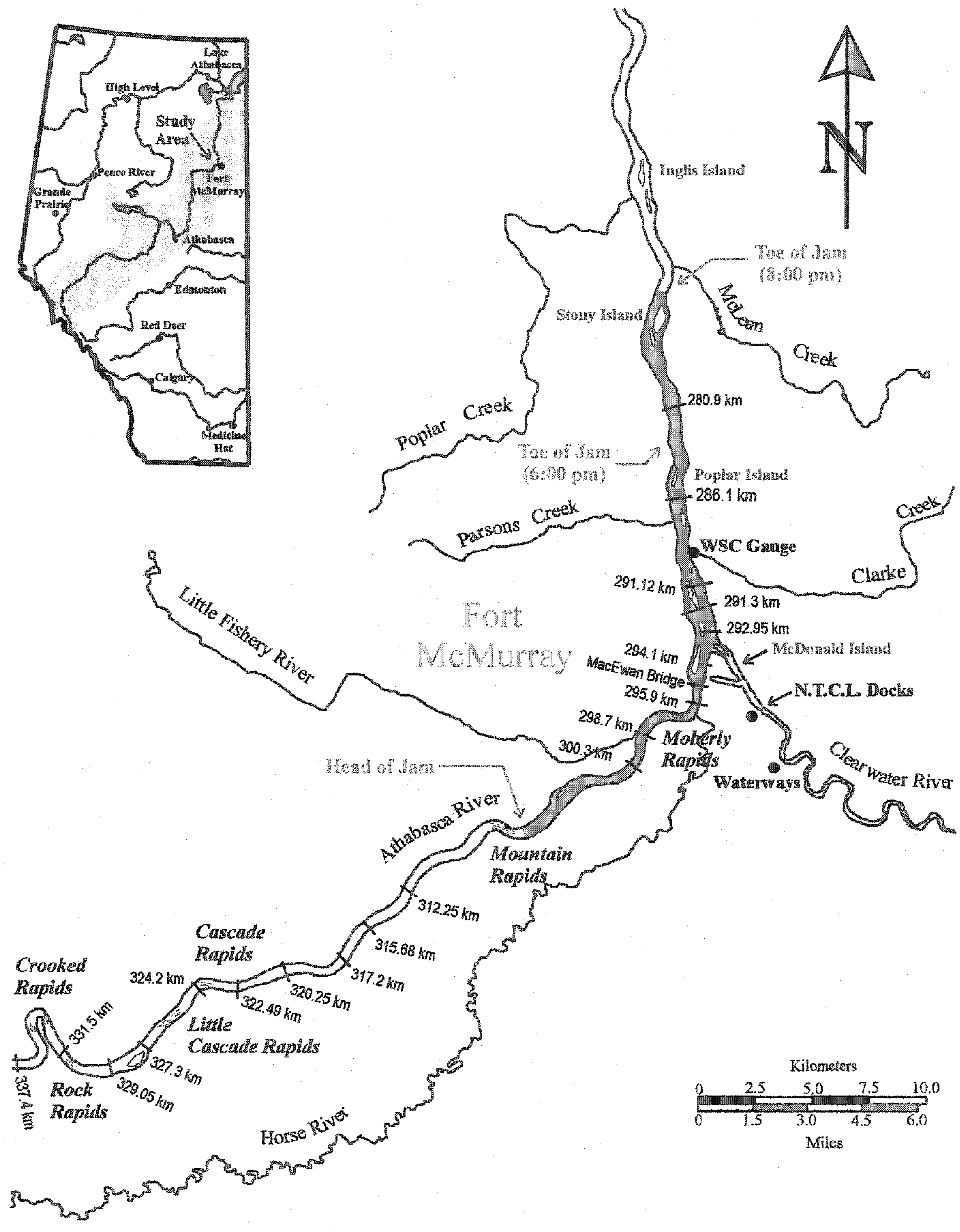

Figure 2.11 Location of the 1987 jams on the Athabasca River at Fort McMurray, April 16th.

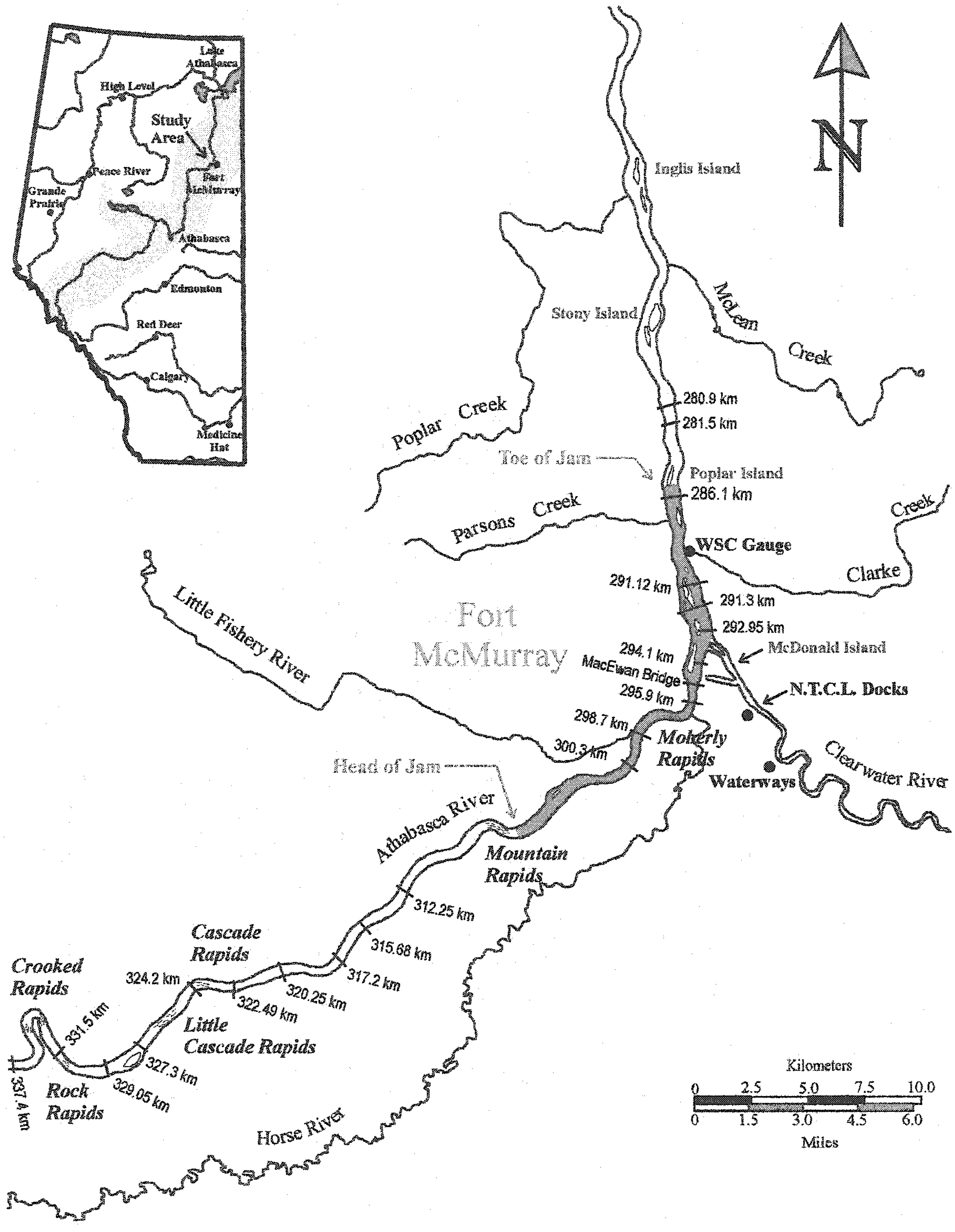

Figure 2.12 Location of the 1988 ice jam on the Athabasca River at Fort McMurray.

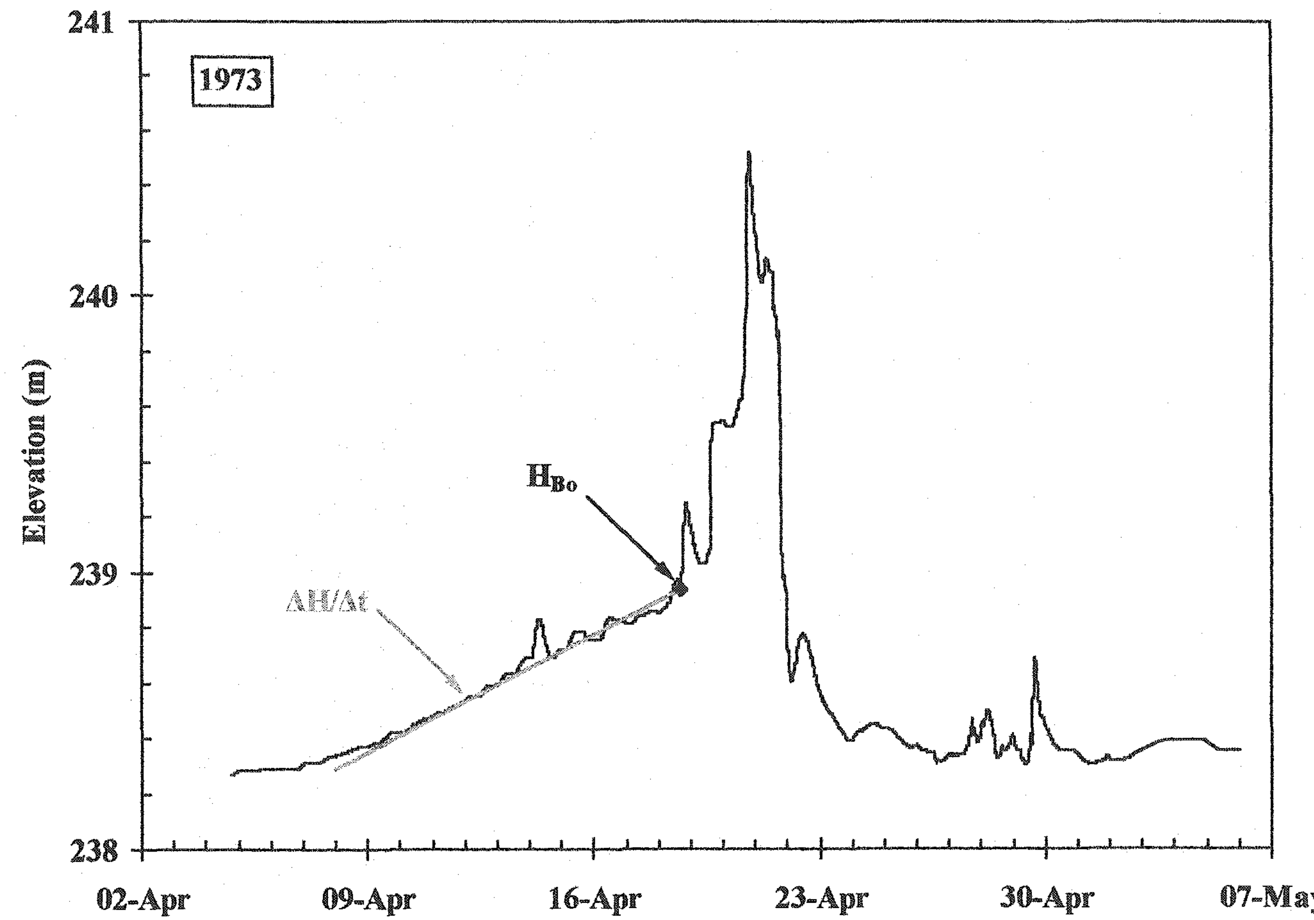

Figure 2.13 ΔH/Δt during the 1973 spring breakup at the WSC gauge below Fort McMurray.

CHAPTER 3 METEOROLOGICAL INFORMATION

The following chapter outlines the meteorological factors that were studied during this research. The air temperature, sunshine, and precipitation records are going to be discussed. The steps followed to establish the complete record will also be presented as well as the parameters calculated with the available data.

3.1 AIR TEMPERATURE

This section will first discuss the importance of air temperature during breakup. The procedure used to establish the complete temperature record will then be presented. Finally, general observations of the temperature data will be given.

3.1.1 Introduction

Air temperature directly influences melting during breakup. When the air temperature is above the freezing point, the ice will start melting reducing its strength. Runoff is also affected by temperature because of the snowmelt. A greater snowmelt runoff will result in a bigger discharge. In order to study the influence of warm weather in the river ice breakup process, the mean daily air temperatures for March and April were analyzed. The historical hourly air temperatures from 1972 to 2001 measured at the Fort McMurray Airport were collected from the Digital Archive of Canadian Climatological Data (Surface), Environment Canada. The University of Alberta (UA) meteorological station located near the Fort McMurray Airport provided the 2001 air temperatures. This data were recorded every 30 minutes.

3.1.2 Establishing the Complete Data Record

Missing temperatures were observed in the Environment Canada record. Two methods were used to estimate the missing values. If only one reading was missing, it was deducted with the average of the two surrounding temperatures. Consecutive missing temperatures were estimated by following the trend line of the hourly temperature graph. The missing temperatures during March 1st, 1997 could not be interpolated by either method and were therefore not considered in this research. Table 3.1 lists all the missing temperatures in the historical record.

As mentioned previously the UA meteorological data were recorded every 30 minutes while the Environment Canada readings were measured hourly. In order to compare the UA meteorological and Environment Canada data, the use of hourly versus 30 minutes readings had to be compared. Linear regressions were performed with the mean daily temperature obtained with 48 readings (30 minutes data) and the mean daily temperature calculated with 24 readings (measured on the hour and half hour) from the UA meteorological record. Figures 3.1 and 3.2 graphically present the results of the linear regressions for October 14th, 2000 to October 26th, 2001. Excellent correlations were found for the mean daily air temperature obtained with the 24 readings measured at the hour and mid-hour resulting in a coefficient of determination, R^2, equal to 1. It was concluded that only one reading per hour is necessary to capture the daily fluctuation of the temperature. In other words, the Environment Canada record provides the same accuracy as the UA meteorological data, in terms of determining the mean daily temperature.

The Environment Canada record was transposed to the UA meteorological station based on a linear regression relationship in order to have a consistent database. The relationship between the mean daily air temperatures for the two meteorological stations was calculated from October 14th, 2000 to August 31st, 2001. The Environment Canada mean daily values were obtained with the hourly readings while the half hour data were used for the UA meteorological station data. Figure 3.3 graphically presents the result of the linear regression. All the readings are very close to the trend line resulting in an R^2 of 0.991. Since this correlation is very good, the linear equation presented in Figure 3.3 was used to transpose the Environment Canada record to UA meteorological data.

3.1.3 General Observations

The average mean daily air temperature was also calculated with the minimum and maximum daily temperatures. If the minimum and maximum daily temperatures could be used to get a good representation of the mean daily air temperature, this procedure would reduce significantly the amount of data to process. Therefore, the correlation between the mean daily temperature obtained with the minimum and maximum daily temperature and the hourly or half hour readings was analyzed with a linear regression. Figure 3.4 graphically presents the results of this regression for the years of 1972 to 2001. All the readings are well scattered around the regression line representing a good correlation. The value of R^2 was equal to 0.993. This correlation shows that both procedures can be used to calculate the mean daily air temperature.

Appendix B provides a summary of the mean daily air temperatures investigated in this research. Supplementary air temperature data received from Environment Canada are also included in Appendix B even if they were not studied during this thesis. This extra information is the hourly air temperature from September 1^{st} to November 30^{th} for the years of 1971 to 1999, the mean daily temperature from December 1^{st} to February 28^{th} (or 29^{th}) for the years of 1944 to 2000, and the mean daily temperature from January 1^{st}, 2000 to August 31^{st}, 2001.

3.2 SUNSHINE

The following section will first discuss the influence of the sun to evaluate ice jam occurrence at Fort McMurray. A list of the available data and their sources will also be provided. Finally, all the steps carried out to establish a complete data record are presented.

3.2.1 Introduction

The solar radiation influences river ice breakup in a manner similar to the temperature, since it increases snowmelt and ice decay. Ashton (1986) stated that the solar radiation was in fact the more relevant influence. For this research, the available sunshine data were provided in hours of bright sunshine and solar radiation. The hours of bright sunshine are measured with a sunshine ball that basically consists of a magnifying glass that burns a paper when the sun is bright. The newer equipment is called a pyranometer. It is a device that provides a continuous measure of the solar radiation even during cloudy days, and which is typically interfaced with a datalogger.

Alberta Environment, Water Sciences Branch, Hydrology / Forecast Section provided the hours of bright sunshine at the Fort McMurray Airport from November 1st, 1971, to March 31st, 1996. The original source of the record was the Digital Archive of Canadian Climatological Data (Surface), Environment Canada. The UA meteorological station near the Fort McMurray Airport provided the hours of bright sunshine for April 22nd to 27th, 2001. The solar radiation was provided by Golder Associates from their Aurora station located approximately 55 km north of Fort McMurray for the years of 1988 to 1989 and 1995 to 2001, as well as by the UA meteorological station from October 2000 to June 2001.

3.2.2 Establishing the Complete Data Record

Some UA meteorological readings were dismissed from the analysis because of the inability of the datalogger to record bright sunshine (due to a programming error). These erroneous values were detected from the record since the datalogger was observed to be measuring zero solar radiation during a period of bright sun. Table 3.2 lists the dates of the UA meteorological data not considered in this research.

The Golder Associates Aurora readings were measured as the daily total global solar radiation ($kW \cdot h/m^2$) while the UA meteorological data were measured as daily average radiation flux (W/m^2). In order to establish a relationship between the solar radiation measured at the Golder Associates Aurora and UA meteorological stations, the Golder Associates Aurora data were divided by 24 hours and multiplied by 1000 to convert the units from $kW \cdot h/m^2$ to W/m^2. For simplicity, solar radiation will be used from now on instead of daily average radiation flux.

A linear regression was performed on the solar radiation data records from October 14th, 2000 to June 9th, 2001. Figure 3.5 graphically presents the relationship between the radiation measured at the Golder Associates Aurora and UA meteorological stations. A very good correlation was obtained from this analysis. The value of R^2 was equal to 0.950. Since the relationship obtained was acceptable, the linear equation presented in Figure 3.5 was used to transpose the Golder Associate Aurora readings to the UA meteorological station.

In order to have a complete solar radiation record, the hours of bright sunshine needed to be converted to radiation values. To do so, the relationship between duration of daylight as a percentage of the maximum possible hours of bright sunshine and the solar radiation as a percentage of the maximum possible solar radiation had to be established.

3.2.2.1 Maximum Possible Hours of Bright Sunshine

The duration of daylight for the 56° and 58° latitudes was tabulated for the 1, 5, 9, 13, 17, 21, 25, and 29th days of each month in List (1958). The corresponding latitude for the UA meteorological station is 56.4 ° North. Linear interpolations were used between the 56° and 58° latitudes to calculate the maximum possible duration of daylight at the UA meteorological station for each day. The interpolated eight days per month values were then used to yield equations to calculate the duration of daylight at the 56.4 ° North for any given day. Two equations were required to fit the trend line of the duration of daylight, which were obtained with the TableCurve software produced by Jandel Scientific. Equation 3.1 best represents the duration of daylight for Julian days 1 to 206 with an R^2 of 1while Equation 3.2 was found to best represent Julian days 207 to 365 with also an R^2 of 1. During leap years, the duration of daylight for day 366 was calculated by averaging the values for Julian days 1 and 365.

$$\ln y = (a + cx + ex^2)/(1 + dx + bx^2) \quad \textbf{[3.1]}$$

where x = Julian day;

y = duration of daylight in hours;

a = 1.9115438;

b = 5.8208461e-06;

c = 0.00081951085;

d = -0.0035778115; and

e = -1.5285961e-05.

$$y = a + dx + bx^{0.5} + e / \ln x + c / x^{0.5} \quad \textbf{[3.2]}$$

where x = Julian day;

y = duration of daylight in hours;

a = 1524186;

b = -10973.548;

c = 9300672.1;

d = 100.55607; and

e = -10844319.

3.2.2.2 Maximum Possible Solar Radiation

The daily total global solar radiation (kW·h/100 m^2), which would be received upon a horizontal surface if there were no atmosphere, by direct radiation from the sun with a solar constant of 135 kilowatts per square decameter (kW/dam^2) was tabulated from Shaw (1936). The maximum possible daily total global solar radiation for the middle day of successive weeks of the year was provided starting with January 4^{th}. The values of available daily total global solar radiation were converted to W/m^2 by first dividing the kW·h/100 m^2 by 24 hours and then multiplying by 1000 to convert kW to W. Linear interpolations were also used between the 50° and 60° latitudes in order to find the corresponding values at 56.4 ° North. Two equations were used to fit the interpolated solar radiations, which were also obtained with the TableCurve software produced by Jandel Scientific. Equation 3.3 can be used to calculate the maximum solar radiation (W/m^2) at 56.4 ° North for Julian days 1 to 200 while Equation 3.4 best represents Julian days 201 to 365. Both of these equations yield an R^2 of 1. The solar radiation for day 366 during a leap year was also calculated with the average values of the Julian days 1 and 365.

$$y = a + c \sin^2 (2\pi x / d + b) \qquad [3.3]$$

where x = Julian day;

y = solar radiation in W/m^2;

a = 52.635096;

b = 3.1446288;

c = 420.42915; and

d = 689.63827.

$$y = a + dx + bx^{0.5} + ex^{0.5} \ln x + cx / \ln x \qquad [3.4]$$

where x = Julian day;

y = solar radiation in W/m^2;

$a = 6568564.9$;

$b = -471.73352$;

$c = -3738222.4$;

$d = 367774.23$; and

$e = 831729.49$.

3.2.2.3 Relationship Between Hours of Bright Sunshine and Solar Radiation

The tabulated values for duration of daylight and maximum solar radiation were used to express the measured daily radiation and measured daily bright sunshine as a percentage of the maximum possible daily radiation and duration of daylight, respectively. Figure 3.6 graphically presents the percentage of the average mean daily radiation based on the transposed Golder Associates Aurora readings versus the percentage of the possible hours of bright sunshine from the Environment Canada sunshine ball record. The graph was plotted for the years of 1988, 1989, 1995 and 1996 omitting missing values in the record. A lot of scatter amongst the data can be observed in Figure 3.6 and the resulting relationship had an R^2 value of only 0.589. Similar results were obtained when plotting each year individually. The following linear equation was derived from the analysis:

$$\text{\% of Solar Radiation} = 0.405\ (\text{\% of Bright Sunshine}) + 0.221 \qquad [3.5]$$

The percentage of the maximum daily radiation and duration of bright sunshine was also determined for the UA meteorological daily radiation and hours of bright sunshine. Figure 3.7 graphically presents the results for April 22nd to 27th, 2001. In this case, the correlation between bright sunshine and radiation was fairly good resulting in a R^2 of 0.907. The preceding equation was derived from the linear regression:

$$\% \text{ of Solar Radiation} = 0.515\ (\% \text{ of Bright Sunshine}) + 0.240 \qquad [3.6]$$

As expected, the solar radiation and hours of sunshine measured at the UA meteorological station produced a better correlation. Since the radiation at the Golder Associates Aurora station was transposed to the UA meteorological station near the Fort McMurray Airport and the Environment Canada hours of bright sunshine were observed at the Fort McMurray Airport, the sun data in this case were more significantly scattered along the linear trend line.

For reasons of simplicity, the transposed Golder Associates Aurora radiation data were plotted against the hours of bright sunshine from Environment Canada in order to convert the historical sunshine values into radiation data. Figure 3.8 graphically presents the correlation for the years of 1988, 1989, 1995 and 1996. A lot of scatter is still observed for this case, but the R^2 value of 0.629 was slightly better then the one observed for the percentage of the maximum daily radiation and sunshine of the analyzed period. Titus and Truhlar (1969) had listed relations between hours of bright sunshine and radiant flux, received at the surface on a daily basis, between the years of 1964 to 1975 in Alberta during April. The mean value of all those relations was plotted in Figure 3.8 in order to compare the results. Titus and Truhlar's (1969) mean linear equation gives greater radiation values than the one observed in this research. It was concluded that the linear equation obtained with the transposed Golder Associates Aurora radiation and the hours of bright sunshine from Environment Canada represents better the situation in this case and therefore it was used to convert the bright sunshine data to radiation. Equation 3.7 presents the relation that was established between the bright sunshine and solar radiation at Fort McMurray.

$$y = 14.317x + 31.304 \qquad [3.7]$$

where x = hours of bright sun; and

y = solar radiation in W/m^2.

A list of the complete daily solar radiation record during March and April from 1972 to 2001 is available in Appendix B. The original solar radiation values from Golder Associates Aurora and the UA meteorological stations investigated in this research are also listed in Appendix B. The hours of bright sunshine received from Alberta Environment and the UA meteorological station are provided in Appendix B.

3.3 PRECIPITATION

Under this section, snow and soil moisture content are discussed. The influence of these factors on the formation of ice jams will be presented. The availability of the data and the steps used the established the complete record are also explained.

3.3.1 Snow

The main reason to study snow is to identify the availability of runoff in the basin during the spring breakup period. The snowmelt runoff increases the discharge resulting in higher velocities and water levels, which may trigger river ice breakup. Alberta Environment, Water Sciences Branch, Hydrology / Forecast Section provided the plains snow course data for the province of Alberta. The drainage basin studied in this research is the Athabasca River basin. Only the snow stations located upstream of the city of Fort McMurray were analyzed since they potentially influence the discharge at the studied site. This portion of the basin will be referred to as the Upper Athabasca River basin although generally this name is given to the upstream section of the basin in the mountains. Figure 3.9 presents the Upper Athabasca River basin and the location of the studied snow stations. It can be observed in Figure 3.9 that the Upper Athabasca River basin does not extend down to the city of Fort McMurray. The downstream limit of the basin was selected approximately 240 km upstream of Fort McMurray since no snow course data were available closer to the studied site. The identification number (ID number), the name and the location of the snow stations are listed in Table 3.3.

Some snow stations have the same ID number and location. This is because some sites were relocated over the years and replaced with a new station, identified differently. Some sites have both a snow survey course station and a snow pillow station. Barnaby (1982) defines a snow course as point sample where the depth of snow and its water equivalent is determined. The snow sample is taken with a sampling tube, which is rotated into the snowpack until the ground is reached. The snow depth is after measured from the tube and weighted in order to determine the snow water equivalent (SWE). The SWE gives an indication of the available snowmelt runoff. A snow survey course reading represents the average SWE of snow samples taken at usually ten permanent locations spaced at 30.5 m (100 ft) intervals (Barnaby, 1982). A snow pillow is a device that looks like a large waterbed placed on the ground surface which records the SWE by converting the weight of the snow pack on top of the snow pillow (Barnaby, 1982). Snow pillows are usually preferred since they provided continuous, automated records, which can be accessed on a real time basis. Only three of the stations listed in Table 3.3 are snow pillow sites. They are Mayerthorpe S.P. (10) for the years of 1982 to 1992, Paddle River H.W. PI (13), and Twin Lakes Pillow (17).

The plains snow course data were documented for the years of 1972 to 2001. Since the reason for assembling this snow data was to evaluate the potential of snowmelt runoff, only data for the months of March and April were considered.

During the spring snowmelt, generally two surveys were done around the first and the fifteen of the month. The actual measurements are done within a week on either side of these dates. Since the snow data available for March and April 15th did not provide a continuous record, they were omitted from the study. Some missing survey dates were also observed for the March and April 1st data. Section 4.3.1.1 describes how the complete data record for March and April 1st was established.

3.3.1.1 Establishing the Complete Data Record

Data from snow stations just outside of the Upper Athabasca River basin limits were considered in addition to the list in Table 3.3 to help fill in the missing data (see Figure 3.9). Three stations were added from the North Saskatchewan River basin. Table 3.4 identifies their ID number, name and location. Two stations were also added from the Peace River basin. Table 3.5 lists the ID number, name and location of these snow stations.

Tables 3.6 and 3.7 together present the SWE measurements in mm for March 1st for the years of 1972 to 2001. Tables 3.8 and 3.9 show the snow data for April 1st from 1972 to 2001. It is important to mention that the 2001 readings were checked by Alberta Environment, but not 'finalized'. It can be observed in Tables 3.6 and 3.8 that there are no snow readings for the years of 1972 and 1973. Therefore, those years were disregarded in the snow analysis. The 1975 and 1976 April 1st data were also not considered in this research, since the majority of the snow surveys were not done (see Table 3.8). The Hinton (7) and Brown Creek (22) snow stations were dismissed since they were discontinued in 1986 (see Tables 3.6, 3.7, 3.8, and 3.9).

Three methods were used to establish a complete and homogenous data record: double-mass analysis, linear regression, and multiple linear regression. The following sections explain how and why these methods were used.

3.3.1.1.1 Establishing a Homogeneous Record

The Paddle River (10) and the Mayerthorpe S.P. (10) stations have the same latitude and longitude coordinates (see Table 3.3). The Paddle River station was discontinued in 1983 while the Mayerthorpe S.P. station was installed in 1982. At first, Mayerthorpe S.P. (10) was a snow pillow station. Since 1993, the data have been measured by a snow survey course. A change of location or instrumentation may cause a relative change in the precipitation catch (Linsley *et al.*, 1975). In order to verify if the SWE record is consistent, a double-mass analysis was done with the Paddle River (10) and the Mayerthorpe S.P. (10) data. If the results showed that the SWE record is not homogenous, it was decided that the Paddle River (10) and the Mayerthorpe S.P. (10) snow pillow values would be transposed to the Mayerthorpe S.P. (10) snow survey course record since this station is presently in use and this process would simplify the update of the SWE record. According to Linsley *et al.* (1975) a "*double-mass analysis tests the consistency of the record at a station by comparing its accumulated annual or* *seasonal precipitation with the concurrent accumulated values of mean precipitation for a group of surrounding stations*".

The following fictitious example is used to explain how the double-mass analysis works. Say station A has been in operation from 1950 to 1980 during which a snow survey course was used to measure the SWE (mm) in late March from 1950 to 1970 while a snow pillow was used to measure the SWE (mm) at the end of March from 1971 to 1980. The first step to the double-mass analysis is to accumulate the SWE from 1950 to 1980. The average SWE measured in late March of surrounding stations also has to be accumulated from 1950 to 1980. For this example, lets assume there are 10 surrounding stations. Figure 3.10 presents the accumulated SWE of station A versus the accumulated SWE of the 10 surrounding stations mean. A change of slope can be observed in Figure 3.10, which indicates a change in the precipitation regime. It should be mentioned that a change in the precipitation catch caused by meteorological events would not affect the slope since all the surrounding stations would be similarly affected (Linsley *et al.*, 1975). The following equation can be used to establish a homogenous record when the precipitation data are not consistent:

$$P_A = P\,(m_A / m) \qquad \textbf{[3.8]}$$

where P_A = adjusted precipitation;
m_A = slope of the data to keep;
m = slope of the data to be corrected; and
P = measured precipitation to be corrected.

For the previous fictitious example, m would be equal to 0.745 and m_A would be equal to 1.084 if the snow pillow data, which are represented by the slope II in Figure 3.10, would be adjusted to the snow survey course values so that a homogeneous record could be established.

In order to verify the consistency of the SWE record, a double-mass analysis was first performed with the March 1st data of station 10 respectively for the years of 1976 to

2001 (see Tables 3.6 and 3.7). A total of 15 surrounding stations were used in the analysis. The following stations were omitted from the double-mass analysis since they had missing values in their 1976 to 2001 records (see Tables 3.6 and 3.7): Meadowview (11), Paddle River H.W. (13), Paddle River H.W. PI (13), Sturgeon Heights (16), Twin Lakes (17), Twin Lakes Pillow (17), Westlock (18), and Brazeau Res. (21). It can be observed in the Table 3.6 and 3.7 that the SWE for March 1st, 1982, was measured at the Mayerthorpe S.P. (10) snow pillow and the Paddle River (10) stations. Since only one measurement can represent the SWE for a specific year, the SWE value of the Mayerthorpe S.P (10) snow pillow station was omitted for 1982. It was important to use all the record from the Paddle River (10) station since it has fewer values compared to the Mayerthorpe S.P. (10) snow pillow station.

Figures 3.11 and 3.12 graphically present the double-mass analysis for March 1st. The results are m_A is equal to 1.050 and m is equal to 1.109 for the Paddle River (10) station, and 1.038 for the Mayerthorpe S.P. (10) snow pillow station (see Figures 3.11 and 3.12). The slopes obtained are very similar. The Paddle River (10) slope is 6% higher than the Mayerthorpe S.P. (10) snow survey course slope. The snow pillow slope at Mayerthorpe S.P. (10) is 1% less then the Mayerthorpe S.P. (10) snow survey course slope. The coefficient of determination (R^2) for each section of the double-mass analysis are all greater then 0.99 representing very good correlations. The results, as expected, were very good since the location of the snow station never changed significantly. The slight deviation between the slopes can be explained by the natural variations related to snow sampling. Even though the double-mass analysis did not show an important discrepancy between the old and new stations, the results were used to adjust the snow precipitation for the Paddle River (10) and Mayerthorpe S.P. (10) snow pillow stations.

The double-mass analysis for the April 1st SWE data at station 10 regarding was done for the years of 1974, and 1977 to 2001 (see Tables 3.8 and 3.9). A total of 15 stations were also used during the April 1st analysis. The following stations were dismissed from the double-mass analysis since their snow record was not complete during the years of 1974, and 1977 to 2001 (see Tables 3.7 and 3.9): High Prairie (6), Paddle River H.W. (13), Paddle River H.W. PI (13), Sturgeon Heights (16), Twin Lakes (17), Twin Lakes Pillow (17), Brazeau Res. (21), and Little Smoky (24). Overlapping values also occurred in 1982 for the Mayerthorpe S.P. (10) snow pillow and the Paddle River (10) stations. For the same reason as described for the March 1st double-mass analysis, the 1982 Mayerthorpe S.P. (10) snow pillow value was dismissed from the April 1st double-mass analysis.

The results of the double-mass analysis for April 1st are presented graphically in Figures 3.13 and 3.14. The value of m_A is equal to 1.703. The Paddle River (10) and Mayerthorpe S.P. (10) snow pillow values for m are 1.302 and 0.956. The Paddle River (10) slope is 24% less then the one at Mayerthorpe S.P. (10) snow survey course while Mayerthorpe S.P. (10) snow pillow is 44% less then Mayerthorpe S.P. (10) snow survey course. This is an important discrepancy between the slopes observed which indicates the need for conducting a double-mass analysis to homogenize the record. The R^2 values are equal or greater then 0.99 for Paddle River (10) and Mayerthorpe S.P. (10) snow pillow while R^2 is only equal to 0.899 for the Mayerthorpe S.P. (10) snow course. The lower R^2 value for Mayerthorpe S.P. (10) snow survey course was acceptable when considering the natural variations in snow depth, but it probably increased the discrepancy between the slopes observed for the double-mass analysis.

In general, the results of the double-mass analysis for April 1st are not as good as the ones for March 1st since lower R^2 values were observed for the April 1st SWE record. The effect of snowmelt during late March and early April may influence the double-mass analysis for April 1st. As mentioned previously, the snow surveys are done within a week of April 1st. During spring, this variation in actual measurement dates can have a significant impact on the readings. Nevertheless, the results obtained for April 1st are acceptable and were used to adjust the Paddle River (10) and Mayerthorpe S.P. (10) snow pillow readings.

3.3.1.1.2 Interpreting Duplicate Measurement Stations

As mentioned previously, two methods are used to measure SWE in the Upper Athabasca River basin: snow survey course and snow pillow. The snow survey course represents the average of 10 snow samples measured with a sampling tube, which is weighted to get the equivalent SWE values of the snow depths. A snow pillow consists of a large plastic bag placed on the ground, which converts the weight of the snow to SWE value. This method is generally preferred since the information can be accessed on a real time basis. The SWE record at station 13 and 17 consists of measurements taken with the snow survey and the snow pillow methods. The consistency of these measurements, given the two ways SWE was measured, was investigated in this section.

First, a linear regression was performed for the snow survey course and snow pillow stations for stations 13 and 17 in order to justify the use of only one station per site. Years with missing record were omitted from the analysis. Figure 3.15 presents the March 1st results for Paddle River H.W. and Paddle River H.W. PI (station 13). The linear regression was performed for the years of 1993 to 1999. A very good correlation can be observed in Figure 3.15 resulting in an R^2 of 0.97. Figure 3.16 shows the results of the linear regression for Twin Lakes and Twin Lakes Pillow (station 17) for March 1st during 1982 to 2001. All the data are distributed around the 45° line. The R^2 value is equal to 0.96 indicating a very good correlation. Figure 3.17 graphically presents the relation between Paddle River H.W. (13) and Paddle River H.W. PI (13) for April 1st. The linear regression was performed for the years of 1993, 1994, 1995, 1998, 1999, and 2001. The snow data are also distributed around the regression line resulting in an R^2 of 0.93. The regression results for April 1st at stations 17 for 1982 to 1999 omitting 1996, is shown in Figure 3.18. The snow readings are scattered around the 45° line. The value of R^2 is 0.95 representing a very good correlation between the snow pillow and snow survey course data. It can be concluded from these results that only one station can represent each site. Since the snow course stations did not have any missing values in their records, they were used in this investigation.

3.3.1.1.3 Filling Missing Measurements

It can be observed in Tables 3.6, 3.7, 3.8, and 3.9 that some measurements are missing from the SWE record. In order to establish a complete snow data record, linear and multiple linear regressions were performed using the data from the surrounding snow stations. Linear regressions were first investigated for each station with missing readings. These linear regressions were determined with the closest surrounding stations, which did not have the same missing values as the station to fill. The linear relationship between variables was verified with the coefficient of determination (R^2). A good correlation would result in R^2 approaching 1.

The multiple linear regressions were first calculated with all the stations used in the linear regressions for a specific station with missing measurements. After each investigation, the value of P, that represents the probability of being wrong in concluding that there is an association between variables, was verified. Stations with the highest P were dismissed one by one until there were only 2 stations remaining. The parameter that was used to evaluate the multiple linear regressions is the adjusted coefficient of determination (Adj R^2).

Dillon and Goldstein (1984) recommend using Adj R^2 for multiple linear regressions instead of R^2 since R^2 does not take into account the number of independent variables used in the analysis. The value of R^2 can be increased simply by adding more independent variables to a regression model therefore higher R^2 may not necessarily indicate the best regression (Dillon and Goldstein, 1984). Adj R^2 is a more conservative indicator of the relationship between variables then R^2. Equation 4.2 demonstrates that Adj $R^2 < R^2$ when $p > 1$ where p is the number of independent variables in the regression model.

$$\text{Adj}\,R^2 = 1 - \left(1 - R^2\right)\frac{n-1}{n-p} \qquad [3.9]$$

where Adj R^2 = adjusted coefficient of determination;

R^2 = coefficient of determination;
p = number of independent variables in the multiple regression model; and
n = number of observations.

Values of Adj R^2 close to 1 represent a good relationship between variables (SPSS Science, 1997). All the multiple linear regressions performed in this research were done with the software SigmaStat which is produced by SPSS Science. The regressions with R^2 or Adj R^2 closest to 1 were choosing to fill in the missing record except when the highest Adj R^2 was only 3% or less greater then the highest R^2, in which case, the missing values were estimated with the linear regression corresponding to the highest R^2 since linear regressions are easier to apply.

There are 8 stations out of 18 in the Athabasca River basin with incomplete records for March 1st. Table 3.10 list the stations with an incomplete record for March 1st. The chosen methods used to fill in the data with their correspondent values of R^2 or Adj R^2 and the ID number of the stations that were used, are also listed in Table 3.10. Some correlations were very good with values of R^2 or Adj R^2 greater then 0.90. Others were less significant with values of R^2 or Adj R^2 reaching as low as 0.62. The correlation coefficients R^2 or Adj R^2 were still acceptable when considering the natural variations related to snow sampling. Appendix C1 provides a list of all the combinations of linear and multiple linear regressions that were performed in this research. The chosen linear regressions are graphically presented in Appendix C2. The results of the chosen multiple regressions can be observed in Appendix C3.

The April 1st snow record only had 4 stations with missing data. The list of the stations with missing years is presented in Table 3.11. It can also be observed in Table 3.11 the methods used to establish the April 1st record, the correlation coefficients, and the ID number of the stations used in the regressions. Very good correlations were observed with three out of four regressions resulting in R^2 and Adj R^2 greater then 0.90. The less significant regression was calculated for station 16 with a R^2 of only 0.60. As mentioned previously, this value was still acceptable when considering all the factors influencing snow sampling. Appendix C4 lists all the combination of the linear and multiple regressions performed for April 1st. Appendix C5 graphically presents the chosen linear regressions while Appendix C6 lists the results of the chosen multiple regression.

3.3.1.2 Averaging the Snow Pack over the Upper Athabasca River Basin

The Thiessen Polygon method was used to determine an average snow depth over the Upper Athabasca River basin. Typically, this method is used to calculate average rainfall. Topography and vegetation influences snow depth. Since the studied reach is relatively flat, the Thiessen Polygon method was used to calculate an average snow depth of the Upper Athabasca River basin. The arithmetic mean method was not considered in this research since it does not provide any weighting factor for each gauge, which reduces the accuracy of the analysis. The isohyethal method was dismissed since it requires detailed contours of equal precipitation. Not enough stations were available to give this method more accuracy then the Thiessen Polygon method.

The first step of the Thiessen Polygon method is to locate all the stations on a map, which has the drainage basin drawn on it. The next step is to draw a line perpendicular to one connecting two stations at half way. All the perpendicular lines will join and form polygons around each station. The boundaries of a station are given with the sides of each polygon (Linsley, R.K. JR. *et al*, 1975). Measuring the area of each polygon and dividing the value by the total area of the drainage basin determine the weighting factors, which represent a percentage of the total drainage area. The polygon method provides a weighting factor for each gauge giving significance to nonuniform distribution of gauges (Linsley, R.K. JR. *et al*, 1975). The weighting factor divides the basin area into sections in accordance with the relative proximity to other gauges. If a gauge was isolated from the others, its weighting is larger since it necessarily represents a greater area. The closer the gauges are to each other, the smaller their weighting factor. Table 3.12 gives the weighting factors of the snow stations in the Upper Athabasca River basin.

The complete data record for March and April 1st established previously was used to determine the average SWE in the studied basin. Appendix B gives more details regarding the complete SWE record. The average SWE value over the Upper Athabasca River basin, by year, for March and April 1st are presented in Table 3.13.

3.3.1.3 Potential of Snow Pillow Sites as Index Stations

As discussed previously in this section, snow pillow stations have continuous automated records and these data can be accessed on a real time basis. The use of data only from snow pillow stations would be an advantage in a forecasting model since this information could be updated on a daily basis, increasing the accuracy of the prediction. To explore this potential, the average SWE for the Upper Athabasca River basin was compared to the measurements from each of the two snow pillow stations presently in service in the basin.

First, linear regressions were performed with the average SWE in the Upper Athabasca River basin and the SWE in the Paddle River H.W. PI (13) for March and April 1st. Figures 3.19 and 3.20 graphically present these results. The March 1st correlation was better then expected with R^2 equal to 0.89. The R^2 value for April 1st was 0.73. Linear regressions were also performed for the Twin Lakes Pillow (17) station. Figures 3.21 and 3.22 represent the regressions results. The value of R^2 for March 1st was equal to 0.92 while the April 1st value is 0.86. The average SWE of the Paddle River H.W. PI (13) and Twin Lakes Pillow (17) was also compared with the average SWE for the studied basin. Figures 3.23 and 3.24 graphically present the observed linear regressions. The March 1st result slightly increased the R^2 value to 0.93 while the April 1st correlation resulted in R^2 of only 0.77. It can be concluded that the Twin Lakes Pillow (17) station could possibly be used in a forecast model since the best correlation was observed for April 1st and other regressions did not significantly improve the March 1st correlation. Surprisingly, the Twin Lakes Pillow (17) area only represents 0.7% of the total Upper Athabasca River basin.

3.3.2 Antecedent Soil Moisture

The antecedent soil moisture directly affects the surface runoff in a basin. Catchments with low soil moisture will generally produce low quantities of runoff since the precipitation will first infiltrate into the soil. High soil moisture will likely produce the opposite effect resulting in higher surface runoff events. The antecedent soil moisture was determined in this research by summing the daily total precipitation (mm) during May 1st to October 15th at the Fort McMurray Airport. This information was provided by Alberta Environment, Water Sciences Branch, Hydrology / Forecast Section. The original source of the record is the Digital Archive of Canadian Climatological Data (Surface), Environment Canada. Table 3.14 presents the antecedent soil moisture for the breakup years of 1973 to 2001.

Table 3.1 List of the missing hourly temperatures during 1972 to 2001 at the Fort McMurray Airport.

Year	Month	Day	Hour
1996	March	3	3:00 [a]
1996	March	3	5:00 [b]
1996	March	3	6:00 [b]
1996	April	1	12:00 [a]
1996	April	4	11:00 [a]
1996	April	12	6:00 [b]
1996	April	12	7:00 [b]
1996	April	13	22:00 [b]
1996	April	13	23:00 [b]
1997	March	1	7:00
1997	March	1	8:00
1997	March	1	9:00
1997	March	1	10:00
1997	March	1	11:00
1997	March	1	12:00
1997	March	1	13:00
1997	March	1	14:00
1997	March	30	13:00 [a]
1998	March	14	21:00 [a]
1998	March	16	1:00 [a]
1998	March	19	2:00 [a]
1998	March	30	15:00 [a]
1998	April	15	12:00 [a]
1998	April	19	8:00 [a]
1999	April	22	13:00 [a]
1999	April	27	7:00 [a]
2000	March	4	19:00 [a]
2000	March	31	2:00 [a]
2000	April	8	9:00 [a]
2000	April	22	12:00 [a]
2000	April	29	17:00 [a]

[a] Interpolated as average of the two surrounding temperatures
[b] Interpolated by following the trend line of the hourly temperature graph.

Table 3.2 Dates of the solar radiation (W/m^2) from the UA meteorological station record not considered.

Dates of Omitted Solar Radiation Readings (DY/MO/YR)		
16/10/00	15/03/01	29/03/01
17/10/00	16/03/01	30/03/01
19/02/01	17/03/01	31/03/01
20/02/01	18/03/01	01/04/01
24/02/01	20/03/01	02/04/01
25/02/01	21/03/01	03/04/01
26/02/01	22/03/01	04/04/01
01/03/01	23/03/01	05/04/01
04/03/01	24/03/01	06/04/01
06/03/01	25/03/01	07/04/01
08/03/01	26/03/01	11/04/01
13/03/01	27/03/01	12/04/01
14/03/01	28/03/01	

Table 3.3 ID number, name, and location of the snow course stations in the Upper Athabasca River basin.

ID Number	Name of Station	Latitude	Longitude
1	Barrhead North	54° 16′	114° 21′
2	Barrhead West	54° 11′	114° 48′
3	Edson #2	53° 35′	116° 14′
4	Flatbush	54° 44′	114° 05′
5	Grassland	54° 49′	112° 41′
6	High Prairie	55° 24′	116° 27′
7	Hinton	53° 32′	117° 57′
8	Kinuso	55° 20′	115° 24′
9	Lodgepole	53° 30′	115° 21′
10	Mayerthorpe S.P.	53° 52′	115° 19′
10	Paddle River	53° 52′	115° 19′
11	Meadowview	54° 00′	114° 40′
12	Obed	53° 34′	117° 13′
13	Paddle River H.W.	53° 52′	115° 32′
13	Paddle River H.W. PI	53° 52′	115° 32′
14	Perryvale	54° 28′	113° 10′
15	Saulteaux River	55° 10′	114° 14′
16	Sturgeon Heights	53° 04′	117° 41′
17	Twin Lakes	54° 03′	114° 48′
17	Twin Lakes Pillow	54° 03′	114° 48′
18	Westlock	54° 00′	113° 58′
19	Whitecourt	54° 05′	115° 36′

Table 3.4 ID number, name, and location of the snow stations in the North Saskatchewan River basin.

ID Number	Name of Station	Latitude	Longitude
21	Brazeau Res.	52° 57′	115° 41′
22	Brown Creek	52° 46′	116° 26′
23	Onoway	53° 43′	114° 10′

Table 3.5 Snow stations ID number, name, and location in the Peace River basin.

Name of Station	ID Number	Name of Station	ID Number
Girouxville	20	55° 46′	117° 20′
Little Smoky	24	54° 44′	117° 09′

Table 3.6 SWE in mm for March 1st from 1972 to 1986.

STATION NAME & ID #	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
Barrhead North (1)			145	46	56	71	63	76	25	56	81	18	31	86	29
Barrhead West (2)			99	61	56	66	48	79	33	45	74	13	33	103	23
Edson #2 (3)				58	81	61	79	71	86	79	155	36	65	135	46
Flatbush (4)			97	53	71	69	79	99	51	61	89	28	51	131	54
Grassland (5)			102	56	24	53	69	74	8	30	58	37	33	88	46
High Prairie (6)			132	71	58	79	53	127	13	46	106	28	0	94	13
Hinton (7)				61	89	41	66	71	81	56	122	51	104	81	
Kinuso (8)			107	71	74	99	74	104	23	48	104	43	58	155	57
Lodgepole (9)			137	61	81	76	79	69	109	51	119	42	82	137	49
Mayerthorpe S.P. (10)											114	36	54	108	38
Paddle River (10)					76	86	71	79	74	55	117				
Meadowview (11)			137	63	76	86	66	81	71	54	104	30	46	113	36
Obed (12)				58	104	0	79	69	97	38	165	29	76	92	48
Paddle River H.W. (13)															
Paddle River H.W. Pl (13)															
Perryvale (14)			137	48	66	61	61	94	36	56	58	32	50	116	59
Saulteaux River (15)			112	74	76	79	69	99	43	57	84	38	53	96	69
Sturgeon Heights (16)															
Twin Lakes (17)											94	28	48	94	33
Twin Lakes Pillow (17)											89	29	48	93	40
Westlock (18)			130	53	53	53	58	66	38	13	76	28	44	91	18
Whitecourt (19)			157	69	89	76	86	104	76	56	99	28	45	106	41
Girouxville (20)			91	48	74	63	41	130	28	53	107	37	22	77	22
Brazeau Res. (21)						74	63	71	89	58	94	51	79	93	54
Brown Creek (22)						36	38	56	132	51	71	43	86	78	
Onoway (23)			109	53	56	56	53	64	46	33	81	15	37	115	33
Little Smoky (24)					117	81	56	104	61	105	141	47	48	110	33

Table 3.7 SWE in mm for March 1st from 1987 to 2001.

STATION NAME & ID #	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Barrhead North (1)	6	0	40	21	49	73	43	101	66	91	109	30	113	20	0
Barrhead West (2)	43	13	36	17	55	82	44	102	59	93	112	36	123	23	0
Edson #2 (3)	67	57	79	73	89	103	86	123	54	103	103	32	147	44	46
Flatbush (4)	54	13	65	54	13	88	65	128	68	101	111	28	110	30	28
Grassland (5)	51	13	37	46	23	77	12	116	57	52	115	23	67	25	18
High Prairie (6)	47	52	39	50	38	69	0	112	50	123	105	33	95	20	24
Hinton (7)															
Kinuso (8)	53	51	68	56	49	88	57	147	67	125	117	36	95	36	43
Lodgepole (9)	61	31	85	80	107	80	67	98	45	98	106	30	140	31	15
Mayerthorpe S.P. (10)	39	32	52	65	89	95	46	126	57	138	119	15	118	18	13
Paddle River (10)															
Meadowview (11)	42	18	52	26	67		60	130	54	102	127	29	128	46	10
Obed (12)	39	38	79	55	79	97	63	142	23	92	99	29	112	20	15
Paddle River H.W. (13)							42	134	70	134	128	15	137	15	3
Paddle River H.W. Pl (13)							37	128	70	123	119	28	146		
Perryvale (14)	58	27	58	74	53	97	56	121	65	81	111	29	94	66	46
Saulteaux River (15)	62	51	78	66	88	99	57	132	73	123	113	43	83	56	28
Sturgeon Heights (16)		76	98	95	141	118	72	155	74	144	146	69	123	50	36
Twin Lakes (17)	31	19	50	38	68	81	45	117	52	128	108	24	112	20	0
Twin Lakes Pillow (17)	25	28	45	47	69	80	48	106	46	107	124	27	114	20	0
Westlock (18)	21	6	29	27	18		13	102	49	78	114	33	74	23	18
Whitecourt (19)	47	46	76	62	95	93	36	134	60	119	136	19	128	20	15
Girouxville (20)	38	19	15	50	8	46	0	116	41	109	109	38	84	20	19
Brazeau Res. (21)	42	28	85	79	103	77	78	142	48	123	105	29	99	61	43
Brown Creek (22)															
Onoway (23)	32	11	58	32	83	66	36	103	43	108	118	20	107	28	20
Little Smoky (24)	70	57	75	66	123	105	51	141	71	126	118	60	127	39	37

Table 3.8 SWE in mm for April 1st from 1972 to 1986.

STATION NAME & ID #	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
Barrhead North (1)			147	58		63	0	58	36	22	112	46	0	19	0
Barrhead West (2)			145	76		69	0	18	38	0	99	35	0	31	0
Edson #2 (3)			122	74		38	0	0	130	5	168	53	36	115	32
Flatbush (4)			175			91	48	58	61	0	122	45	0	104	22
Grassland (5)			130	76		38	33	61	28	0	97	58	0	39	0
High Prairie (6)			185	63		81		97	26	0	156	52	0	46	0
Hinton (7)			137	86		46	74	0	109	30	157	68	109	74	
Kinuso (8)			163			117	0	64	41	22	155	43	0	137	107
Lodgepole (9)			165	71		53	0	0	137	0	157	74	49	123	18
Mayerthorpe S.P. (10)											150	59	18	95	8
Paddle River (10)			188	69	84	86	53	23	97	13	142				
Meadowview (11)			160			61	0	0	84	25	124	54	15	64	0
Obed (12)			173	76		18	53	0	135	10	196	63	50	58	4
Paddle River H.W. (13)															
Paddle River H.W. Pl (13)															
Perryvale (14)			150			79	66	71	48	0	84	36	12	105	52
Saulteaux River (15)			198			94	30	74	43	23	124	61	5	97	33
Sturgeon Heights (16)															
Twin Lakes (17)											119	43	11	67	8
Twin Lakes Pillow (17)											114	47	8	73	22
Westlock (18)			160	53		41	0	0	41	0	104	45	0	27	0
Whitecourt (19)			157			89	81	9	107	0	109	49	0	112	35
Girouxville (20)			102			69	0	124	0	0	116	32	0	23	0
Brazeau Res. (21)						36	58	0	117	8	126	61	58	69	1
Brown Creek (22)						79	41	43	147	18	87	54	88	59	
Onoway (23)			196			0	0	0	76	0	107	2	0	63	0
Little Smoky (24)			152			46		97	93	0	164	27	0	83	0

Table 3.9 SWE in mm for April 1st from 1987 to 2001.

STATION NAME & ID #	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Barrhead North (1)	8	0	66	0	32	0	0	84	24	71	122	3	99	0	0
Barrhead West (2)	35	0	15	0	60	0	0	89	0	63	137	0	119	0	0
Edson #2 (3)	78	39	103	36	127	7	41	104	24	75	128	17	157	36	13
Flatbush (4)	72	0	75	17	0	0	0	125	0	94	137	0	97	0	0
Grassland (5)	59	3	60	0	6	0	0	83	0	6	115	0	15	0	0
High Prairie (6)	50	0	60	22	33	0	0	66	50	93	79	0	62	0	0
Hinton (7)															
Kinuso (8)	83	25	84	49	120	39	0	154	66	127	145	0	94	0	18
Lodgepole (9)	73	0	98	63	135	0	36	69	33	89	128	19	131	28	0
Mayerthorpe S.P. (10)	30	0	71	10	95	0	25	140	41	144	130	0	112	8	0
Paddle River (10)															
Meadowview (11)	36	0	55	0	102	0	5	121	36	103	154	0	132	25	0
Obed (12)	39	0	97	36	92	3	47	104	15	37	123	53	100	20	13
Paddle River H.W. (13)							27	123	69	125	166	15	155	10	0
Paddle River H.W. Pl (13)							31	127	77			62	181		3
Perryvale (14)	65	5	94	60	66	0	0	122	0	53	137	2	61	41	0
Saulteaux River (15)	79	6	80	31	50	44	0	135	41	97	118	20	86	8	5
Sturgeon Heights (16)		58	114	91	152	11	43	150	74	122	144	0	60	43	0
Twin Lakes (17)	39	0	58	7	84	0	10	106	32	92	149	0	117	13	0
Twin Lakes Pillow (17)	40	0	53	1	80	9	7	95	0		136	0	126		
Westlock (18)	26	0	42	0	0	0	0	78	0	36	112	0	18	0	0
Whitecourt (19)	42	12	76	26	106	0	42	101	14	95	150	0	122	10	0
Girouxville (20)	46	0	50	0	3	0	0	72	38	91	88	0	52	0	0
Brazeau Res. (21)	53	27	73	40	86	0	42	94	0	106	121	3	58	23	8
Brown Creek (22)															
Onoway (23)	17	0	69	0	73	0	0	85	0	65	138	0	99	5	0
Little Smoky (24)	64	0	99	5	117	0	0	75	30	85	109	0	108	0	0

Table 3.10 List of the methods used to fill in the missing record for March 1st.

Station Name & ID	Missing Years	METHODS USED TO ESTIMATE MISSING VALUES		
		Regression	Year	Parameter (Station Used)
Edson #2 (3)	1974	Linear	1975 to 2001	$R^2 = 0.78$ with Stn 9
Mayerthorpe S.P. (10)	1974, 1975	Linear	1976 to 2001	$R^2 = 0.90$ with Stn 19
Meadowview (11)	1992	Multiple	1982 to 2001, omitting 1992	Adj $R^2 = 0.95$ with Stn 17 and 2
Obed (12)	1974	Linear	1975 to 2001	$R^2 = 0.62$ with Stn 9
Paddle River H.W. (13)	1974 to 1992	Linear	1993 to 2001	$R^2 = 0.98$ with Stn 19
Strugeon Heights (16)	1974 to 1987	Linear	1988 to 2001	$R^2 = 0.75$ with Stn 9
Twin Lakes (17)	1974 to 1981	Multiple	1982 to 2001	Adj $R^2 = 0.95$ with Stn 1 and 19
Westlock (18)	1992	Linear	1974 to 2001, omitting 1992	$R^2 = 0.80$ with Stn 1

Table 3.11 List of the methods used to fill in the missing record for April 1st.

Station Name & ID	Missing Years	METHODS USED TO ESTIMATE MISSING VALUES		
		Regression	Year	Parameter (Station Used)
High Prairie (6)	1978	Multiple	1974, 1977, 1979 to 2001	Adj $R^2 = 0.90$ with Stn 20 and 15
Paddle Rive H.W. (13)	1974, 1977 to 1992	Linear	1993 to 2001	$R^2 = 0.95$ with Stn 11
Strugeon Heights (16)	1974, 1977 to 1987	Linear	1988 to 2001	$R^2 = 0.60$ with Stn 9
Twin Lakes (17)	1974, 1977 to 1981	Linear	1982 to 2001	$R^2 = 0.98$ with Stn 11

Table 3.12 Thiessen Polygon weighting factor (%) for the snow stations in the Upper Athabasca River basin.

Station Name & ID	Weighting Factor (%)
Barrhead North (1)	2.4
Barrhead West (2)	3.0
Edson #2 (3)	7.7
Flatbush (4)	5.0
Grassland (5)	11.9
High Prairie (6)	8.1
Kinuso (8)	8.2
Lodgepole (9)	4.2
Mayerthorpe S.P. (10)	1.4
Meadowview (11)	1.5
Obed (12)	10.6
Paddle River H.W. (13)	1.4
Perryvale (14)	2.9
Saulteaux River (15)	8.1
Sturgeon Heights (16)	15.2
Twin Lakes (17)	0.7
Westlock (18)	1.3
Whitecourt (19)	6.3

Table 3.13 Average SWE (mm) for the Upper Athabasca River basin during March and April 1st.

Year	Average SWE (mm)	
	March 1st	April 1st
1974	129	162
1975	66	
1976	76	
1977	69	67
1978	77	27
1979	90	38
1980	63	83
1981	54	11
1982	110	141
1983	39	60
1984	58	22
1985	117	89
1986	50	27
1987	56	63
1988	42	16
1989	68	83
1990	61	36
1991	73	83
1992	92	9
1993	50	20
1994	129	112
1995	58	33
1996	107	81
1997	117	128
1998	36	10
1999	108	86
2000	34	16
2001	25	4

Table 3.14 Antecedent soil moisture (mm) for the breakup years of 1973 to 2001.

Year	Soil Moisture (mm)
1973	315.1
1974	520.2
1975	329.2
1976	468.2
1977	438.1
1978	280.0
1979	345.8
1980	335.2
1981	380.1
1982	234.9
1983	260.8
1984	280.5
1985	425.5
1986	262.0
1987	258.0
1988	249.9
1989	347.5
1990	382.9
1991	289.0
1992	463.2
1993	295.3
1994	299.1
1995	228.8
1996	365.0
1997	460.1
1998	378.9
1999	162.9
2000	249.4
2001	373.3

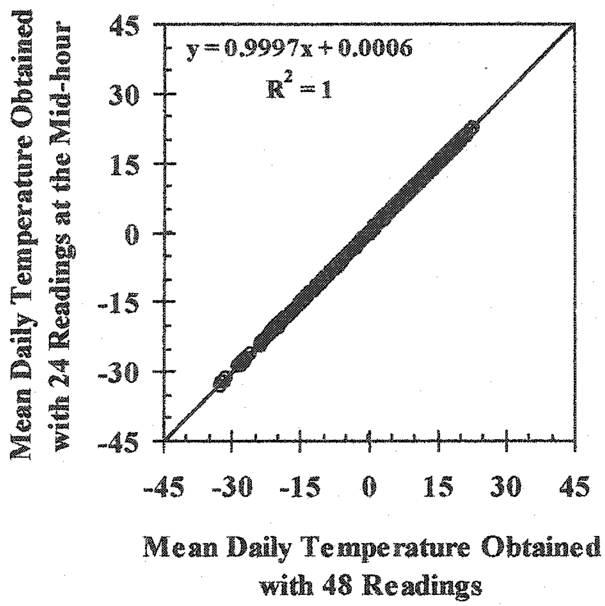

Figure 3.1 Mean daily air temperature (°C) obtained with 24 readings measured at the mid-hour versus mean daily air temperature (°C) obtained with 48 readings measured every 30 minutes from October 14th, 2000 to October 26th, 2001.

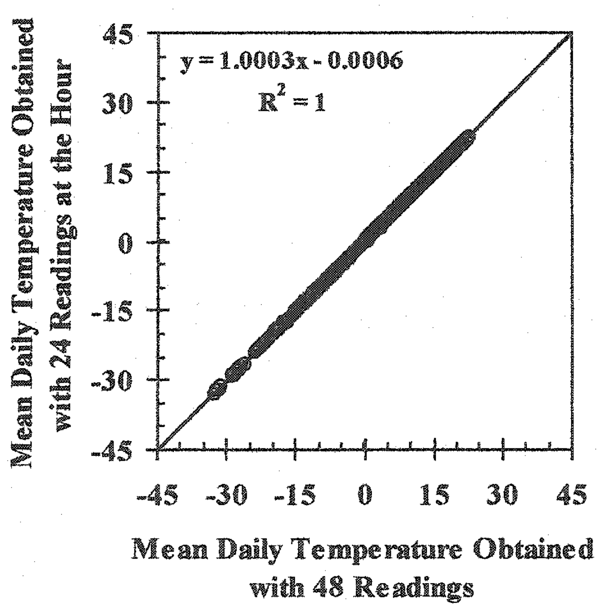

Figure 3.2 Mean daily air temperature (°C) obtained with 24 readings measured at the hour versus mean daily air temperature (°C) obtained with 48 readings measured every 30 minutes from October 14th, 2000 to October 26th, 2001.

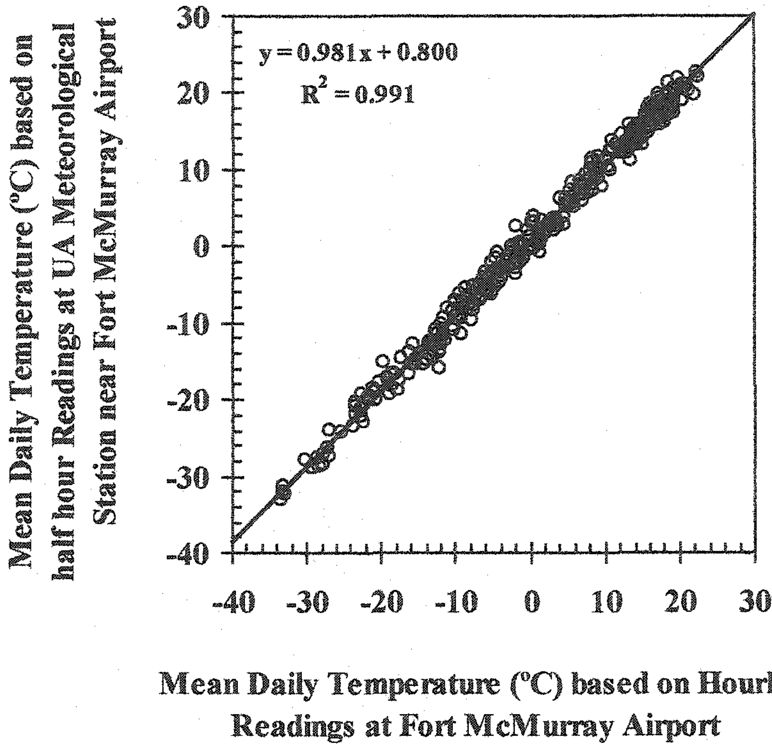

Figure 3.3 **Mean daily air temperature (°C) based on half hour measurements at UA meteorological station near Fort McMurray Airport versus mean daily temperature (°C) based on hourly measurements at Fort McMurray Airport from October 14th, 2000 to August 31st, 2001.**

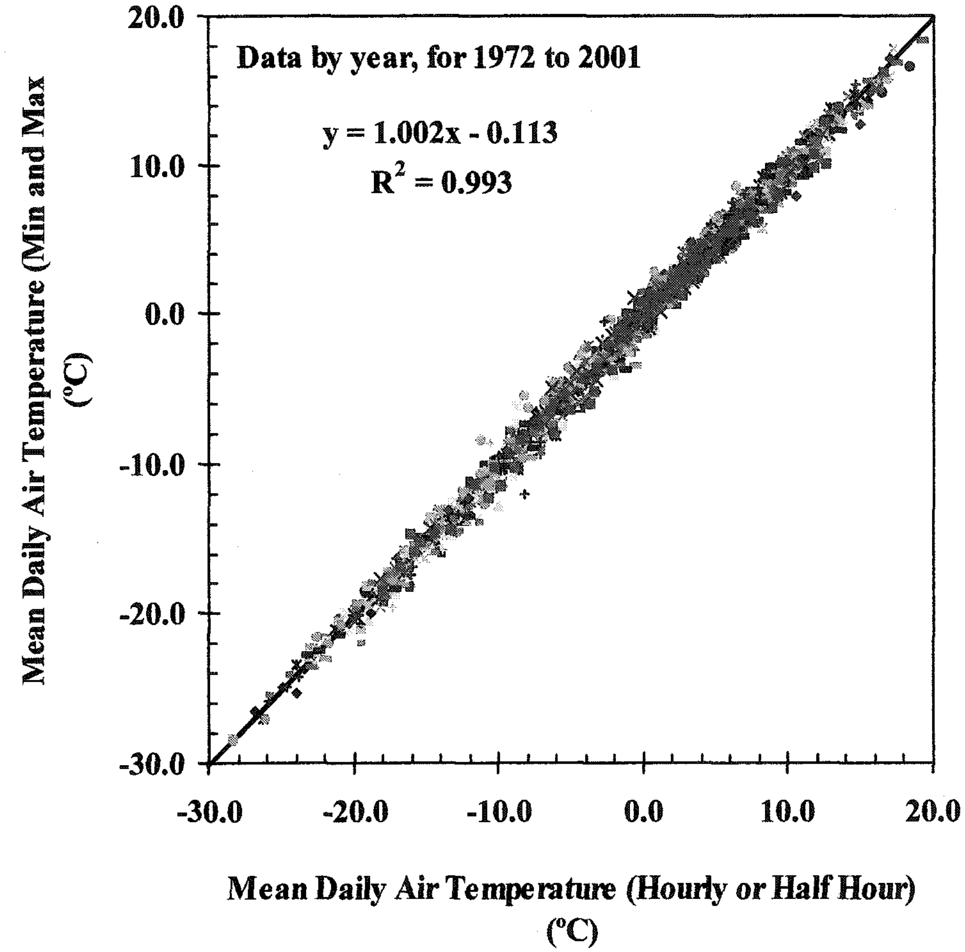

Figure 3.4 **Maximum and minimum mean daily air temperature (°C) versus hourly or half hour daily air temperature (°C) for the years of 1972 to 2001.**

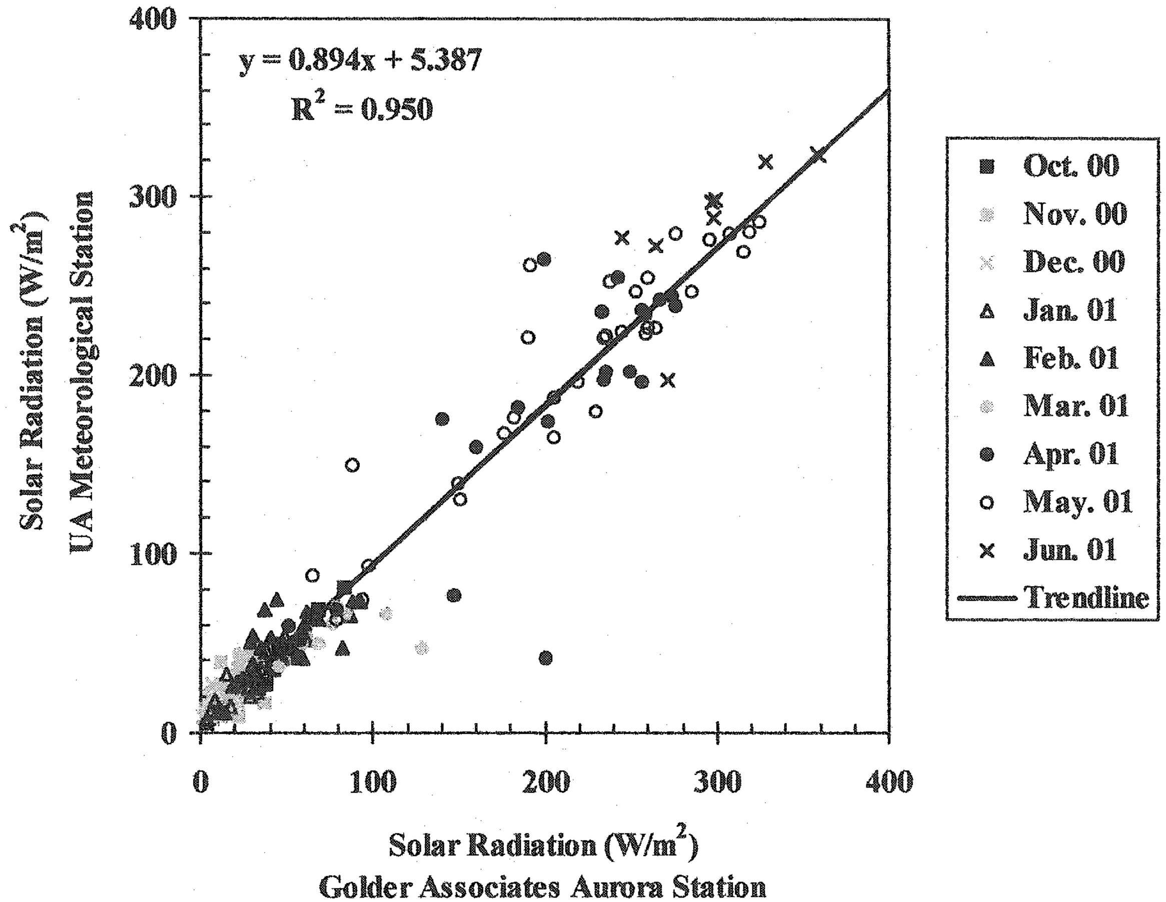

Figure 3.5 Solar radiation (W/m^2) at the UA meteorological station versus the solar radiation (W/m^2) at the Golder Associates Aurora station for October 14th, 2000 to June 9th, 2001.

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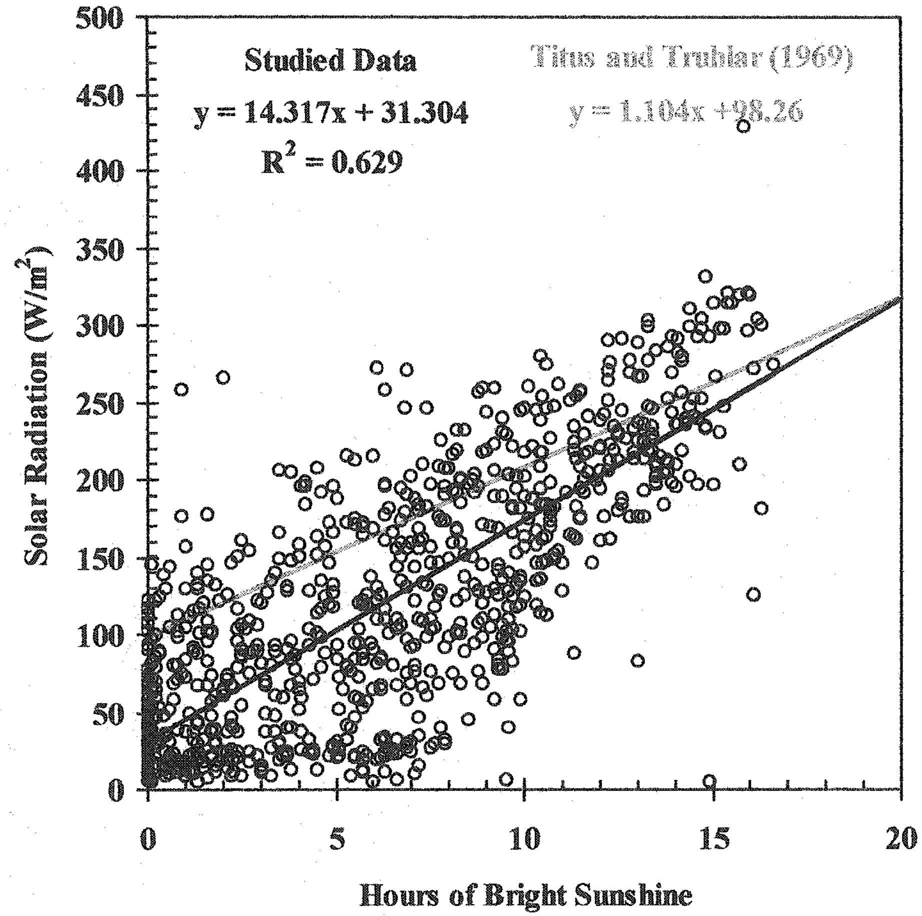

Figure 3.8 **Transposed Golder Associates Aurora solar radiation (W/m^2) versus the hours of bright sunshine from Environment Canada for the years of 1988, 1989, 1995 and 1996.**

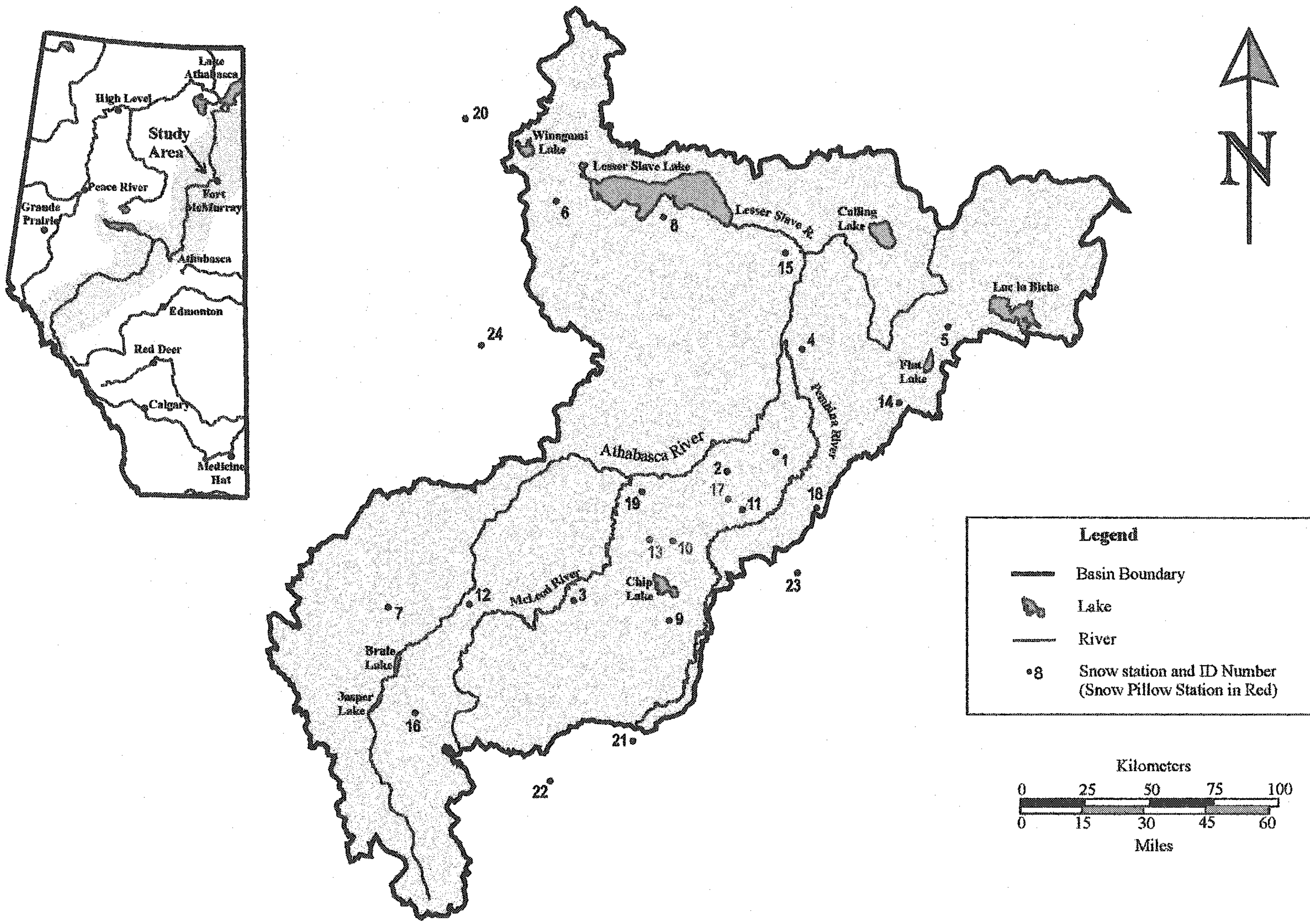

Figure 3.9 Upper Athabasca River basin and location of snow stations.

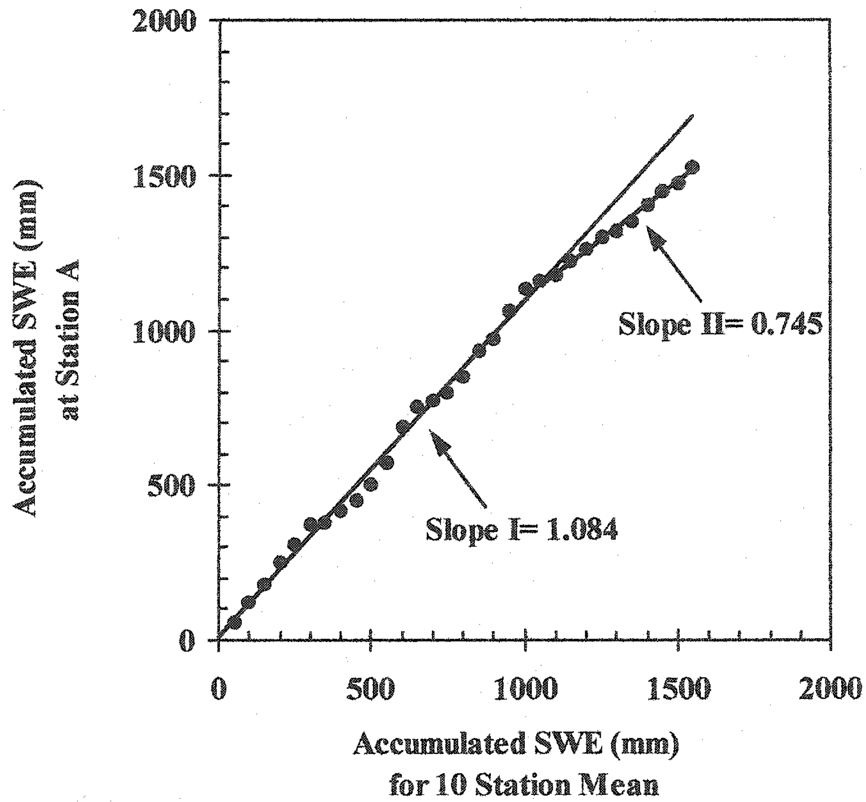

Figure 3.10 Double-mass analysis for the end of March accumulated SWE (mm) at station A and the late March accumulated SWE (mm) of 10 stations mean for the years of 1950 to 1980.

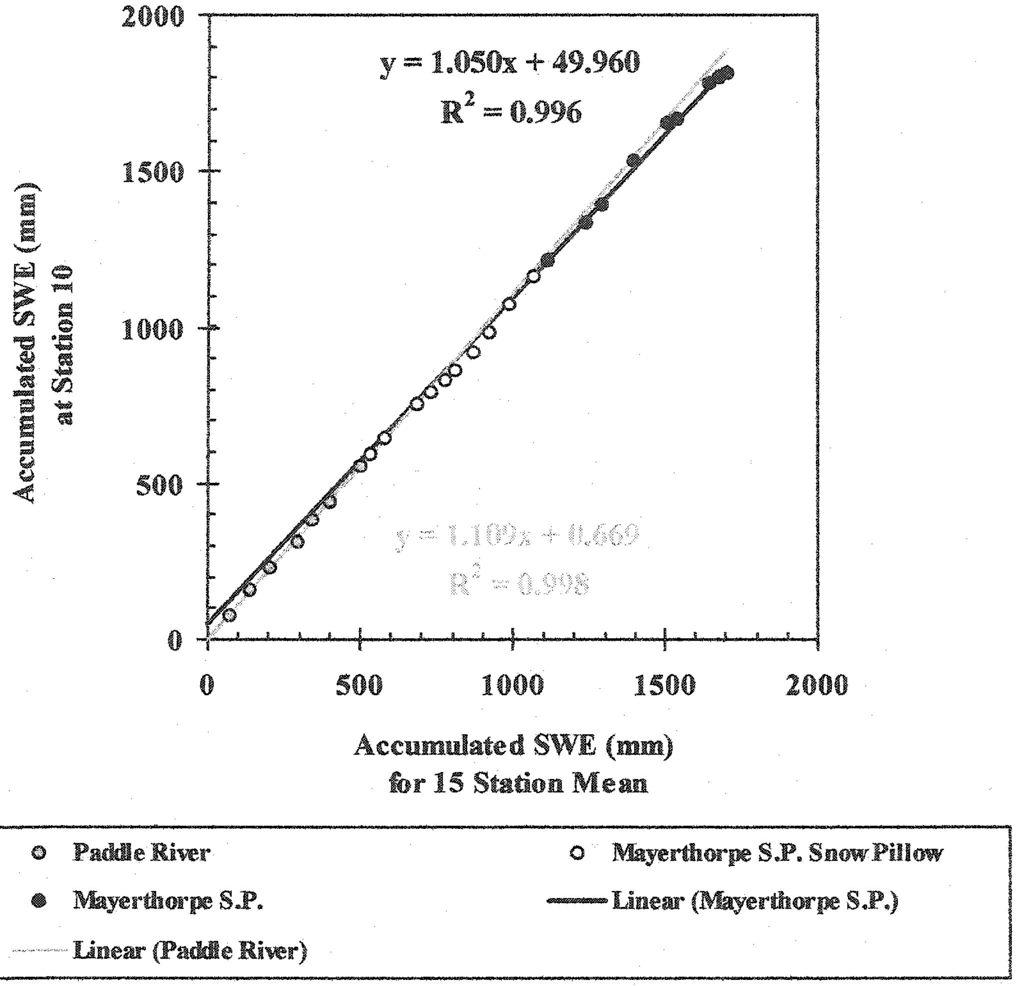

Figure 3.11 March 1st double-mass analysis for the accumulated SWE (mm) at Paddle River and Mayerthorpe S.P. (station 10), and the accumulated SWE (mm) of 15 stations mean for the years of 1976 to 2001.

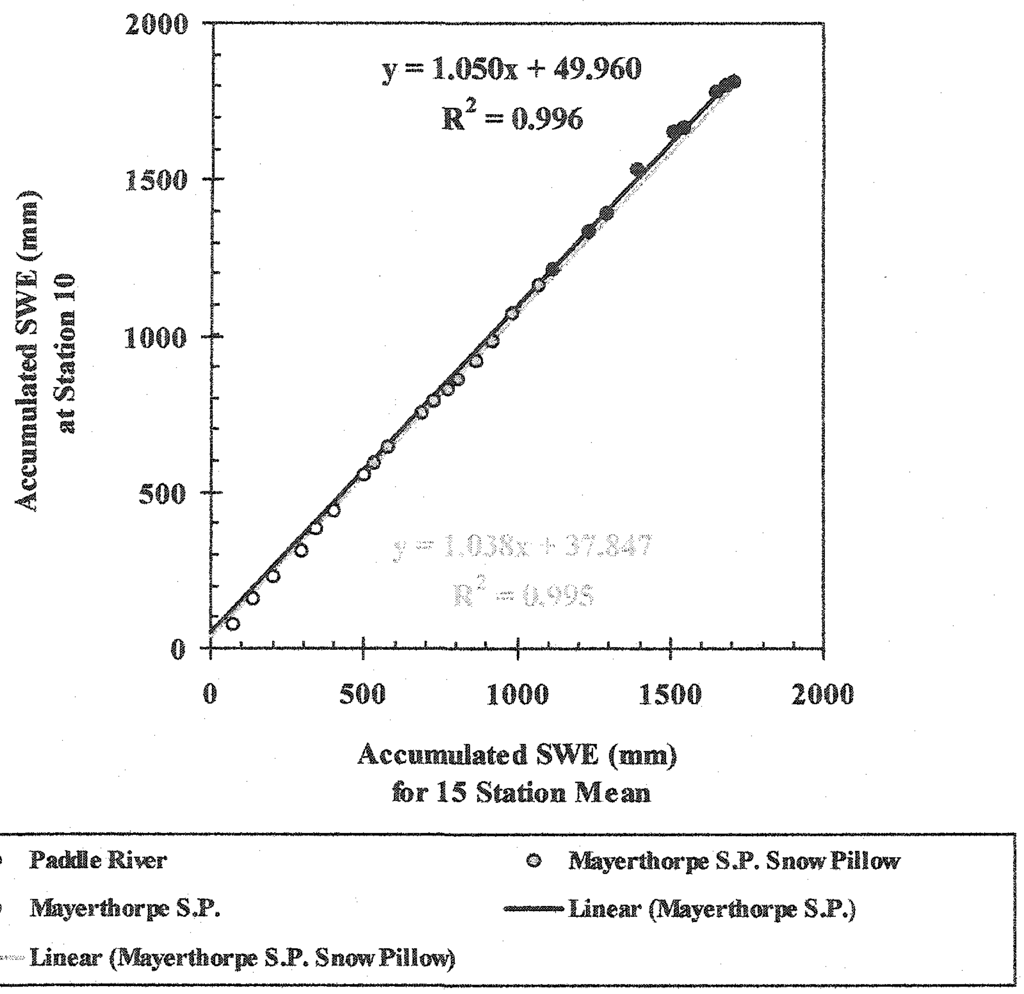

Figure 3.12 March 1st double-mass analysis for the accumulated SWE (mm) at Mayerthorpe S.P. snow pillow and Mayerthorpe S.P. (station 10), and the accumulated SWE (mm) of 15 stations mean for the years of 1976 to 2001.

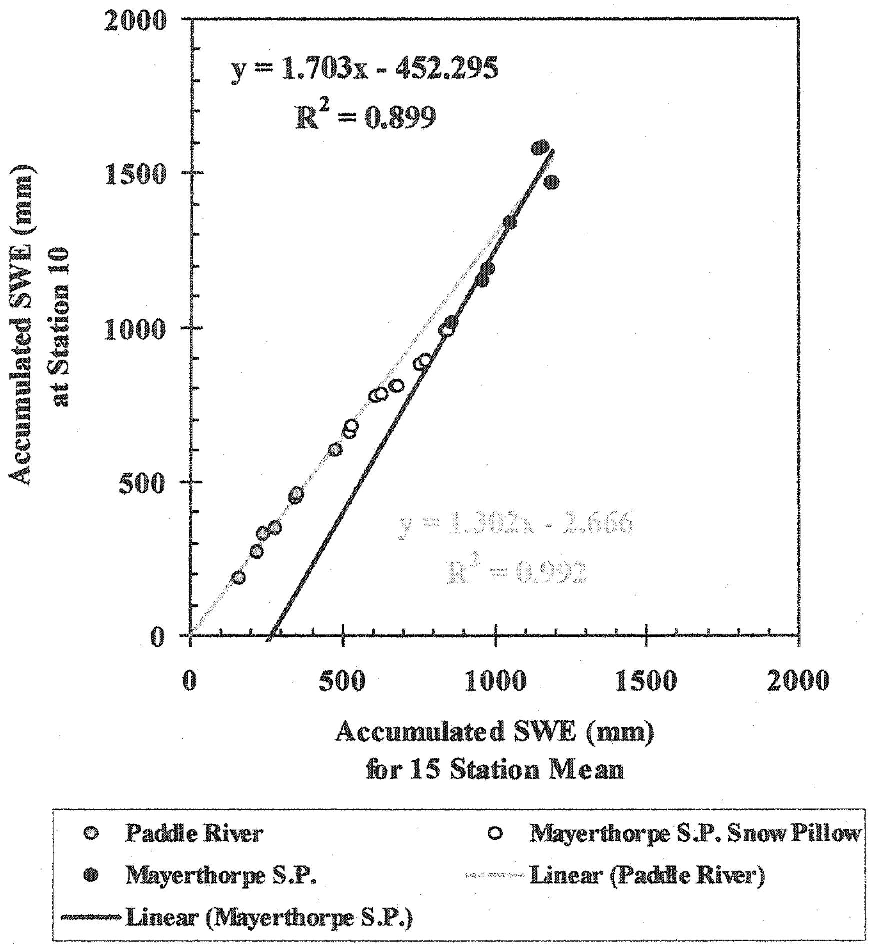

Figure 3.13 April 1st double-mass analysis for the accumulated SWE (mm) at Paddle River and Mayerthorpe S.P. (station 10), and the accumulated SWE (mm) of 15 stations mean for the years of 1974, and 1977 to 2001.

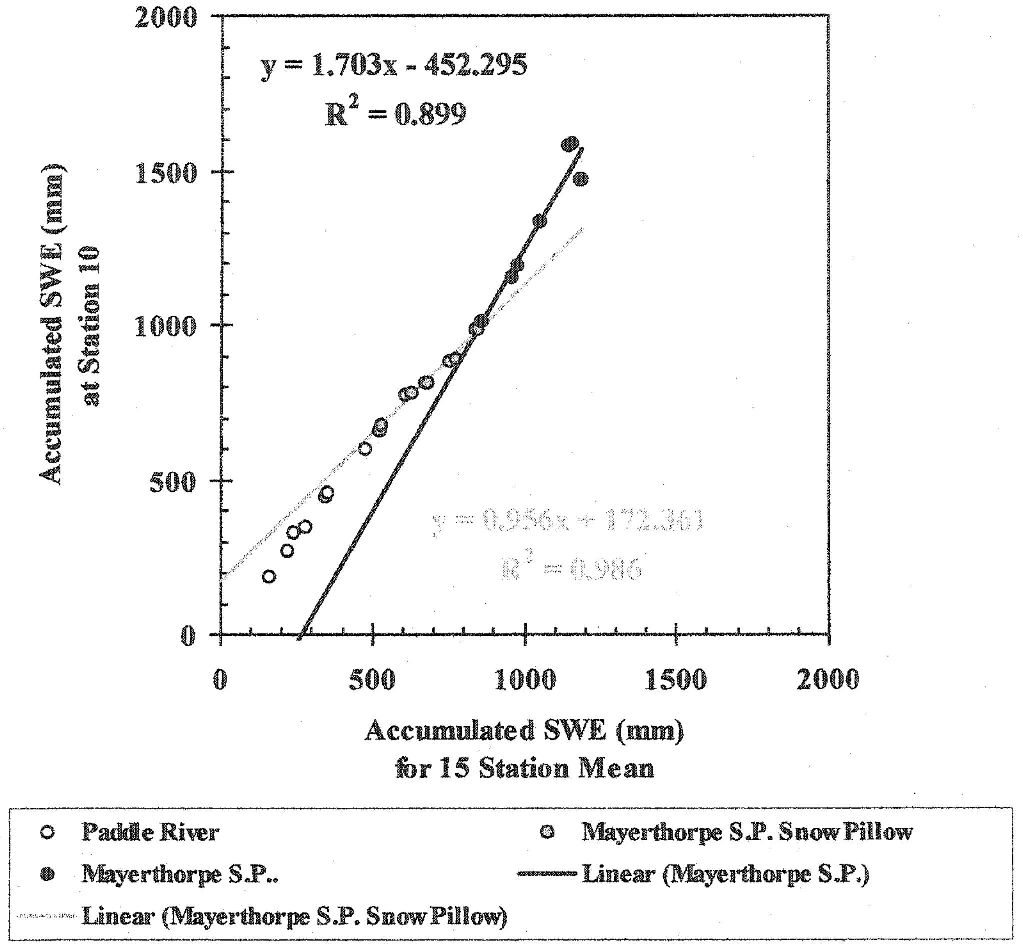

Figure 3.14 April 1st double-mass analysis for the accumulated SWE (mm) at Mayerthorpe S.P. snow pillow and Mayerthorpe S.P. (station 10), and the accumulated SWE (mm) of 15 stations mean for the years of 1974, and 1977 to 2001.

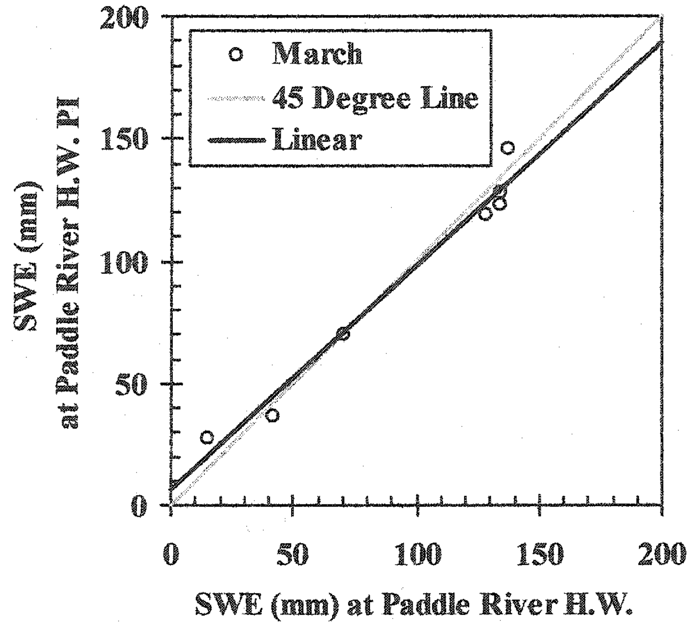

Figure 3.15 SWE (mm) for Paddle River H.W. in function of Paddle River H.W. PI during March 1st for the years of 1993 to 1999 (station 13).

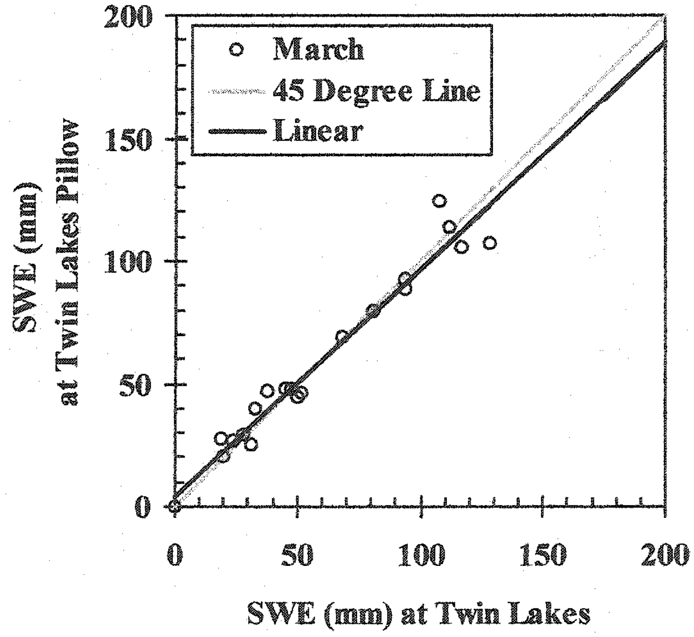

Figure 3.16 SWE (mm) for Twin Lakes Pillow versus Twin Lakes during March 1st for the years of 1982 to 2001 (station 13).

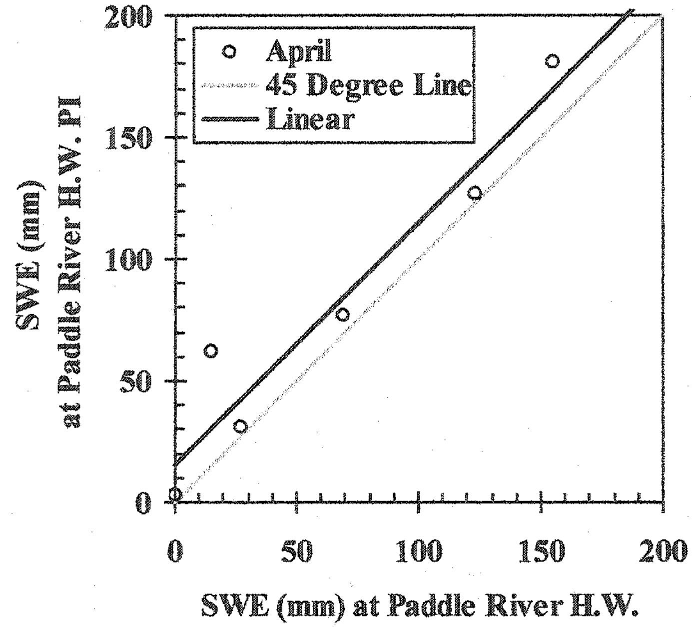

Figure 3.17 SWE (mm) for Paddle River H.W. versus Paddle River H.W. PI during April 1st for the years of 1993 to 1995, 1998 to 2001 (station 17).

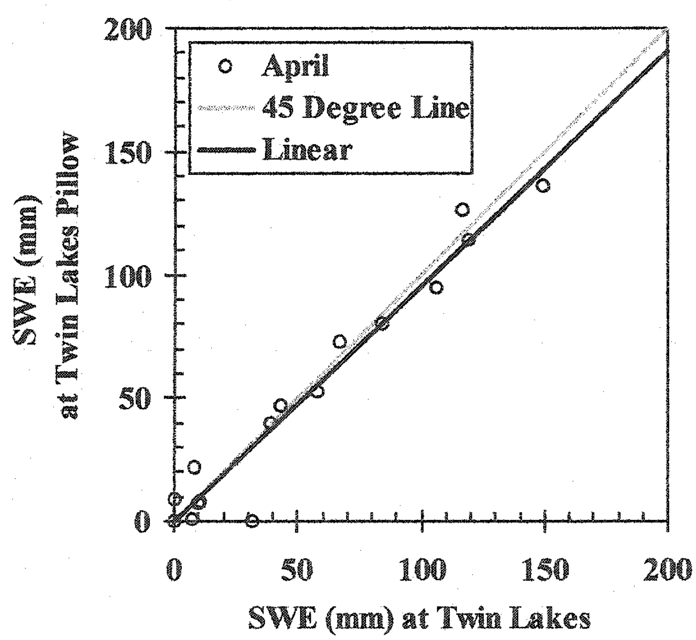

Figure 3.18 SWE (mm) for Twin Lakes Pillow versus Twin Lakes during April 1st for the years of 1982 to 1999, except 1996 (station 17).

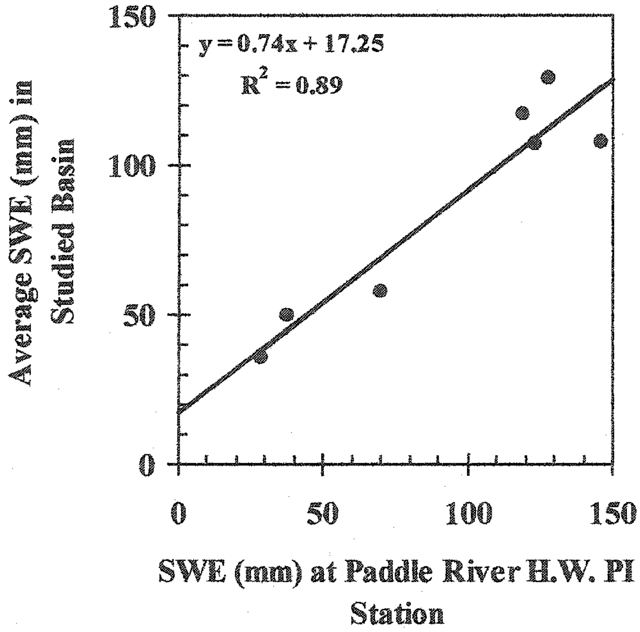

Figure 3.19 Average SWE (mm) in the Upper Athabasca River basin versus the SWE (mm) at the Paddle River H.W. PI station for March 1st.

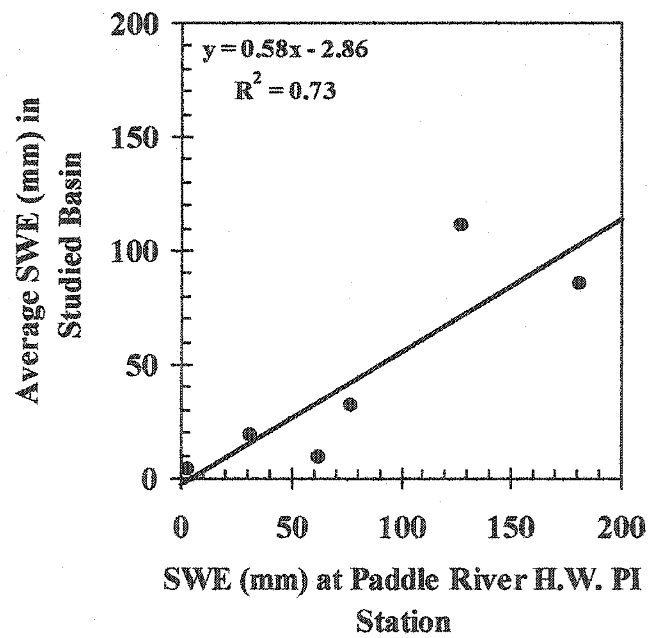

Figure 3.20 Average SWE (mm) in the Upper Athabasca River basin versus the SWE (mm) at the Paddle River H.W. PI station for April 1st.

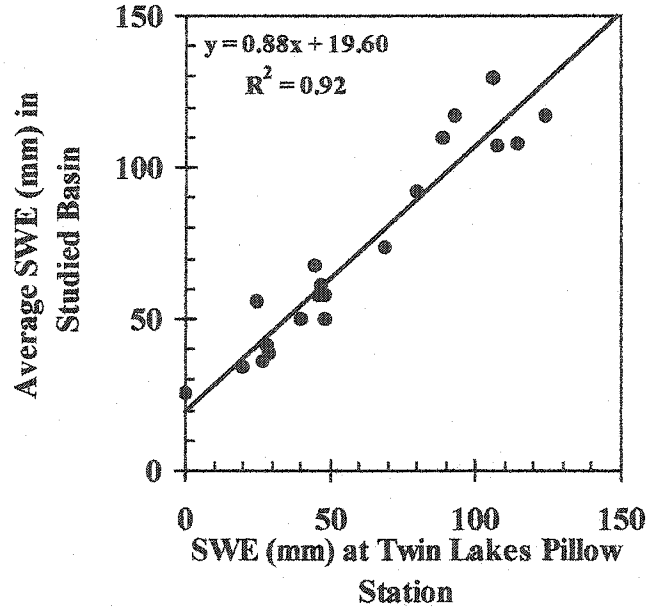

Figure 3.21 Average SWE (mm) in the Upper Athabasca River basin versus the SWE (mm) at the Twin Lakes Pillow station for March 1st.

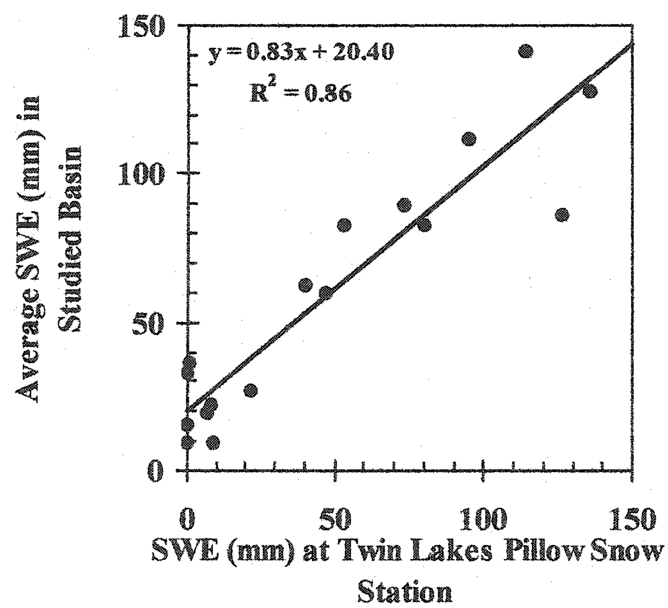

Figure 3.22 Average SWE (mm) in the Upper Athabasca River basin versus the SWE (mm) at the Twin Lakes Pillow station for April 1st.

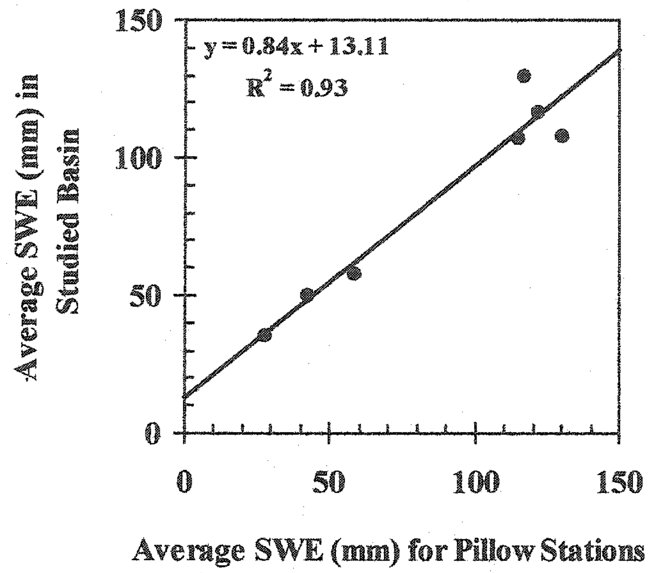

Figure 3.23 Average SWE (mm) in the Upper Athabasca River basin versus the average SWE (mm) of the pillow stations for March 1st.

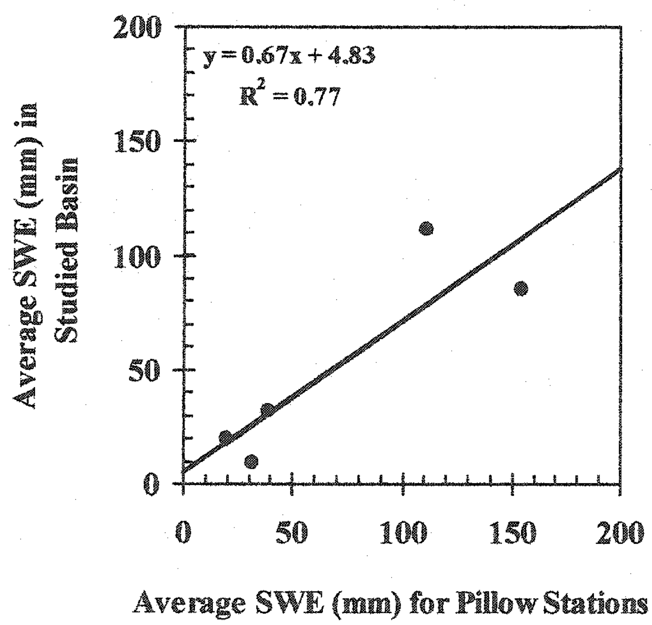

Figure 3.24 Average SWE (mm) in the Upper Athabasca River basin versus the average SWE (mm) of the pillow stations for April 1st.

CHAPTER 4 FORECASTING BREAKUP

Two methods have been used to identify the hydrometeorological factors influencing breakup at Fort McMurray. Threshold models were first investigated in order to identify if lower and higher threshold limits exist during spring breakup regarding the formation of ice jams. Regressions models were also used to establish the relationship between the studied variables.

Before discussing the results, a brief review of breakup process at Fort McMurray will be presented to reinforce the complexity of the situation. A list of the variables used to conduct the results will then be described and also their influence on river ice breakup.

4.1 BREAKUP AT FORT McMURRAY

Open leads are the first indication of the river ice breakup on the Athabasca River upstream of Fort McMurray. Generally, the open leads are first observed in the numerous rapids upstream of the city. The next event observed during the breakup process is the fracture of the river ice sheets, which is likely caused by the thermal deterioration of the ice cover and the increase in discharge. These ice sheets will naturally flow downstream (ice run) until an obstacle obstructs their way. A competent ice cover, or man-made structures such as a bridge, can obstruct the passage of an ice run. An ice jam will form if the passage of the ice is obstructed.

Ice jams are commonly observed upstream of Fort McMurray likely because this reach is very steep causing breakup to be generally governed by dynamic events. The release of an ice jam upstream of town will generate a water wave and a significant ice run which has the potential to lift and break the river ice downstream. If the ice run generated by the jam release stalls downstream of the Clearwater River confluence, serious flooding may occur in Fort McMurray. The decrease in the riverbed slope and the many islands in the vicinity of Fort McMurray classify this area as highly potential for ice jams occurrence.

4.2 FACTORS INFLUENCING BREAKUP

Ice jam formation involves very complex phenomena that interact with meteorological and hydraulic processes. The meteorological parameters that were used in this research are the antecedent soil moisture, the accumulated SWE, the air temperature, and the solar radiation. These factors were first studied separately in order to identify which one may influence breakup more significantly. The soil moisture may give a general indication of the water level on the Athabasca River during freeze-up. Dry summers generally result in very low discharge causing the ice to form at lower elevations. Beltaos (1997) describe the freeze-up level as a general indicator of the stage that must be exceeded in spring before the ice cover is free from the banks and other river constraints. Basins with high soil moisture will also likely produce high quantities of runoff since the snowmelt runoff is less likely to be absorbed by the soil. High runoff has the potential to flex the ice cover, which is likely to cause the ice to break. An important snow pack in the basin will generate higher discharge. The air temperature and the solar radiation are factors influencing snowmelt and river ice decay. The ice strength is directly related to the formation of ice jams. A strong ice cover is likely to produce severe ice jam events.

As mentioned previously, the antecedent soil moisture represents the daily total precipitation from May 1st to October 15th at Fort McMurray. The snow measurements for March 1st and April 1st were considered in the analysis since they represent the availability of runoff in the Upper Athabasca River basin during breakup. The air temperature was considered in three forms: as the accumulated degree-days of thaw up to the breakup date (ADDT); as the degree-days accumulated in the 10 days prior to the breakup date (T_{10}); and as the number of days with maximum temperatures greater than 0°C prior to breakup (T_{max}) calculated from the ADDT starting date.

The accumulated solar radiation received from the date degree-days of thaw accumulation was started up to the breakup date (S), and the accumulated solar radiation received in the 4 days prior to breakup (S_4) were also factors considered in this research. The use of T_{10} and S_4 was to identify if the weather conditions prior to breakup had a greater influence on the severity of breakup then longer term indicators ADDT and S. Beltaos (1995) documented that the heat transfer to the ice cover during spring breakup is mainly caused by solar radiation. Therefore, a shorter time period was used to study solar radiation prior to breakup, than was used for air temperature effects.

The hydraulic factors considered were the freeze-up water level (H_F) that represents the highest stage during freeze-up, the pre freeze-up water lever (H_{Fo}), the river ice thickness prior to breakup (h_i), the fairly steady increase in water level preceding breakup ($\Delta H/\Delta t$), the stage immediately before breakup (H_{Bo}), and the maximum stage observed during breakup (H_B). The values of H_F, H_{Fo}, $\Delta H/\Delta t$, and H_{Bo} were measured at the WSC gauge below Fort McMurray. Since the maximum water level at the Clearwater River confluence ($H_{B,\ Clearwater}$) is an indication of the severity of flooding in Fort McMurray, it was analyzed as well as the maximum stage at the WSC gauge below Fort McMurray (H_B). The roles of H_F and H_{Fo} in this study were previously mentioned with the antecedent soil moisture description. The factor $\Delta H/\Delta t$ is an indicator of discharge increase prior to breakup, which may influence the severity of breakup. The bigger $\Delta H/\Delta t$, the more likely breakup will be dynamic since the ice strength probably did not reduce significantly before the increasing flow lifted and broke the ice. The H_{Bo}, $H_{B,\ Clearwater}$ and H_B were used in this research to help distinguish a breakup that is mainly governed by either thermal or dynamic processes.

4.3 THRESHOLD MODELS

Threshold models are used to identify limits separating ice jam years from uneventful thermally dominated breakups. White (2002) defines two categories of threshold models: simple and complex. Simple models generally use one or two variables while the complex models include multiple variables and may use indices or weighing factors. A perfect example of a simple threshold model is given by Shulyakovskii (1963). His model identifies the relationship between the water level at freeze-up and the occurrence of ice jams on the Yenisei River downstream of Krasnoyarsk, eastern Siberia. Figure 4.1 graphically presents Shulyakovskii's result, which clearly demonstrates that the likelihood of ice jam occurrence was greater when the freeze-up water level was higher.

A good illustration of a complex threshold model is Wuebben *et al.* (1995). The goal of Wuebben's model was to discriminate high and low potential for ice jams on the Missouri River near Williston, North Dakota. The variables used were the accumulated degree-days of freezing (ADDF), the Julian day (JD) representing the maximum ADDF ($ADDF_{max}$), the JD of the maximum runoff during breakup (Q_{max}), the number of days between $ADDF_{max}$ and Q_{max}, the breakup discharge (Q_b), the Lake Sakakawea elevation (located downstream of the studied reach), the total snow fall during winter, and finally the snowfall timing. The Lake Sakakawea stage was included in Wuebben *et al.* (1995) since the lake is a potential location for ice jams, because of the energy slope transition from steep to mild. Table 4.1 presents the lower and higher threshold limits, and the weighting factors Wuebben *et al.* (1995) obtained for the Missouri River near Williston. Variables with a value in the lower threshold limit are given a negative weight, while values in the higher threshold limit are given a positive weight. Wuebben *et al.* (1995) have determined that if the sum of the negative and positive weighting factors is less than one, ice jam flooding will not likely occur, while the likelihood of ice jam events is greater when the values are greater than one.

4.3.1 Simple Threshold Models

Simple threshold models were first considered in this research in order to determine which breakup variables can be used to establish the likelihood of ice jams on the Athabasca River near Fort McMurray. The general weather tendency will be discussed first. This method analyzed the breakup variables based on daily air temperatures and solar radiation. Histograms are presented after describing graphically lower and higher threshold limits, as was done by Shulyakovskii (1963).

4.3.1.1 General Weather Tendency

This section will first present the breakup variables based on daily air temperatures. The solar radiation factors will then be discussed. Finally, an attempt to find a relationship between the air temperature and the solar radiation is presented.

Variables Based on Daily Air Temperature

Different parameters were calculated based on the daily air temperatures to help determine the factors influencing breakup ice jam occurrence at Fort McMurray. First, the accumulated degree-days of thaw (ADDT) were determined since it has the potential to provide a measure of ice strength (Ashton, 1986). The ADDT were calculated starting with the first 5 consecutive days of above zero daily air temperatures and then summed up to the breakup date. In cases where such a commencement was followed by negative mean daily temperatures, the degree-days calculation was reinitiated if 5 or more below zero days occurred and if a value less than –10°C was also observed. This reinitiating procedure was used since it was considered that a few days of mean daily temperature below zero not exceeding –10°C will not affect significantly the melting process. Negative values were not deducted in obtaining the ADDT. Another parameter evaluated was the sum of degree-days accumulated in the 10 days prior to the breakup date (T_{10}). In this case, mean daily temperatures below zero were also deducted in the calculation. The last parameter established was the number of days prior to breakup with daily maximum temperature greater then zero (T_{max}) calculated from the ADDT starting date. Table 4.2 presents ADDT with the starting date, T_{10}, and T_{max} for the years of 1972 to 2001.

Over this period of record, the ADDT on the day of breakup varies from a minimum of 33.8 °C-days in 1979 to a maximum of 340.0 °C-days in 1980. As discussed previously, ADDT may be an indicator of the ice strength, with greater ADDT values possibly representing a weaker ice cover. Since, the occurrence of ice jams is directly influenced by the strength of the river ice, one would expect major ice jam events to be associated with strong ice. If ADDT is a good indicator, then this value should be small for highly dynamic breakups. In fact, a major ice jam was documented on the Athabasca River at Fort McMurray in 1979 (Doyle *et al.*, 1979) the year with the minimum ADDT. Unfortunately, the occurrence of ice jams near Fort McMurray is not that simple to predict. In 1977, the ADDT was equal to 214.9 representing a fairly high value. The peak water levels cause by the 1977 ice jam was about 1 m higher then the ones observed in 1979 (Doyle *et al.*, 1979).

Table 4.2 shows that the ADDT starting date varies from March 11th to April 22nd. A late starting date may resulted in the formation of an ice jam because the warmer temperatures started late which might cause a more sudden breakup thus more dynamic, but it was not necessarily the case. In 2000, the ADDT starting date was April 16th but no ice jam was observed. The values of T_{10} vary from 18.1 to 91.8°C. A low value of T_{10} might imply that the possibility of an ice jam occurrence is high since there is less heat to melt the ice. It was not always the case. In 1994, the value of T_{10} was equal to 19.8 and no ice jam was observed in the vicinity of Fort McMurray.

The range of T_{max} was between 5 to 38 days. Like T_{10}, lower values of T_{max} might be representative of high risk for an ice jam occurrence. For example, in 1997, a severe ice jam occurred in Fort McMurray. The T_{max} for that year was equal to 5 days. Nevertheless, a value of 5 days was also observed for the year of 1983 when no ice jam was documented in the studied reach.

In general, it appears that, on their own, the variables based on mean daily air temperature do not indicate the likelihood of occurrence of breakup ice jams at Fort

McMurray. As expected, other factors need to be studied in order to understand better the complexity of factors contributing to ice jam occurrence in this area.

Variables Based on Solar Radiation

As mentioned in section 4.2, two variables based on solar radiation were considered in this research: the accumulated daily average radiation flux from the start date of ADDT to breakup date (S); and the accumulated daily average radiation flux 4 days prior to breakup (S_4). Table 4.3 presents these data. No solar radiation data were available in March for the year of 1994. Therefore, only S_4 could be calculated for that year since the starting date of S was March 11th. In 2000, no solar radiation was available from April 3rd to the breakup date so the value of S and S_4 could not be calculated for that year.

It can be observed in Table 4.3 that the values of S varied between 730.4 to 5276.9 W/m^2. Lower values of S should be indicative of a stronger ice cover that has the potential to generate ice jams. However, the minimum value of 730.4 W/m^2 was observed in 1983 during which no ice jam was documented in the vicinity of Fort McMurray. The variable S_4 ranged from 317.1 to 789.5 W/m^2. Once again, the lowest value observed represents a year with no ice jam in the studied reach. It can be concluded from these results that alone solar radiation is not sufficient to provide an indication on the likelihood of ice jams at Fort McMurray.

Relationship between Air Temperature and Solar Radiation

This next step was carried out to identify if the daily air temperature and the solar radiation together are sufficient as an indicator of the breakup process in the studied reach. Figures 4.2, 4.3, and 4.4 present the hourly air temperature and the value of S for each year for which it is known that an ice jam occurred in the vicinity of Fort

McMurray. The last date on the plots represents the day following breakup. It can be observed from Figures 4.2, 4.3, and 4.4 that the air temperature was not following any particular pattern and no visible relationship between the air temperature and S was apparent for these ice jam years. The value of S for these 'event years' varied from 1000 to 3500 W/m^2 and in general, the accumulation of the solar energy (S) followed a fairly steady increase quite similar for each jam year.

Non-jam years were also examined; Figures 4.5, 4.6, and 4.7 graphically present these data. Once again, no relationship between the air temperature and S was noticeable, and the air temperature did not follow a particular pattern that would be indicative of expected thermal breakup. The slope of the accumulated solar radiation was fairly constant just as observed for the ice jam years. The values of S ranged from 500 to 5500 W/m^2; the lower range was actually smaller then the minimum observed for the ice jam years. This low value of 500 W/m^2 was calculated for the 1983 breakup during which an ice jam was documented upstream of the studied reach. A noticeable drop in the temperature on April 8th had reinitiated the start date for ADDT and S, resulting in a low total value of S for that year. Prior to this temperature drop, the mean daily air temperature was well above zero for a week and would have been reducing the ice strength. This illustrates the problems associated with using simple index indicators for breakup forecasting.

To investigate the significance of a possible relationship between the air temperature and the solar radiation, a linear regression was performed with ADDT and S (Figure 4.8). The ice jam years are evenly distributed around the linear regression line and no pattern, which could predict the likelihood of jams at Fort McMurray, is observed. The relationship between ADDT and S is weak (R^2 = 0.47). Ice jam years were also studied separately to see if the relation between ADDT and S would be stronger. The results are graphically presented in Figure 4.9. In Fact, the correlation was slightly worse than the one observed in Figure 4.8 (R^2 = 0.43).

Since it is believed that the heat input immediately prior to breakup greatly influences the breakup process at Fort McMurray, the relationship between T_{10} and S_4 was also examined in this section. As Figure 4.10 indicates, no relation exists between T_{10} and S_4 ($R^2 = 0.01$). The non-jam, unknown, and jam years are evenly distributed around the linear regression line and no threshold limits can be identified. The relationship between T_{10} and S_4 for only the ice jams years was also studied (Figure 4.11). Again no correlation was observed ($R^2 = 0.02$).

As expected, breakup at Fort McMurray cannot be predicted by only the air temperature or the solar radiation. Even when the variables were studied together they did not provide any indication on the likelihood of ice jam occurrence. Hydraulic factors have a great influence on spring breakup in the studied reach. Other meteorological variables like the snow pack in the basin are also important to consider since all of the variables are indirectly related and create the complex event of river ice breakup.

4.3.1.2 Histograms

This section presents the histograms established in this research to help identify lower and higher threshold limits for the variables likely to influence the breakup process at Fort McMurray. The meteorological factors are discussed first followed by the hydraulic variables.

In section 4.3, it was documented that the air temperature and the solar radiation do not provided an indication of the likelihood of ice jams near Fort McMurray. Here, an attempt was made to consider the cumulative heat input effects related to temperature and solar radiation, specifically, rather than considering a full energy budget (for which we did not have sufficient data). A linear heat transfer approach was taken. In essence, available cumulative heat energy input was determined by assuming that the temperature dependent terms in the energy budget could be approximated with a linear heat transfer approach. Thus the cumulative heat would be calculated as:

$$\phi = h(\Delta T) + S \quad [4.1]$$

where $\Delta T = T_{air} - T_{ice} \approx T_{air}$ during the melt period;

h = linear heat transfer coefficient in $W/m^2 \cdot °C$; and

S = incoming solar radiation.

A value of $h = 8\ W/m^2$ was used based on earlier investigators work. For example, Andres (1988) documented that the heat transfer coefficient between the air and the ice cover usually range from 5 to 20 $W/(m^2 \cdot °C)$ at Fort McMurray. Hicks *et al.* (1997) reported a value of 8 $W/(m^2 \cdot °C)$ in southern Northwest Territories. Similar values were also documented by Van Der Vinne (1995) for a small lake near Edmonton, Alberta. Since Fort McMurray is approximately located in between Edmonton and the northern limit of Alberta, a heat coefficient of 8 $W/(m^2 \cdot °C)$ appeared to be reasonable for this study. It should be remembered that this value is a constant and therefore the global pattern remains the same regardless of the actual value used.

The values for ADDT and S were summed in this research, to get an indication of the heat transfer starting with the first 5 consecutive days of above zero mean daily temperature up to the breakup date, and T_{10} and S_4 were added to give an indication of the energy received just before breakup. The result for the sum of ADDT and S is presented in Figure 4.12. No lower or higher threshold limit can be identified for the sum of ADDT and S since the jam years are once again evenly distributed in the histogram. Figure 4.13 graphically presents the total heat obtained from T_{10} and S_4. A greater number of ice jam years are noticeable for the lower values of the histogram implying that jams are likely to occur when the total heat prior to breakup is smaller, which suggests that a stronger ice cover has a higher risk for ice jam occurrence. However, since a considerable amount of jam years are observed for high values of total heat preceding breakup, no limits can be identified. The last meteorological factor studied was T_{max}, which is the number of days with maximum temperatures greater than 0°C prior to breakup calculated from the ADDT starting date. The result obtained for this variable is graphically presented in Figure 4.14. The T_{max} values are evenly distributed in the left and central part of the histogram. This pattern is once again not enough to determine limits in the likelihood of ice jams at Fort McMurray.

Figure 4.15 presents the histogram for the average snow water equivalent (SWE) in mm for March 1st. No threshold limit can be determined for this variable. Ice jam years are generally evenly distributed for the average SWE in early March except in the central section of the histogram where unknown events were more dominant. The results for the average SWE for April 1st are presented in Figure 4.16. Once again, no threshold limits are noticeable for this variable. Another meteorological factor studied was the antecedent soil moisture (Figure 4.17). An important amount of jam years are noticeable in the lower values of the antecedent soil moisture, but this pattern is still not enough to identify lower and higher threshold limits. Nevertheless, this observation suggests that low antecedent soil moisture, which is likely to indicate a low late fall discharge, may contribute to a low freeze-up water level that has the potential to increase moderate ice jam occurrence.

It should be mentioned before discussing the hydraulic factors that some of the histograms have the symbol "^" on top of certain columns. This represents values that were observed when the Water Survey Canada (WSC) gauge below Fort McMurray was malfunctioning and is likely to be underestimating the real values.

The first hydraulic variable considered in this section is the freeze-up water level (H_F). Figure 4.18 presents these data. The ice jam values are evenly distributed and therefore, no threshold limits can be identified. A similar situation is observed in Figure 4.19 graphically representing the pre freeze-up water level (H_{Fo}). The difference between H_F and H_{Fo} was also studied (Figure 4.20). No threshold limits are noticeable for this variable. Figure 4.21 presents the river ice thickness prior to breakup (h_i), which shows an important amount of jam years for greater h_i values, though this pattern is not significant enough to identify a lower and a higher threshold limit. It should be noticed in Figure 4.21 that the 1973 reading is significantly greater than the rest of the record. Sadly, no documentation of spring breakup was available to classify the 1973 event. The stage immediately before breakup (H_{Bo}) is graphically shown in Figure 4.22. No pattern can be identified for this variable though 5 out of 8 ice jam years are located in the upper scale of the histogram. Figure 4.23 presents the fairly steady increase in water level preceding breakup ($\Delta H/\Delta t$). Once again, the jam years are evenly distributed so no limits can be identified.

The H_B result representing the maximum stage measured at the WSC gauge below Fort McMurray is showed in Figure 4.24. As expected, a great amount of jam years result in high water level, meanwhile in 1994 a fairly important stage was documented during an uneventful breakup. This stage might have been produced by the release of an ice jam upstream of Fort McMurray, which did not stall in the studied reached. The 1982 ice jam event corresponds to a fairly low water level. As indicated in Figure 4.24, the gauge was malfunctioning during breakup therefore the maximum stage was not measured. Another explanation for this low value is the fact that the 1982 jam formed between the MacEwan Bridge and the Clearwater River confluence, thus not affecting significantly the stage at the WSC gauge. Although the H_B result is promising, a lower and a higher threshold limits delimitating the likelihood of ice jams could not be determined with great confidence. This is more a factor of the gauge location than anything else.

Figure 4.25 graphically presents the maximum water level at the Clearwater River confluence ($H_{B,\ Clearwater}$). The ice jam years also resulted in high water level at the Clearwater River confluence. The uneventful 1974 breakup generated a very high water level even though no ice jam was documented that year. Yaremko (1974) described that an important ice run on the Athabasca River had pushed the Athabasca River ice into the Clearwater River confluence blocking the water passage and flooding Fort McMurray along the Clearwater River during the 1974 spring breakup. Yaremko (1974) believes that the ice run was generated by the release of an ice jam upstream of the city. Another observation noticed in Figure 4.25 is the location of the 1985 and 1983 non-jam years in between ice jams events. During those two years, ice jams were documented upstream of the studied reach. The maximum water levels were observed after the jams had released. It should also be mentioned that the 1978 and 1982 ice jams were located upstream of the Clearwater River confluence resulting in lower maximum stage observed for these years.

Because of the complexity of river ice breakup at Fort McMurray just previously discussed, threshold limits were not evident for the $H_{B,\ Clearwater}$ variable.

The result obtained for the difference between H_B and H_F is shown in Figure 4.26. The values are evenly distributed in the central and right section of the histogram thus no threshold limits could be identified. It should be mentioned that the difference between H_B and H_F for the 1989 and 1993 spring breakups was smaller than zero and therefore were not shown in Figure 4.26.

Figure 4.27 presents the result for the difference between $H_{B,\ Clearwater}$ and H_F. Seven out of eight jam years are located at the upper scale of the histogram. The only jam year in the lower scale is the 1978 breakup during which an ice jam formed upstream of the Clearwater River confluence resulting in a lower stage then the rest of the jam events. However an uneventful year is associated with high water level during breakup (spring 1974). Once again, threshold limits could not be identified to predict the occurrence of ice jams in the studied reach.

It was observed in this section that simple threshold models do not provide limits to the likelihood of ice jams at Fort McMurray. This section confirms that the factors involved in ice jams formation are very complex and it is not fruitful to consider them individually. The next logical step would be to consider all variables together. Some researchers (e.g. Wuebben *et al.*, 1995) have had some success considering multi-variable threshold models. However, since lower and higher threshold limits could not be identified for any of the studied variables, the complex threshold models could not be studied.

4.4 REGRESSION MODELS FOR BREAKUP FORECASTING

The role of a regression is to determine the relationship between one or several independent variables and a dependent variable. A dependent variable represents what you want to be able to predict in a forecasting context (e.g. H_{Bo}, H_B, $H_{B, Clearwater}$, $H_B - H_F$, $H_{B, Clearwater} - H_F$) while the independent variable represents measurable hydrometeorological variables that are considered to be contributing factors in terms of the likelihood of ice jam occurrence. A linear regression analyzes the linear relationship between one independent variable and one dependent variable, while a multiple linear regression studies the linear correlation between several independent variables and one dependent variable. The parameters used to evaluate the correlation between the variables are the coefficient of determination (R^2) for the linear regression and the adjusted coefficient of determination (Adj R^2) for the multiple linear regressions. As mentioned previously, Dillon and Goldstein (1984) recommend using Adj R^2 for multiple linear regressions instead of R^2 since R^2 does not consider the number of independent variables used in the calculations. Adj R^2 is also a more conservative indicator of the relationship between variables.

Values of R^2 and Adj R^2 close to 1 represent a good relationship between independent and dependent variables (SPSS Science, 1997). All the multiple linear regressions performed in this research were done with the software SigmaStat which is produced by SPSS Science. This section will first present the linear regressions and will follow with the multiple linear regressions established during this research.

4.4.1 Linear Regressions

The first independent variables studied were the average SWE for March 1st and April 1st. Figures 4.28 and 4.29 graphically present the correlation between H_{Bo} and the average SWE during early March and April. It can be observed in Figures 4.28 and 4.29 that the average SWE does not provide an indication on the value of H_{Bo}. No pattern for the jam and non-jam years is noticeable either in Figure 4.28 or 4.29.

The average SWE for March 1st and April 1st were also studied as possible indicators for with H_B and $H_{B, Clearwater}$. The results for H_B are presented in Figures 4.30

and 4.31, for March 1st and April 1st, respectively. These figures show that the average SWE for March and April cannot be used to predict H_B. No patterns for jam or non-jam years are observed in Figures 4.30 and 4.31. Figures 4.32 and 4.33 present the $H_{B, Clearwater}$ results. Again, no relationship is apparent.

The values of $H_B - H_F$ and $H_{B, Clearwater} - H_F$ were also studied as possible functions of the average SWE for March 1st and April 1st. Figure 4.34 shows the results for $H_B - H_F$ versus the average SWE at the beginning of March while Figure 4.35 presents the results for $H_B - H_F$ as a possible function of the average SWE in early April. The data is quite scattered in Figures 4.34 and 4.35, thus no correlation is observed. The jam and non-jam years are evenly distributed in Figures 4.34 and 4.35. The linear regressions between $H_{B, Clearwater} - H_F$ and the average SWE for March 1st and April 1st are graphically presented in Figures 4.36 and 4.37. Once again, the data are very scattered in both figures; therefore the correlation between the variables is poor. No significant patterns for the jam and non-jam years are observed.

The variable H_F was analyzed next as the independent variable. Figure 4.38 presents H_B versus H_F. A poor correlation can be deducted from Figure 4.38, and no patterns are noticeable for the jam and non-jam years. It should be mentioned that the average H_F value is 238.9 m over 28 years while the standard deviation is equal to 0.5 m. This minimal variation in the value of H_F may explain why H_F does not provide an indication on the likelihood of ice jams at Fort McMurray.

The linear regression between $H_{B, Clearwater}$ and H_F was also studied in this research and the result is shown in Figure 4.39. The values are scattered and no relationship is apparent from Figure 4.39. The jam and non-jam years do not indicate any pattern. The values of $H_{B, Clearwater}$ are greater than the ones observed for H_B (refer to Figures 4.38 and 4.39). This can be partially explained by the fact that the WSC gauge below Fort McMurray is generally malfunctioning during breakup, thus the maximum water level is not typically measured. Meanwhile, the water level at the Clearwater River confluence is manually measured during river ice breakup so extreme water levels have been documented. The location of an ice jam also influences the water level. If the toe of an ice jam is located in between the WSC gauge and the Clearwater River confluence, the gauge will not measured a water level as high as the one observed at the confluence.

Since h_i provides an indication on how much river ice is available to generate an ice jam, this factor was also studied as an independent variable. The first relationship investigated was the difference in water level between breakup and freeze-up at the WSC gauge ($H_B - H_F$) versus h_i. Figure 4.40 graphically presents the result, which shows that no correlation between the variables is apparent and that the jam and non-jam years do not follow any specific patterns. It should be mentioned that the average h_i over 29 years is equal to 0.78 m while the standard deviation is 0.21 m. A large amount of river ice is typically available at the end of the winter to generate ice jams on the Athabasca River. Therefore, studying only h_i does not provide any indication on the likelihood of ice jams at Fort McMurray. To verify this statement, the difference between the breakup stage at the Clearwater River confluence and the freeze-up stage at the WSC gauge ($H_{B,\ Clearwater} - H_F$) was also studied in function of h_i. It can be seen in Figure 4.41 that once again h_i does not provided any pattern between jam and non-jam years, and no correlation is apparent between the two variables.

The last independent variable analyzed in this section is H_{Bo}, which is the water level prior to breakup. The first relationship studied was H_B versus H_{Bo}. Figure 4.42 graphically shows that no apparent relationship exists between H_{Bo} and H_B. It can also be observed in Figure 4.42 that the jam and non-jam years are evenly distributed therefore no patterns of the likelihood of ice jams at Fort McMurray are indicated. The H_{Bo} values do not vary significantly over the year as shown in Figure 4.42. In fact, the average H_{Bo} value over 26 years is equal to 238.8 m while the standard deviation is 0.4 m. The fact that H_{Bo} remains fairly constant over the years may explain why it does not provided any indices on ice jams formation at Fort McMurray. To verify this statement, the relationship between H_{Bo} and $H_{B,\ Clearwater}$ was also studied. Figure 4.43 graphically shows that no strong correlation exists between H_{Bo} and $H_{B,\ Clearwater}$ and that these two variables do not give an indication of the jam and non-jam years.

None of the correlations examined in this research provided a good relationship between the variables studied. When the results were graphically presented it was obvious that no patterns for the jam and non-jam years was present. Therefore, it appears that the formation of ice jams at Fort McMurray is very complex and that all the variables studied in this research should be analyzed in combination in order to identify which interaction between the studied variables could indicate the likelihood of jams at Fort McMurray.

4.4.2 Multiple Linear Regressions

The following dependent variables were studied in this section: H_{Bo}, $\Delta H/\Delta t$, H_B, $H_{B,\ Clearwater}$, $H_B - H_F$, $H_{B,\ Clearwater} - H_F$, and t_B. The symbol t_B represents the breakup date in Julian days. The independent variables used to calculate the multiple linear regressions are the average SWE for March 1st and April 1st, antecedent soil moisture, $\Delta H/\Delta t$, H_F, h_i, ADDT, S, T_{10} and S_4. Since S and S_4 both represent the solar radiation, they were used separately in the multiple regressions. The same scenario was applied for ADDT and T_{10} because they represent the cumulative heating effects related to air temperature. In other words, ADDT and S were used to determine the relationship between the studied variables or T_{10} and S_4. It should also be mentioned that the variable $\Delta H/\Delta t$ was used as both an independent and a dependent variable in this study since $\Delta H/\Delta t$ is a breakup variable but it also has the potential to predict other breakup variables since it is the first breakup value observed during spring. Obviously, when $\Delta H/\Delta t$ was studied as an independent variable, it was not used as a dependent variable.

As mentioned previously, the Adj R^2 was used to assess the significance of the relationship between variables. An Adj R^2 close to 1 indicates that a good relationship exists between the independent and dependent variables. In order to find the relation with the greatest Adj R^2 value, all of the independent variables were first studied for each dependent variable. One by one, the independent variables were eliminated by checking the output P that represents the probability of being wrong in concluding that there is a true association between the variables. An independent variable with a high P is not correlated to the dependant variable and was therefore eliminated from the multiple linear regression.

Table 4.4 presents the results obtained for all of the dependent variables analyzed in this section. As expected, the dependent variable t_B had the worst correlation with an Adj R^2 of only 0.28. The timing of breakup is one of the events that researchers have been studying for years, but no one to date can predict this factor with certitude. The variable $\Delta H/\Delta t$ also resulted in a low Adj R^2 of 0.49. Meanwhile, Table 4.4 shows that a very good correlation was obtained for $H_{B,\ Clearwater}$ and $H_{B,\ Clearwater} - H_F$ with an Adj R^2 equal to 0.95 and 0.93 respectively. Seven dependent variables were significant for $H_{B,\ Clearwater}$ while eight variables were significant for $H_{B,\ Clearwater} - H_F$. These observations confirm that river ice breakup is a very complex phenomenon and that a lot of factors interact together during such events. The fact that $H_{B,\ Clearwater}$ and $H_{B,\ Clearwater} - H_F$ generated a better correlation then H_B and $H_B - H_F$ likely reflects the incomplete nature of the WSC gauge record since it was typically malfunctioning and therefore the maximum water level is likely underestimated for those years. Table 4.4 also presents the result obtained for H_{Bo}. A value of 0.67 was calculated for the Adj R^2 representing a fairly good correlation with the dependent variables. Another observation from Table 4.4 is that the energy in the form of S appears to be a significant factor for H_B and $H_B - H_F$ while T_{10} and S_4 were important for $H_{B,\ Clearwater}$ and $H_{B,\ Clearwater} - H_F$. Appendix D1 presents details of the multiple linear regression results for breakup forecasting at Fort McMurray.

In order to graphically present all the multiple linear regressions performed in this study, the actual dependent variables were plotted against the corresponding modeled dependent variables. Figure 4.44 presents the results for H_{Bo}. With this model, the value of H_{Bo} could be estimated within $\pm$ 0.5 m. This error may be considered fairly small in terms of the accuracy with which we can measure ice jams; however it is actually large since H_{Bo} values varied only over a 2.0 m range over the record period. The $\Delta H/\Delta t$ result is graphically shown in Figure 4.45. The majority of the $\Delta H/\Delta t$ values are located in the lower scale of Figure 4.45. Only 3 points have an $\Delta H/\Delta t$ value greater than 0.2 m/day, two of which represent ice jams events while the other is from a non ice jam year. Intuitively, a high $\Delta H/\Delta t$ value would be expected to indicate a potential for ice jam events, since a sudden increase in stage has the potential to lift and fracture the ice cover. Based on Figure 4.45, we can conclude that other factors are involved.

The modeled versus actual H_B values are presented in Figure 4.46. The greatest values observed in Figure 4.46 are ice jam events. This model provides the ability to predict H_B within ± 2.0 m, which is significant since the data range was around 6.0 m over the period of record. Figure 4.47 graphically presents the $H_{B,\ Clearwater}$ result. Five water levels were used to verify the $H_{B,\ Clearwater}$ model (1974, 1981, 1992, 1994 and 1996). These values were not included in the regression analysis since they were only received after the calculation was done (Alberta Environment provided these water levels, which were retrieved from old archives not accessible to the public). It can be observed in Figure 4.47 that the values used to model $H_{B,\ Clearwater}$ provide a very good correlation, in fact, this model can predict $H_{B,\ Clearwater}$ with an error of ± 0.5 m, which is very good considering the data is distributed over an 8.0 m range. Unfortunately, three out of the five values used to verify the model do not agree with the preceding result. An approximate ± 3.0 m error is observed for the 1974, 1994 and 1996 breakup years.

Figure 4.48 graphically presents the $H_B - H_F$ result. This model could provide an estimate of the $H_B - H_F$ value with a ± 1.5 m error. Considering that the studied data only vary by 6.0 m, the error related to the H_B - H_F model is still significant. The $H_{B,\ Clearwater}$ - H_F result is presented in Figure 4.49. As demonstrated in Table 4.4, a very good correlation was obtained with the $H_{B,\ Clearwater}$ - H_F model. In fact, the value of $H_{B,\ Clearwater}$ - H_F can be predicted with a ± 0.5 m error, which is very good for an 8.0 m data range. Unfortunately, again, the values used to validate the model do not agree well, with three out of five having an error in the order of ± 3.0 m.

Since the values used to verify the $H_{B,\ Clearwater}$ and $H_{B,\ Clearwater}$ - H_F models did not support the results obtained, the multiple linear regressions were redone with all the available data. Table 4.5 shows that the best correlation available for $H_{B,\ Clearwater}$ resulted with an Adj R^2 of 0.80. This value is significantly less then the Adj R^2 of 0.95 obtained previously in Table 4.4. The same result was obtained with $H_{B,\ Clearwater}$ - H_F. The updated Adj R^2 is equal to 0.74 while the previous value was 0.93. Appendix D2 presents details of the updated multiple linear regression results of $H_{B,\ Clearwater}$ and $H_{B,\ Clearwater}$ - H_F. Figure 4.50 graphically presents the $H_{B,\ Clearwater}$ result. The values are evenly distributed around the 45° line, but they are further away from the 45° line than observed in Figure 4.47. Therefore, the error in estimating $H_{B,\ Clearwater}$ is greater. An error of ± 1.5 m can be expected when using the update $H_{B,\ Clearwater}$ model. Figure 4.51 graphically presents the updated $H_{B,\ Clearwater}$ - H_F result. As expected, the values are further away from the 45° line then what was observed in Figure 4.49. A maximum error of ± 1.5 m can occur when predicting $H_{B,\ Clearwater}$ - H_F.

The t_B result is shown in Figure 4.52. The actual and modeled t_B values are well distributed but fairly far from the 45° line explaining why the Adj R^2 value was so low. This t_B model could predict the breakup date with a ± 7 days error. Consequently, this model is not useful to predict the timing of breakup at Fort McMurray because it provides an interval of 14 days in which breakup could occur. If a very high water level would be predicted with the updated $H_{B,\ Clearwater}$ model, a 14 day interval for the breakup date would not be useful for the City of Fort McMurray since after being on alert for a day or so the Fort McMurray residents would likely not take the situation seriously.

In general, it was demonstrated in this section that analyzing the studied variables together has a potential to determinate a reliable forecasting model of the river ice breakup at Fort McMurray. Although significant errors were obtained with the calculated models, a crude estimate of the breakup variables can be used to have an indication of the likelihood of ice jam related high water levels.

4.5 DISCUSSION OF RESULTS

Threshold and regression models are classified as empirical models, which are based on physical observations. Meanwhile, numerical models are based on computer programs that can simulate river ice regime. Although numerical models are very promising, they are not advanced enough to provide a complete picture of river ice breakup. In order to study breakup, a numerical model would have to consider the complete physics of flow, the mechanical properties of ice, and the deposition and transport of ice. It would also need to consider the geomorphology of the river. One of the fundamental ice jam characteristics not well understood to date is the process of ice shoving. When an ice jam is not strong enough to withstand the external forces applied by flow shear and gravity, the ice jam will collapse (Beltaos, 1995). This process is also called ice shoving. Numerical models may try to simulate this event, but no quantitative data are available to support their results. The lack of quantitative data currently stalls the advancement of knowledge in this field.

Threshold models were used in this research to identify the likelihood of ice jams at Fort McMurray. Simple threshold models were first investigated. A general weather tendency was studied with the daily air temperatures and the solar radiation measured at Fort McMurray. When these two variables were analyzed individually, they did not provide any indication on the occurrence of ice jams. An attempt to find a relationship between the daily air temperature and solar radiation was also done, but no significant correlations or ice jam patterns were obtained.

The next simple threshold model used in this research was the histograms. The goal of this method was to establish lower and higher threshold limits for the studied variables likely to influence the occurrence of ice jams at Fort McMurray. The meteorological factors that were analyzed in this section are the average SWE for March 1^{st} and April 1^{st}, the soil moisture, ADDT, S, T_{10}, S_4 and T_{max}. Since it was shown previously that the daily air temperature and the solar radiation do not provide an indication on the likelihood of ice jams at Fort McMurray, these two variables were combined in order to estimate the total heat input. The ADDT variable was added to S while T_{10} was summed with S_4. The following hydraulic variables were also studied in this section: H_F, H_{Fo}, $H_F - H_{Fo}$, h_i, H_{Bo}, $\Delta H/\Delta t$, H_B, $H_{B,\ Clearwater}$, $H_B - H_F$ and $H_{B,\ Clearwater} - H_F$. No lower or higher threshold limits could be identified for any of the studied variables. Therefore, no complex threshold models could be investigated.

Regression models were also investigated in this research in order to identify the relationship between one or several independent variables and a dependent variable. Linear regressions were studied first followed by the linear multiple regressions. The linear regressions calculated in this research did not provide any relationship between two investigated variables or patterns on the likelihood of ice jams. The best multiple linear regressions obtained during this research are presented in Table 4.4. Very good correlations were obtained for the dependent variables $H_{B,\ Clearwater}$ and $H_{B,\ Clearwater} - H_F$. When five breakup water levels were used to verify the $H_{B,\ Clearwater}$ and $H_{B,\ Clearwater} - H_F$ models, the results obtained did not validate the models. Therefore, the multiple regressions were recalculated with the complete records. Table 4.5 presents the updated $H_{B,\ Clearwater}$ and $H_{B,\ Clearwater} - H_F$ results. The Adj R^2 values obtained are significantly smaller than the ones observed previously but they are still acceptable.

Table 4.1 Lower and higher threshold limits and weighting factors in Wuebben *et al.* (1995) model used to determine the potential of ice jam on the Missouri River near Williston, North Dakota.

Variable	Lower Limit	Higher Limit	Weight
ADDF (°C)	< 927	> 1427	2
$ADDF_{max}$ (JD)	< 150	> 165	1
Q_{max} (JD)	< 155	> 170	1
Q_{max} (JD) - $ADDF_{max}$ (JD)	< -8 or > 10	> -5 or < 7	2
Q_b (m^3/s)	< 708 or > 2549	> 850 or < 1982	1
Lake elevation (m)	< 559	> 561	1
Total snowfall (cm)	< 51	> 102	2
Timing of snowfall	< 13 cm after JD = 90	> 25 cm after JD = 90 > 13 cm after JD = 120	1

Table 4.2 ADDT (°C-days) with the starting date, T_{10} (°C-days), and T_{max} (number of days) for the years of 1972 to 2001.

Year	ADDT (°C-days)	ADDT Starting Date	T_{10} (°C-days)	T_{max} (Number of Days)
1972	89.9	April 10th	21.0	12
1973	142.0	March 28th	44.3	21
1974	165.3	April 7th	66.1	12
1975	126.7	April 8th	53.9	17
1976	254.0	March 26th	91.8	18
1977	214.9	April 5th	69.7	9
1978	145.3	March 27th	20.4	20
1979	33.8	April 22nd	24.4	6
1980	340.0	March 27th	59.4	19
1981	102.3	April 19th	20.6	10
1982	115.0	April 10th	53.1	16
1983	122.2	April 13th	24.3	5
1984	279.6	March 19th	52.9	22
1985	174.5	March 11th	56.1	38
1986	156.3	March 26th	18.1	19
1987	216.5	March 30th	47.6	17
1988	135.0	April 9th	42.6	7
1989	102.5	April 10th	30.9	11
1990	134.6	March 27th	33.5	22
1991	205.7	March 29th	60.9	15
1992	146.1	April 13th	30.1	23
1993	198.4	March 20th	42.3	28
1994	204.1	March 11th	19.8	29
1995	116.6	April 9th	45.5	13
1996	108.4	April 4th	31.2	12
1997	110.5	April 15th	43.3	5
1998	252.6	March 22nd	57.5	18
1999	221.7	March 18th	34.0	27
2000	137.4	April 16th	56.2	7
2001	127.7	April 3rd	35.7	21

Table 4.3 S (W/m^2), and S_4 (W/m^2) for the years of 1972 to 2001.

Year	S (W/m^2)	S_4 (W/m^2)
1972	1834.4	593.4
1973	3580.7	763.8
1974	2079.2	789.5
1975	2762.6	604.8
1976	2878.3	652.1
1977	1419.7	586.2
1978	2598.2	423.0
1979	1039.5	619.2
1980	2770.8	477.4
1981	1297.9	563.3
1982	2313.2	607.7
1983	730.4	530.4
1984	2886.2	334.2
1985	5276.9	606.3
1986	3424.1	374.3
1987	2069.6	526.1
1988	1309.0	765.1
1989	2282.3	691.0
1990	3425.5	675.0
1991	2535.3	576.2
1992	2835.7	408.7
1993	3083.6	317.1
1994	-	760.9
1995	1420.4	656.4
1996	2265.9	717.4
1997	1233.0	798.8
1998	2890.4	653.1
1999	3963.4	670.4
2000	-	-
2001	3995.7	774.6

Table 4.4 Dependent and independent variables used in the multiple linear regressions and their correspondent Adj R^2 values.

Dependent Variable	Independent Variables	Adj R^2
H_{Bo}	Average SWE for March 1st and April 1st, antecedent soil moisture, $\Delta H/\Delta t$, H_F, h_i	0.67
H_B	S, average SWE for March 1st, antecedent soil moisture, $\Delta H/\Delta t$, H_F, h_i	0.63
$H_B - H_F$	S, average SWE for March 1st, antecedent soil moisture, $\Delta H/\Delta t$, h_i	0.62
$\Delta H/\Delta t$	S, average SWE for March 1st, H_F	0.49
t_B	ADDT, S, average SWE for March 1st and April 1st, h_i	0.28
$H_{B,\ Clearwater}$	T_{10}, S_4, average SWE for March 1st and April 1st, antecedent soil moisture, $\Delta H/\Delta t$, h_i	0.95
$H_{B,\ Clearwater} - H_F$	T_{10}, S_4, average SWE for March 1st and April 1st, antecedent soil moisture, $\Delta H/\Delta t$, h_i, H_F	0.93

Table 4.5 Dependent and independent variables used in the updated multiple linear regressions of $H_{B,\ Clearwater}$ and $H_{B,\ Clearwater} - H_F$, and their correspondent Adj R^2 values.

Dependent Variable	Independent Variables	Adj R^2
$H_{B,\ Clearwater}$	S, average SWE for March 1st and April 1st, antecedent soil moisture, $\Delta H/\Delta t$, h_i	0.80
$H_{B,\ Clearwater} - H_F$	S, average SWE for March 1st and April 1st, antecedent soil moisture, $\Delta H/\Delta t$, h_i, H_F	0.74

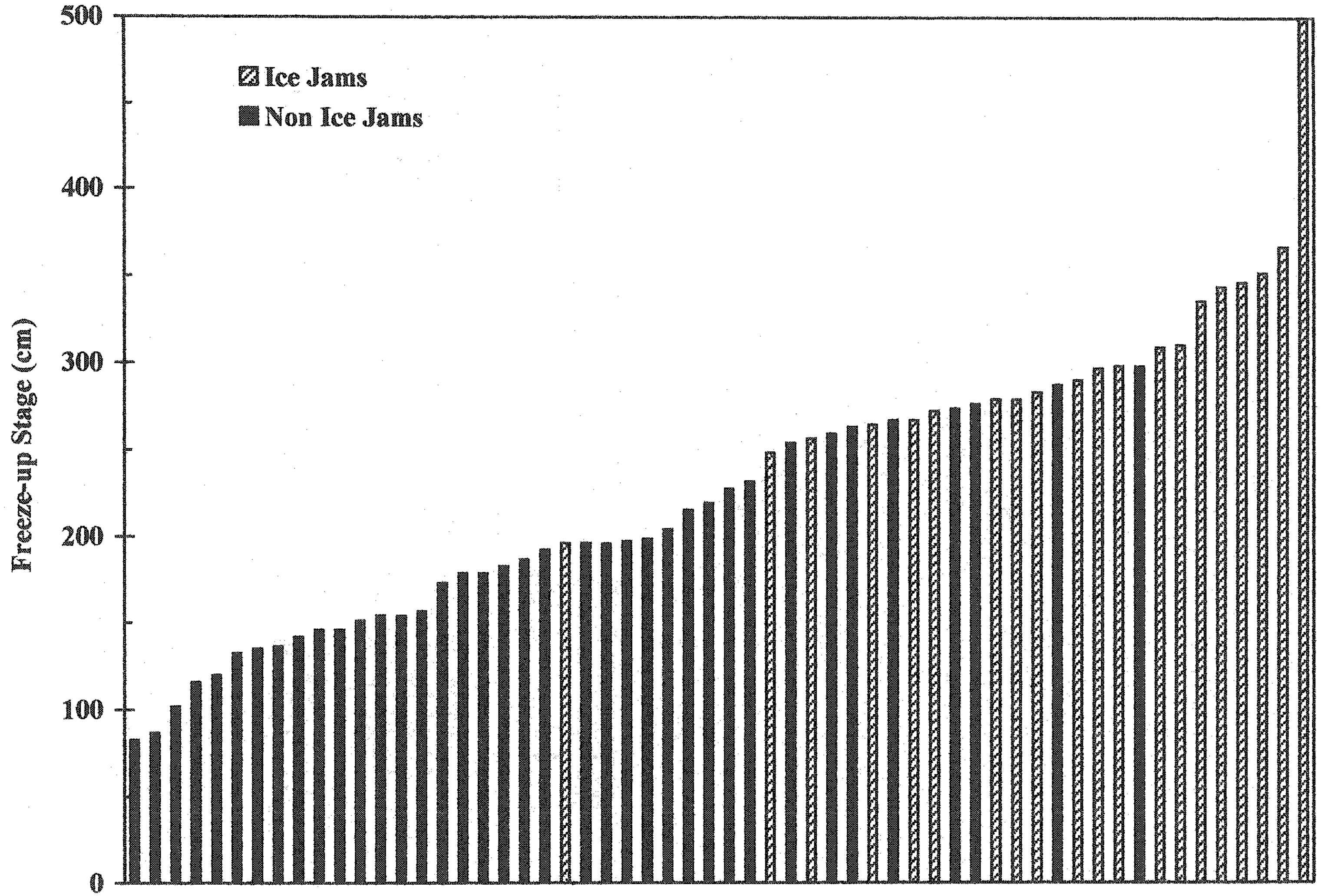

Figure 4.1 **Freeze-up water level during jam and no jam years on the Yenesei River near Krasnoyarsk, Eastern Siberia (after Shulyakovskii, 1963).**

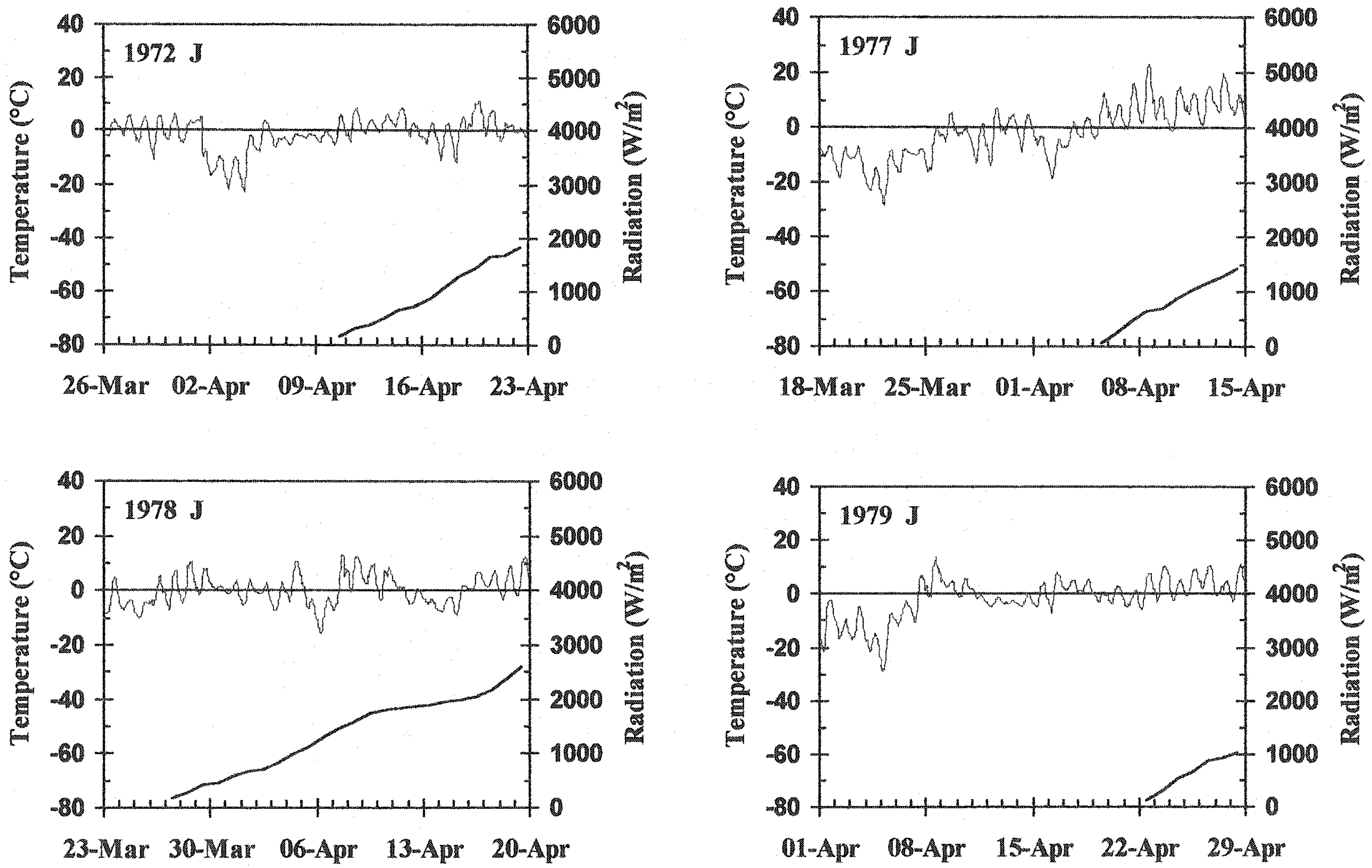

Figure 4.2 Air temperature (°C) and solar radiation (W/m^2) for spring 1972, 1977 to 1979 at Fort McMurray.

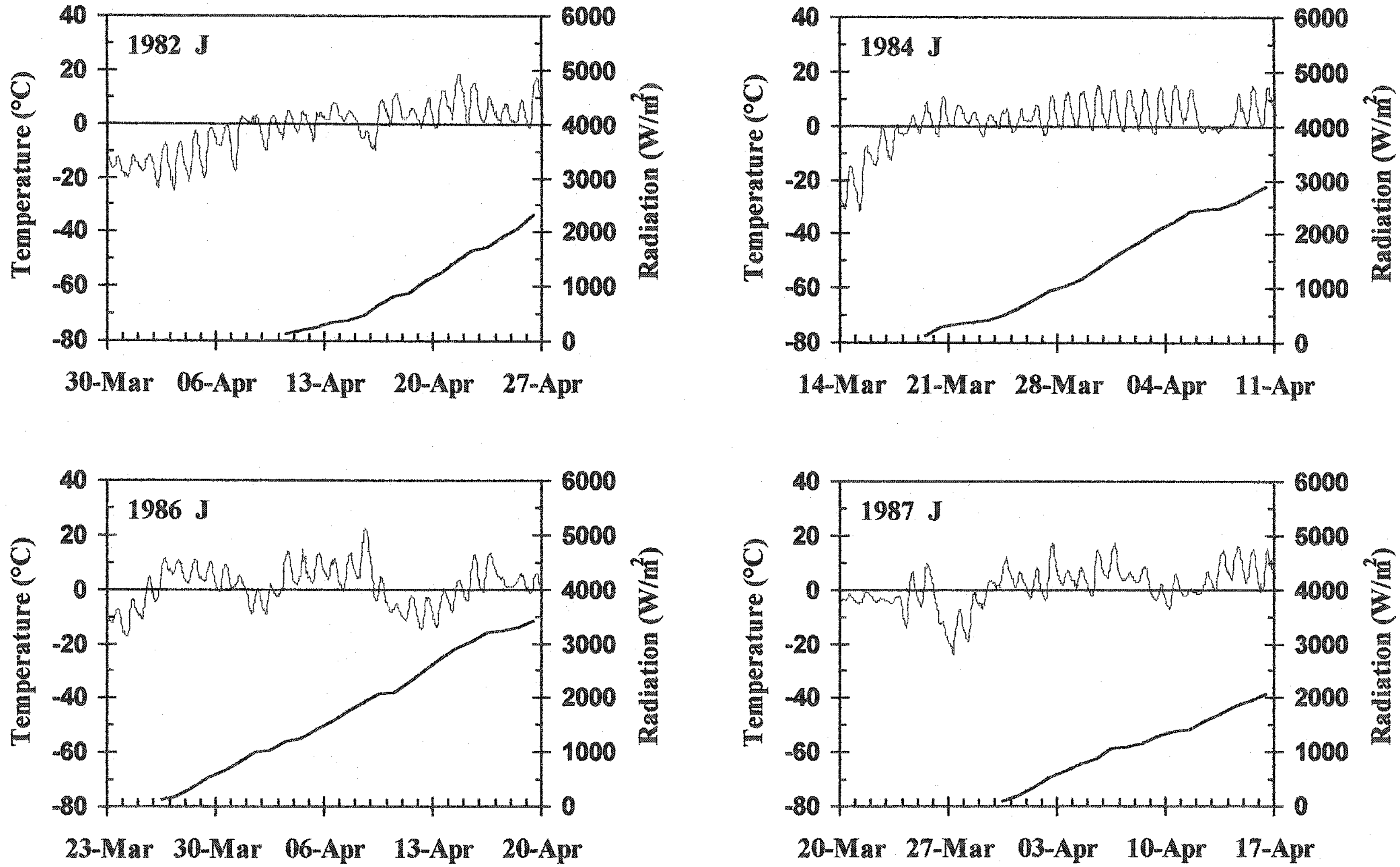

Figure 4.3 Air temperature (°C) and solar radiation (W/m²) for spring 1982, 1984, 1986, and 1987 at Fort McMurray.

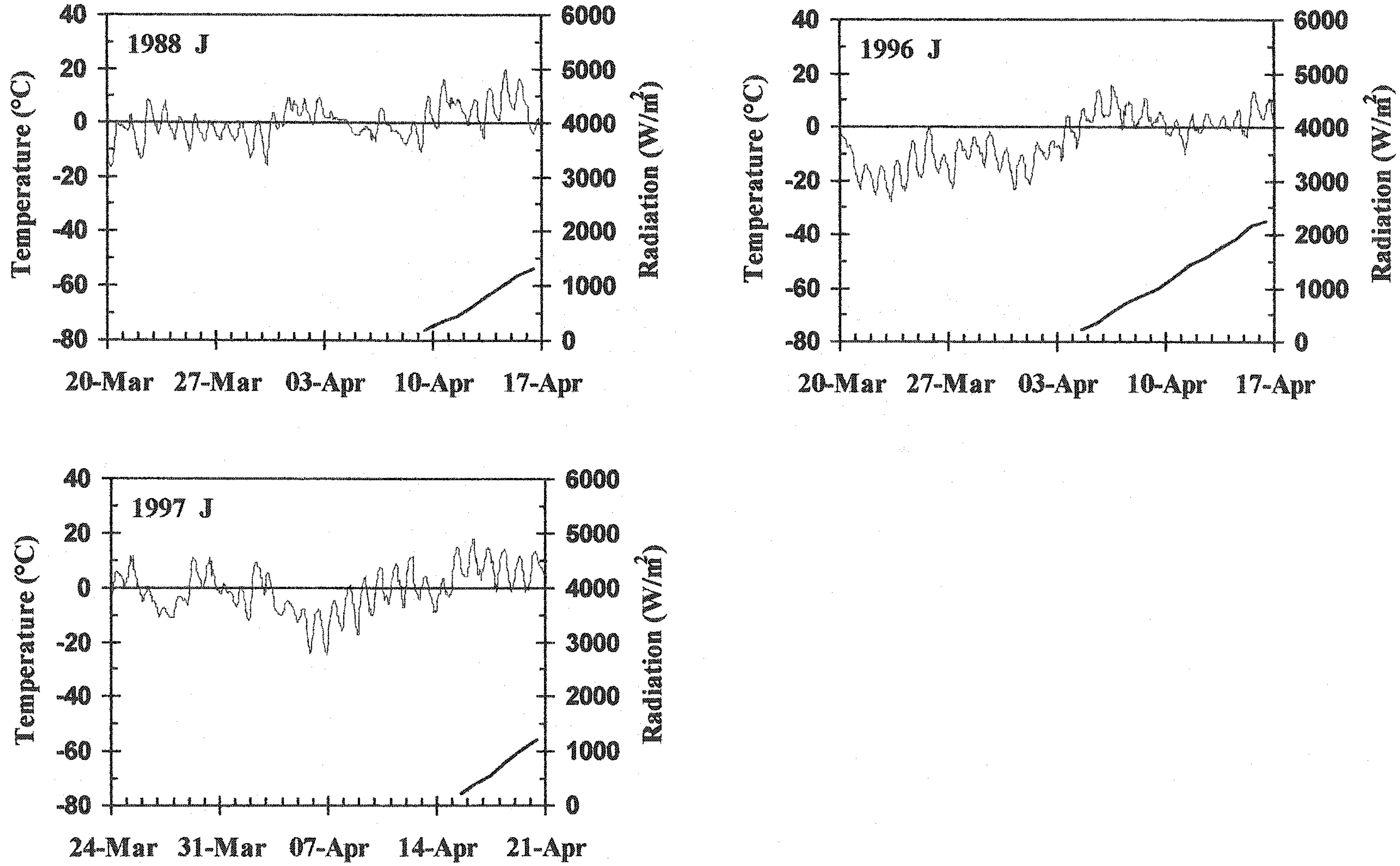

Figure 4.4 Air temperature (°C) and solar radiation (W/m^2) for spring 1988, 1996, and 1997 at Fort McMurray.

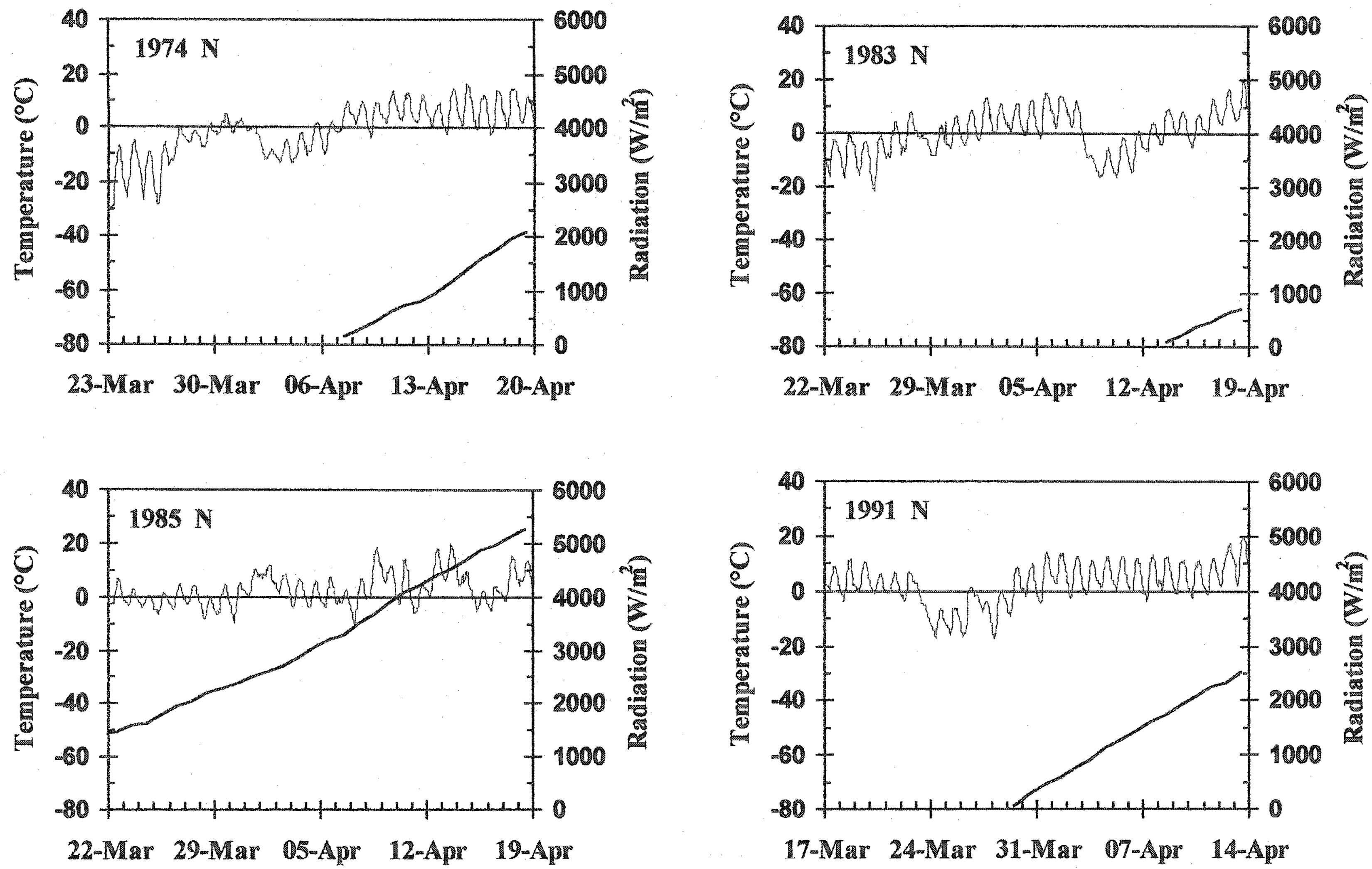

Figure 4.5 Air temperature (°C) and solar radiation (W/m^2) for spring 1974, 1983, 1985, and 1991 at Fort McMurray.

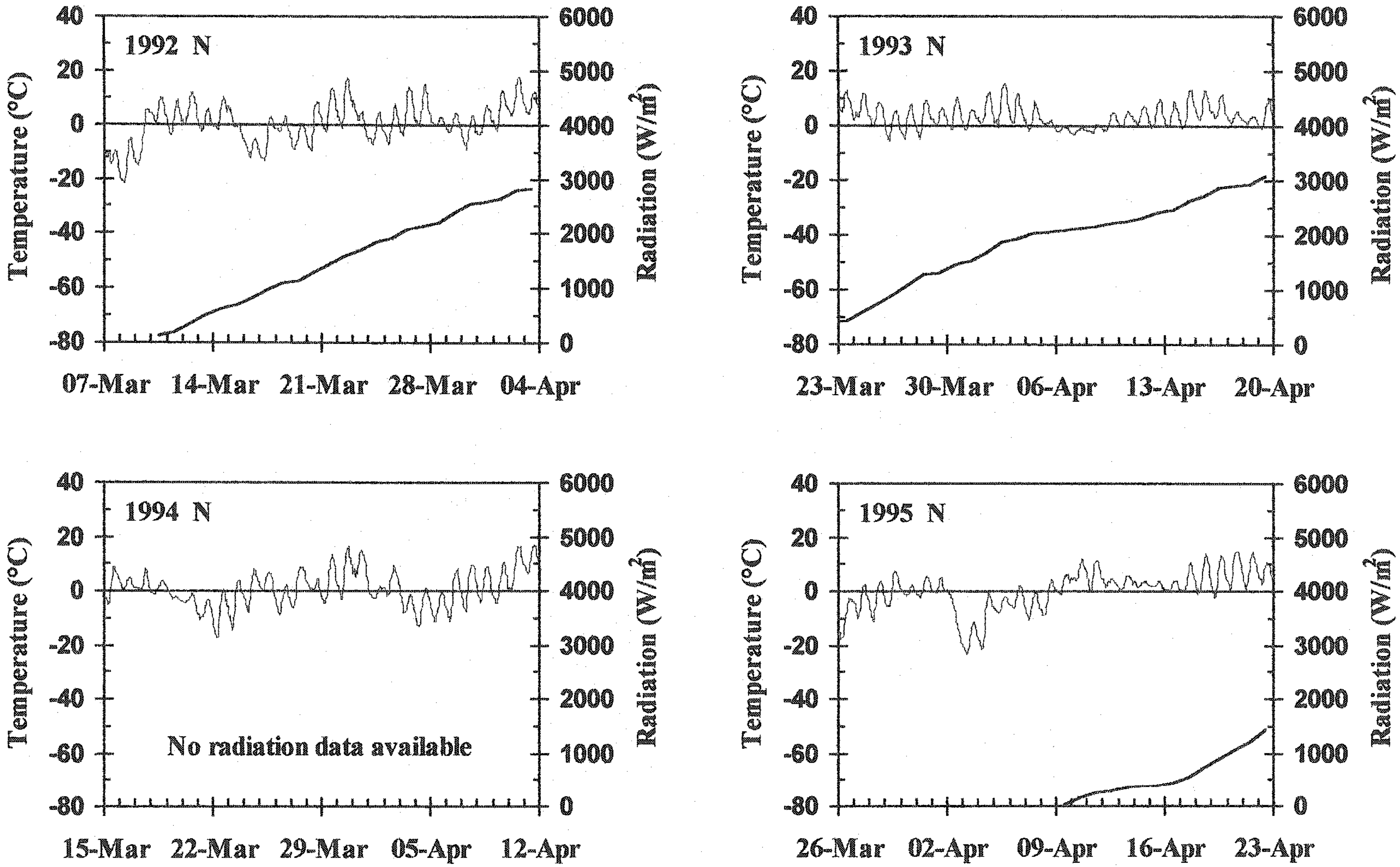

Figure 4.6 Air temperature (°C) and solar radiation (W/m^2) for spring 1992 to 1995 at Fort McMurray.

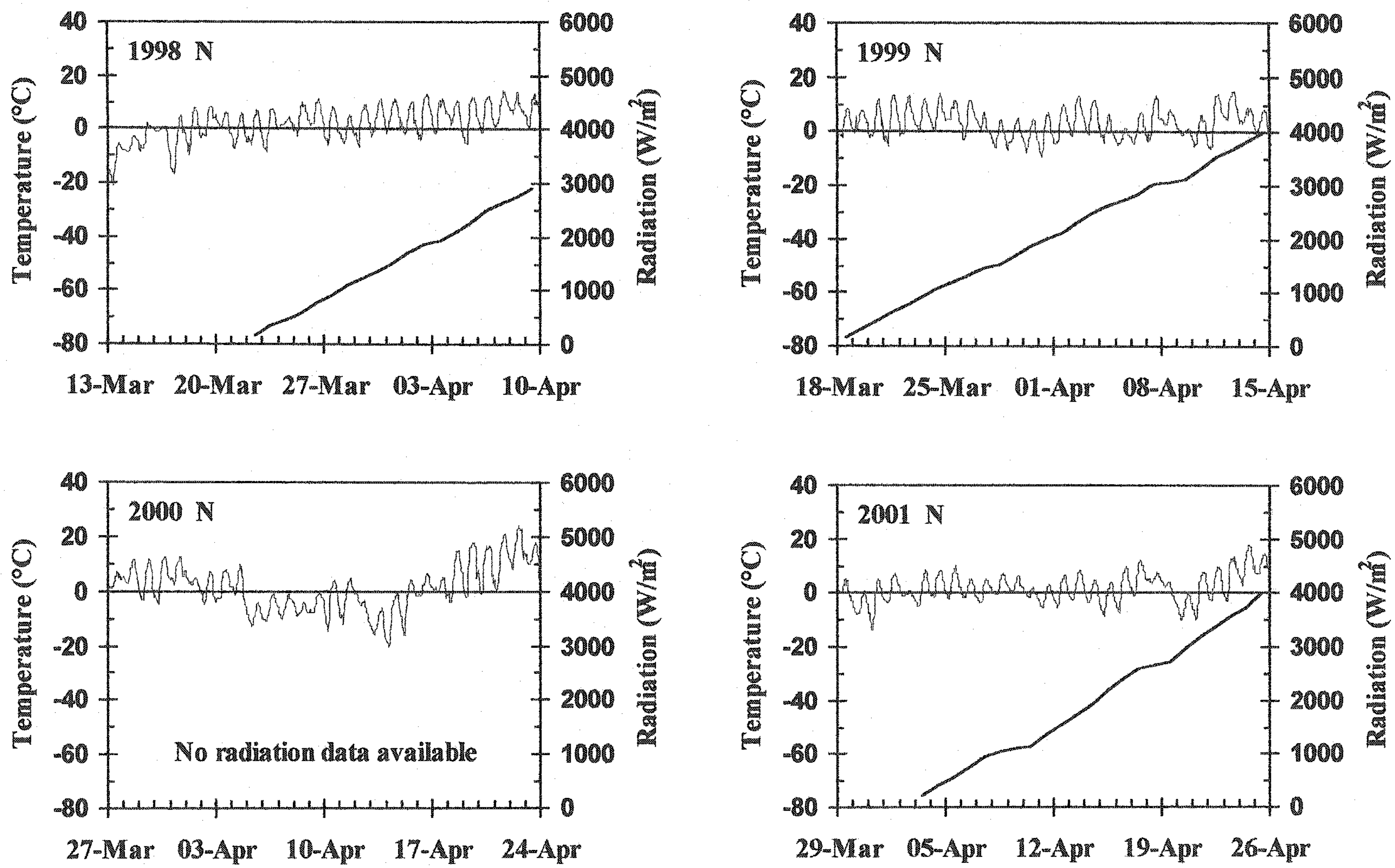

Figure 4.7 Air temperature (°C) and solar radiation (W/m²) for spring 1998 to 2001 at Fort McMurray.

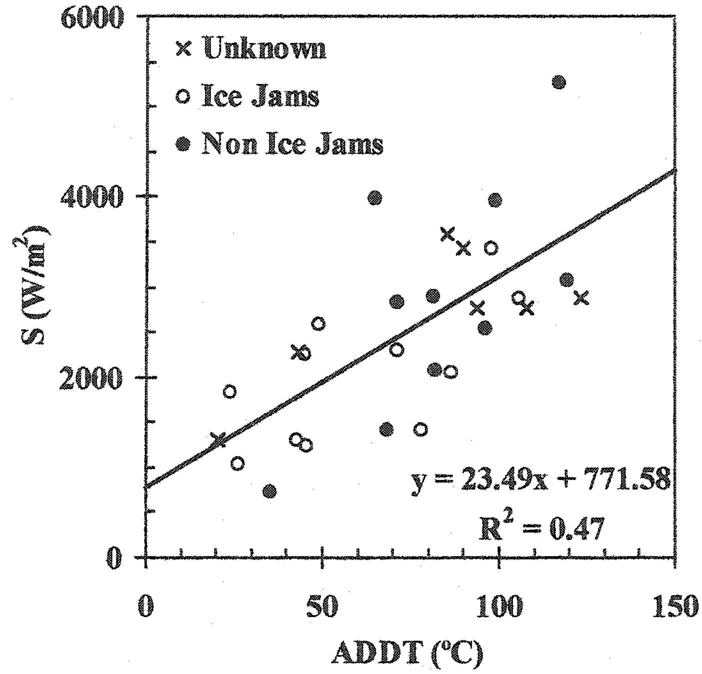

Figure 4.8 ADDT (°C) versus S (W/m^2) during jam, no jam and unknown years.

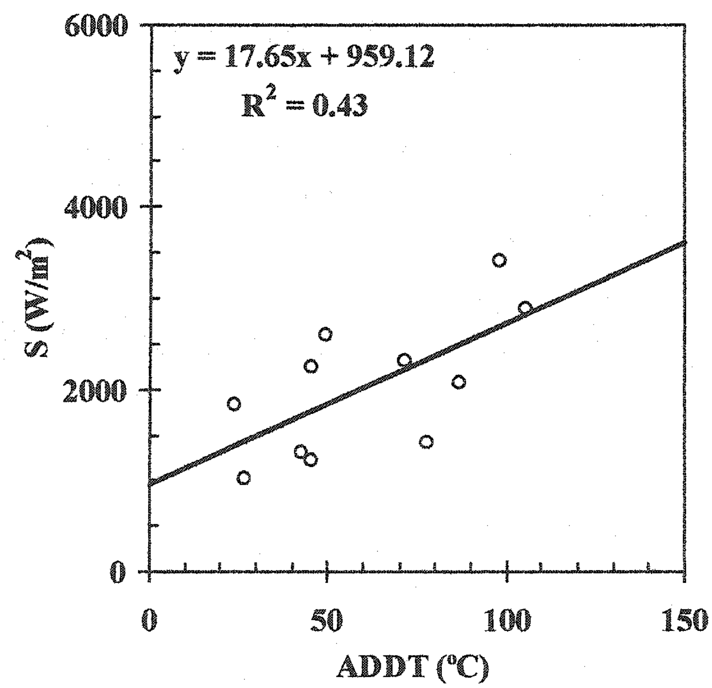

Figure 4.9 ADDT (°C) versus S (W/m^2) during ice jam years.

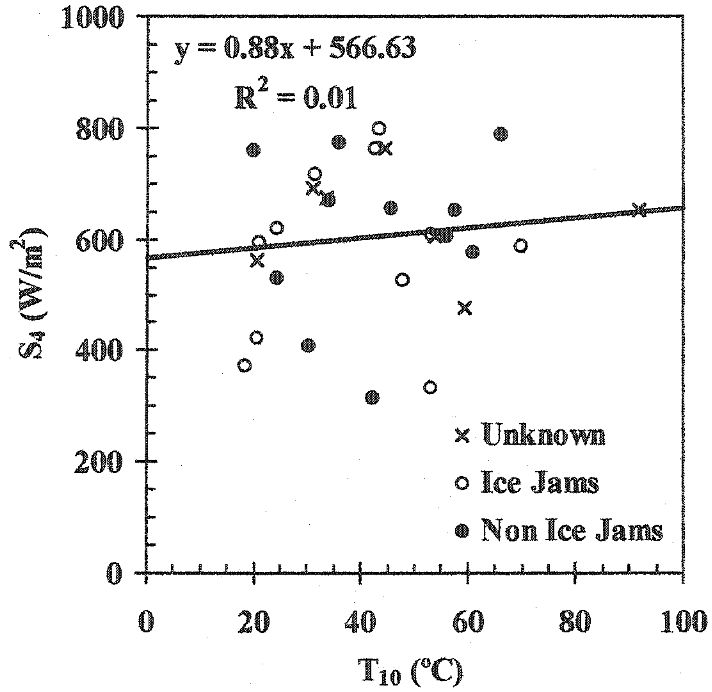

Figure 4.10 T_{10} (°C) versus S_4 (W/m^2) during jam, no jam and unknown years.

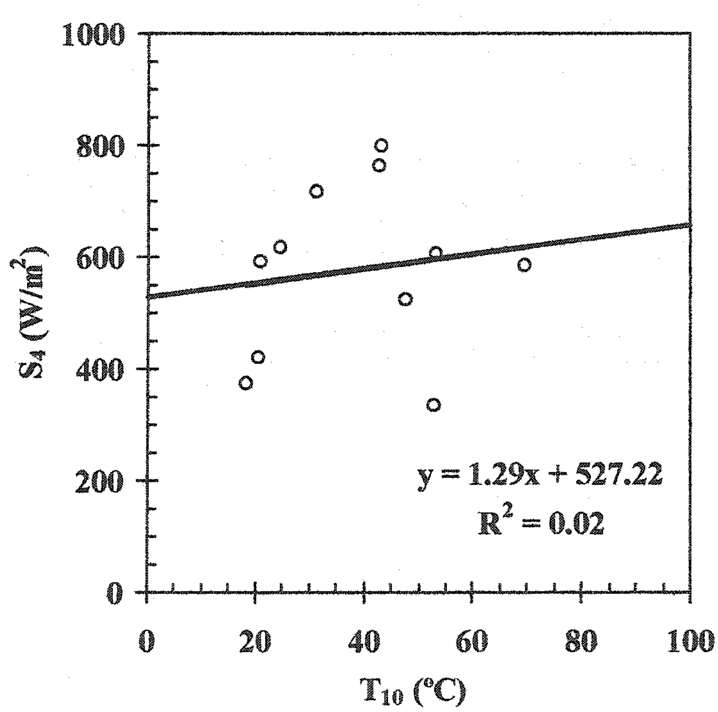

Figure 4.11 T_{10} (°C) versus S_4 (W/m^2) during ice jam years.

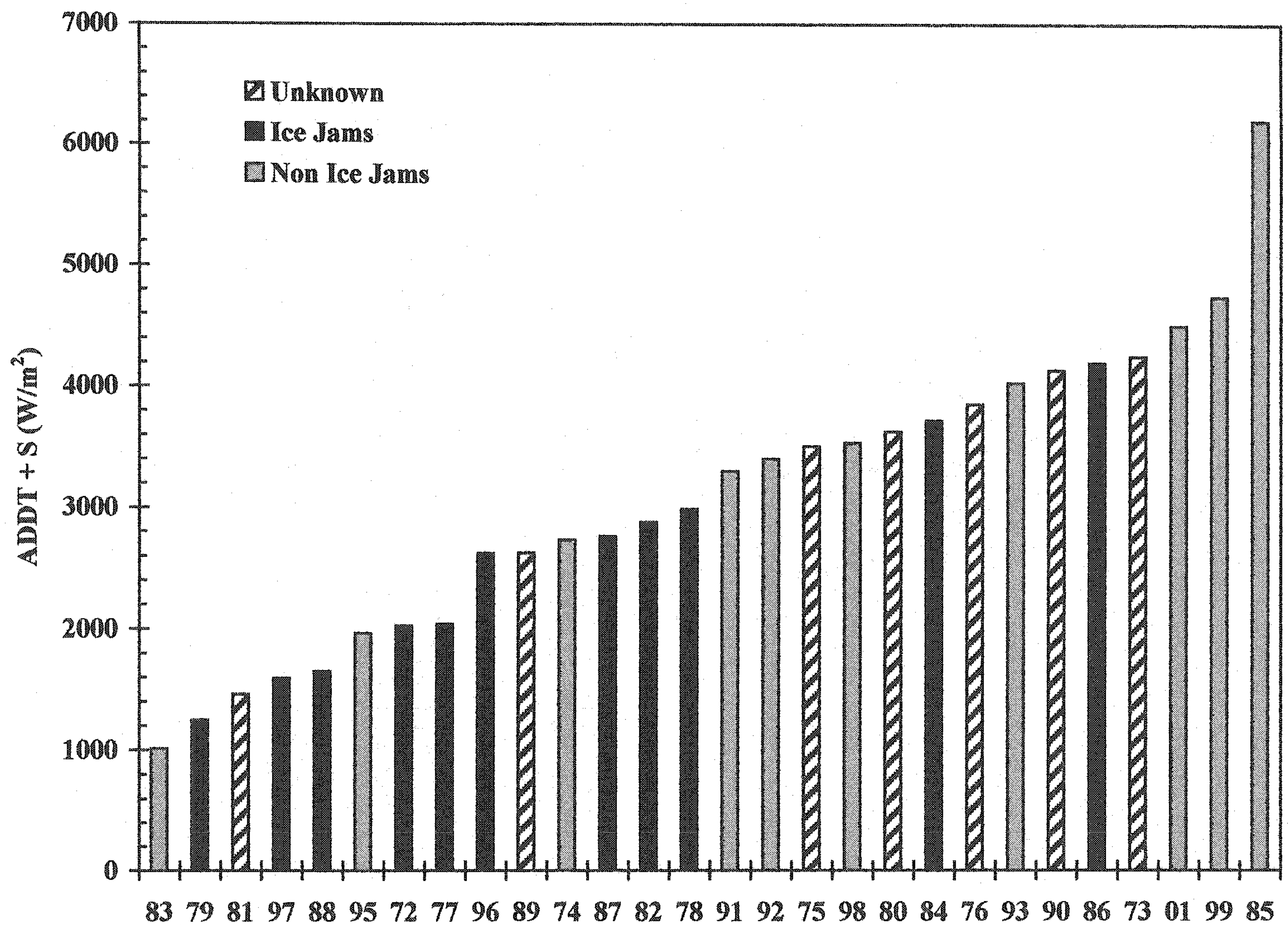

Figure 4.12 Total of ADDT (W/m^2) and S (W/m^2) during jam, no jam and unknown years.

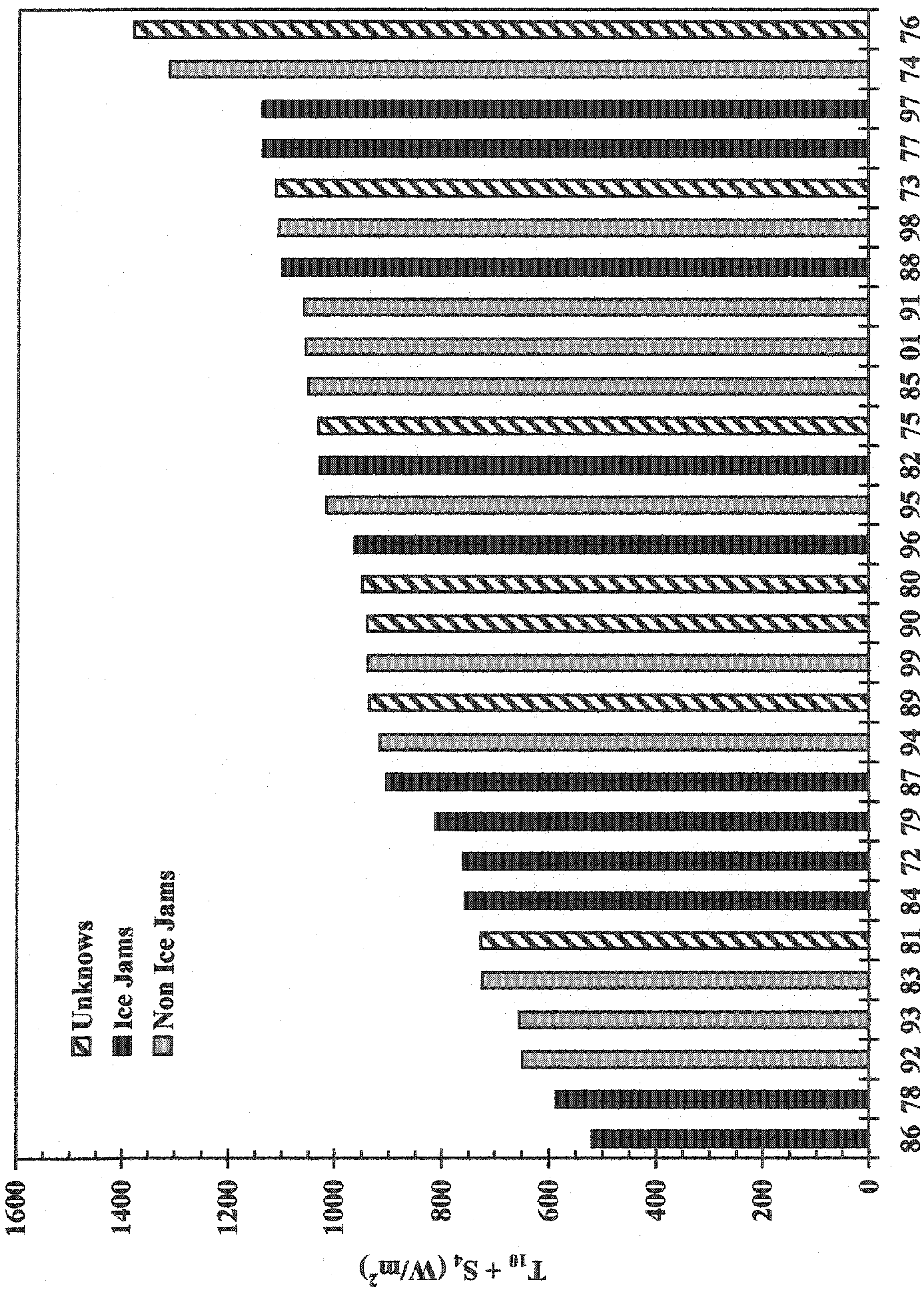

Figure 4.13 Total of T_{10} (W/m^2) and S_4 (W/m^2) during jam, no jam and unknown years.

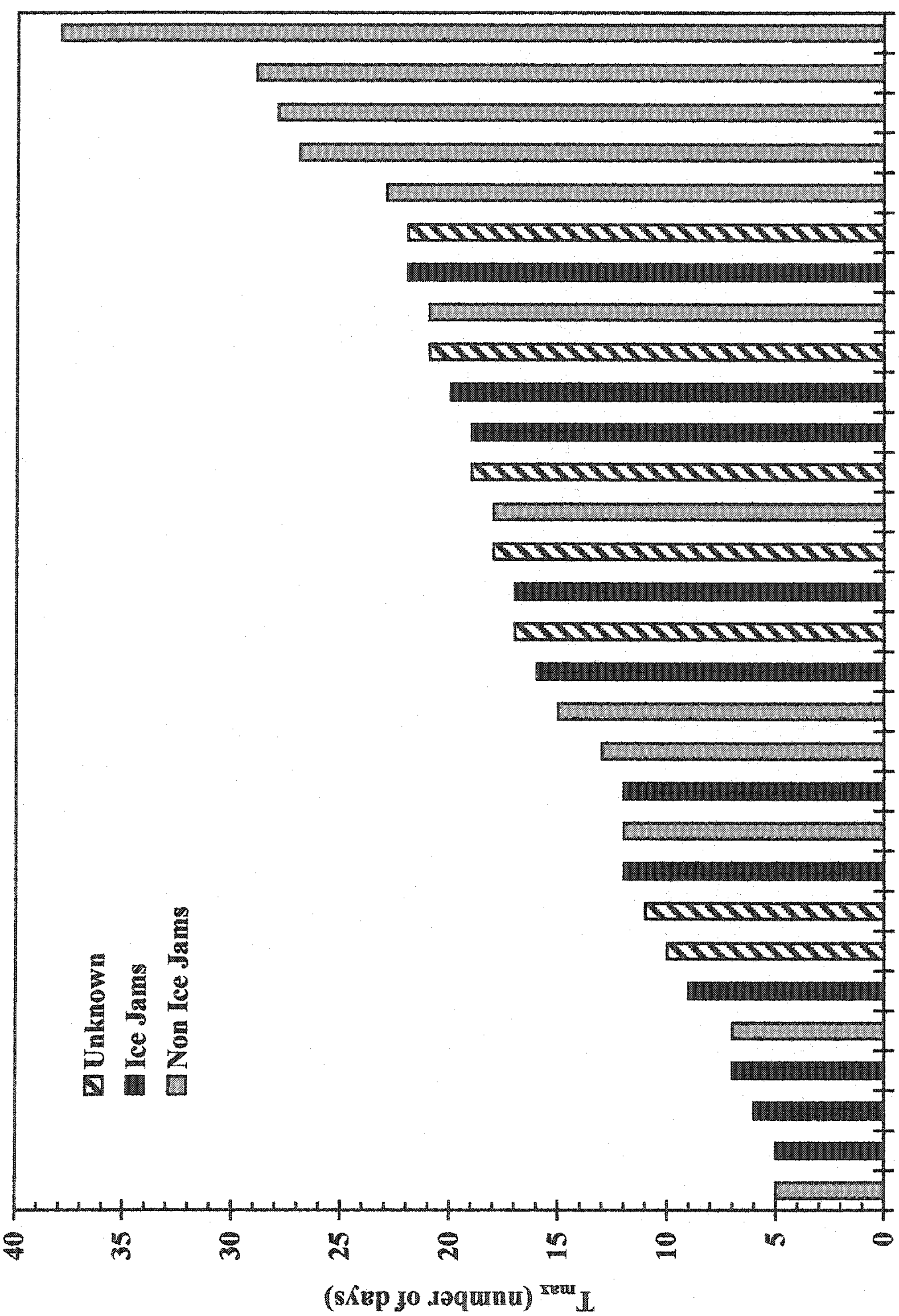

Figure 4.14 T_{max} (number of days) during jam, no jam and unknown years.

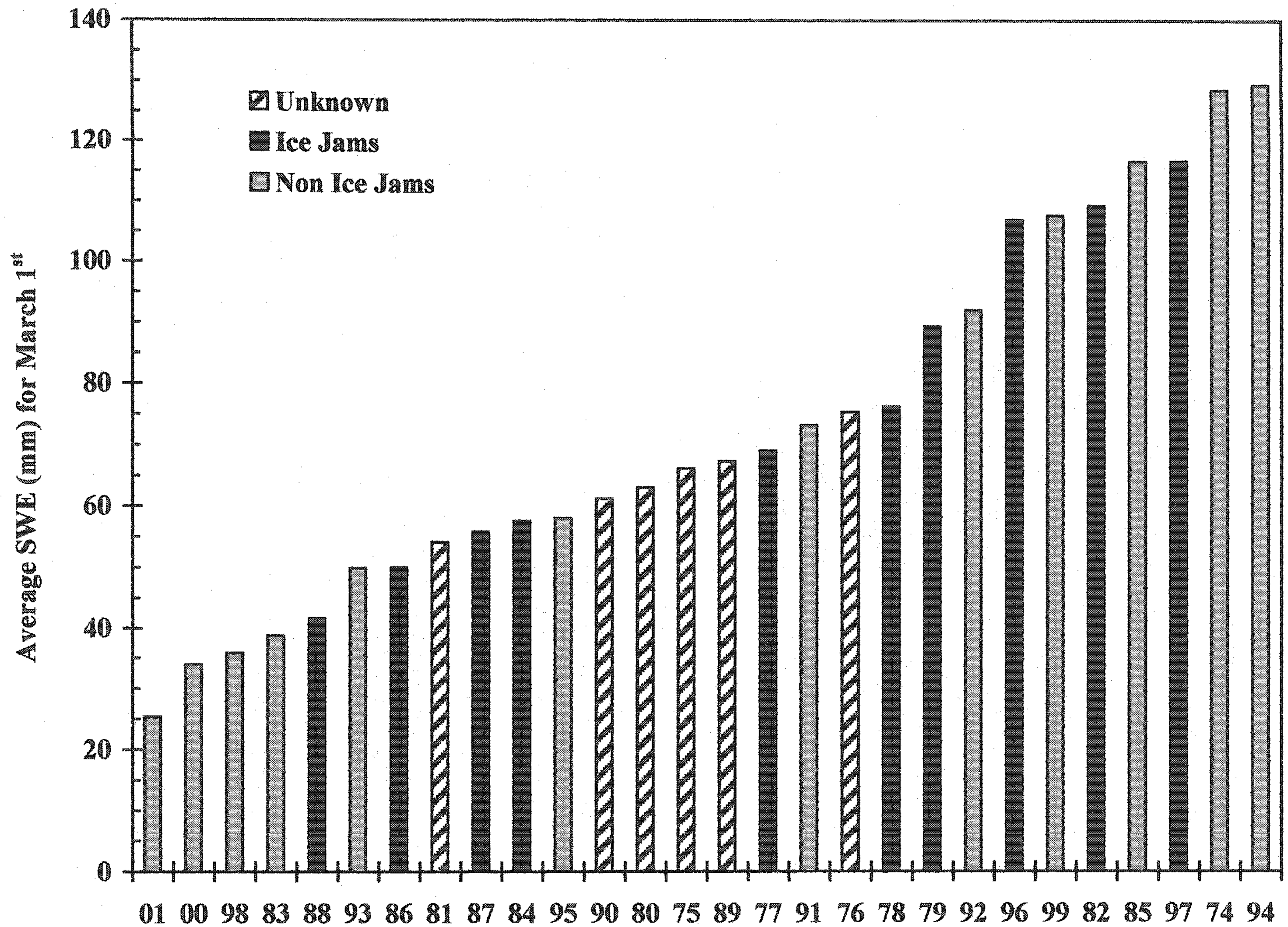

Figure 4.15 Average SWE (mm) for March 1st during jam, no jam and unknown years.

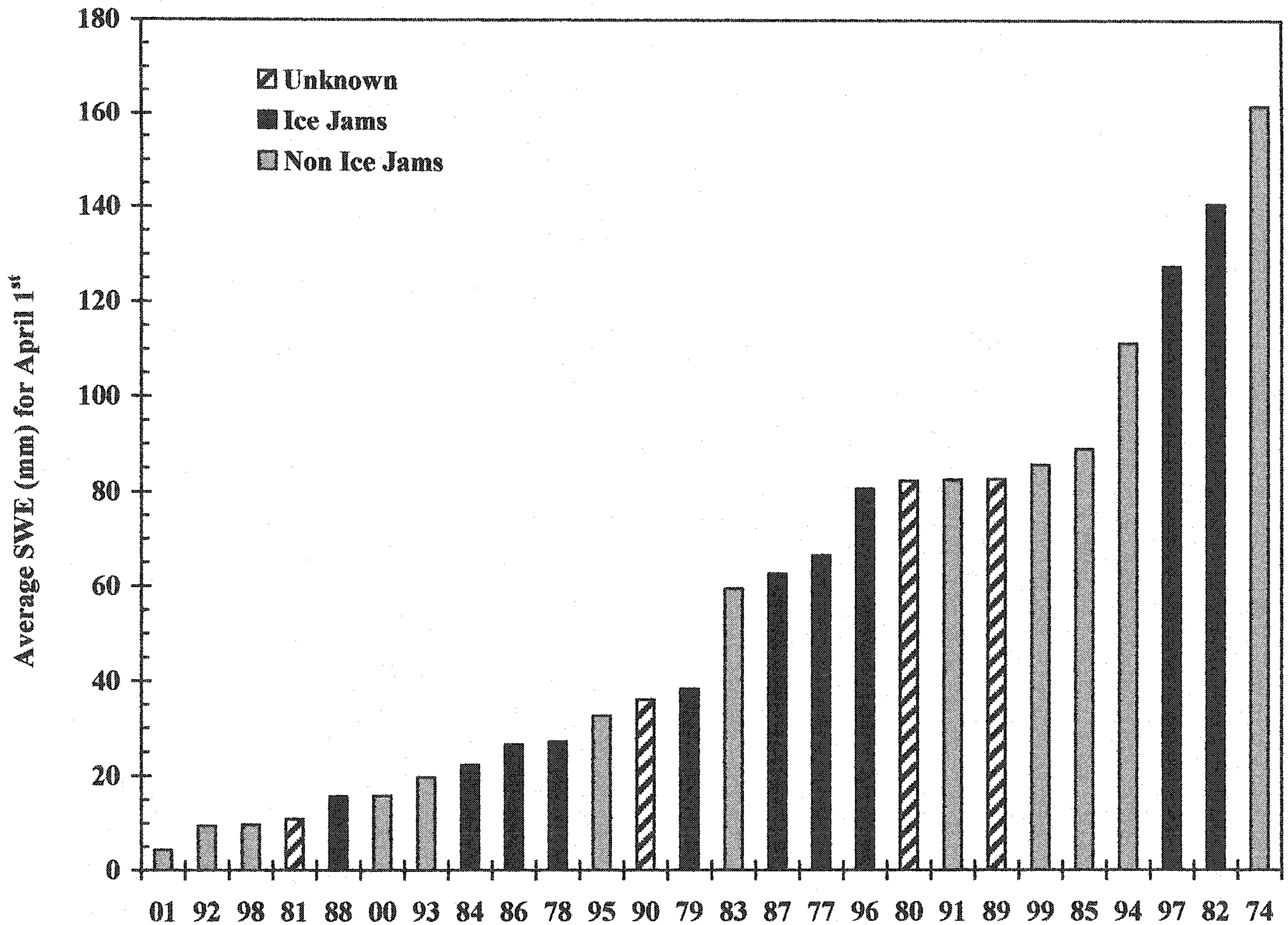

Figure 4.16 Average SWE (mm) for April 1st during jam, no jam and unknown years.

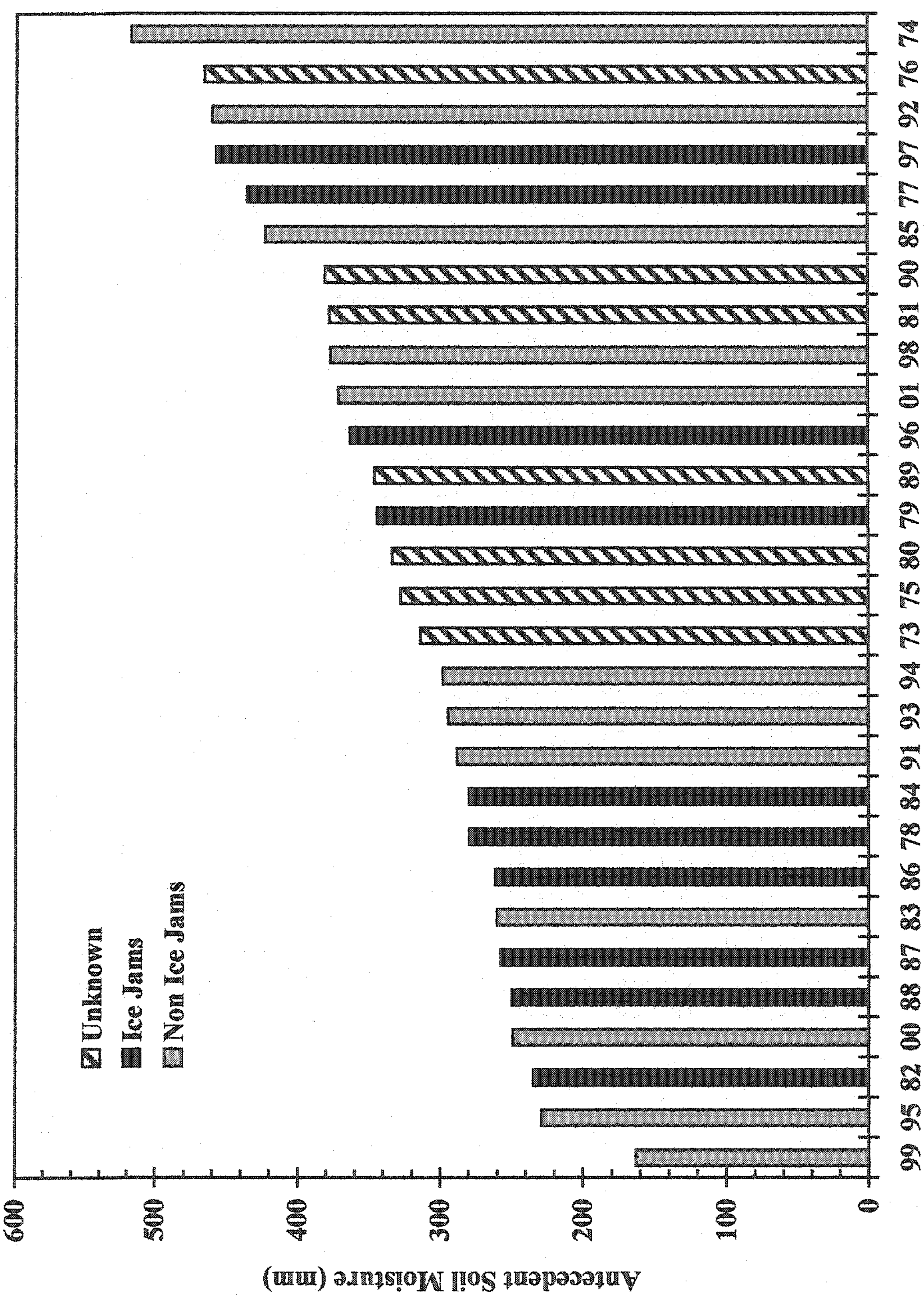

Figure 4.17 Antecedent soil moisture (mm) during jam, no jam and unknown years.

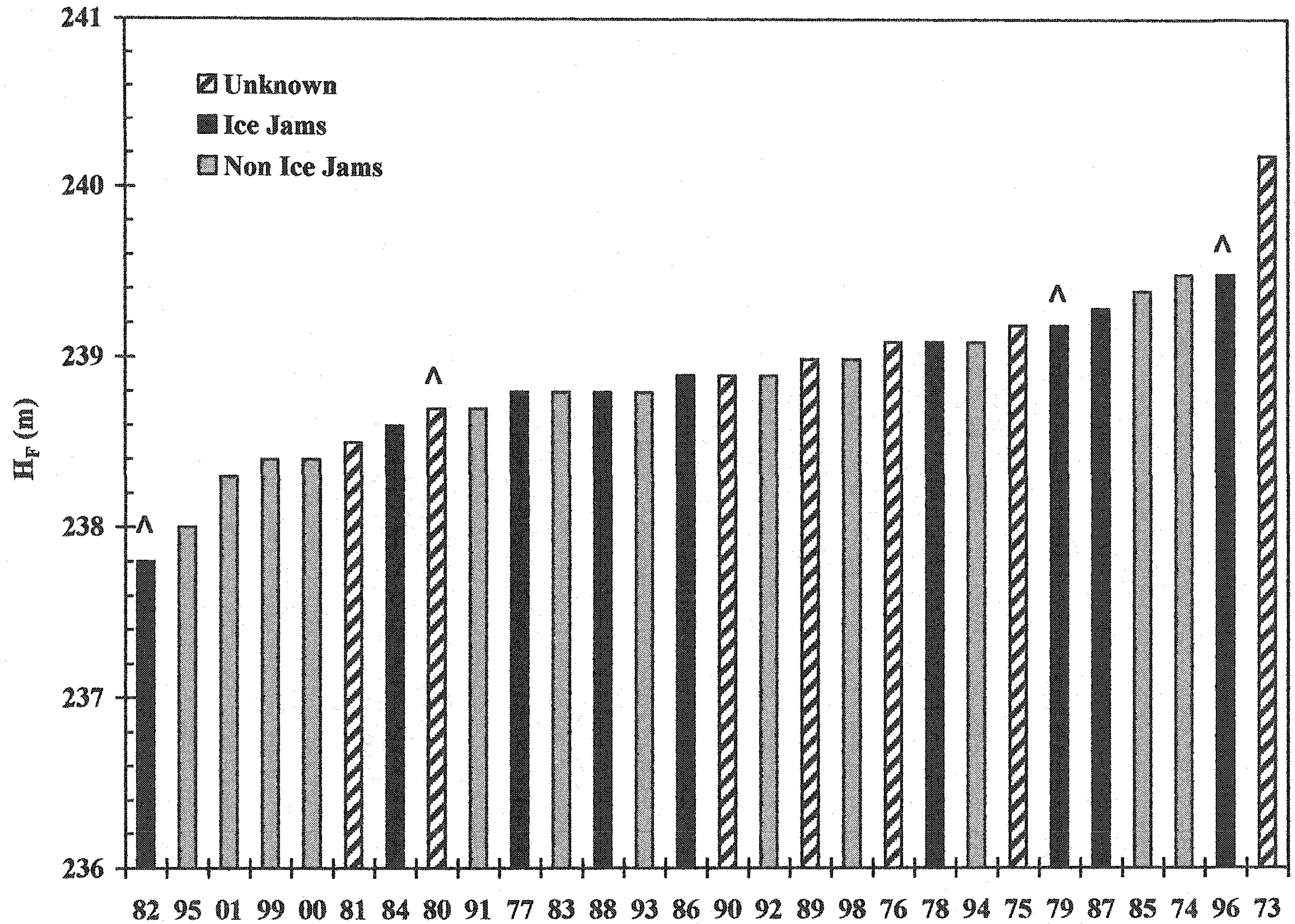

Figure 4.18 H_F (m) during jam, no jam and unknown years.

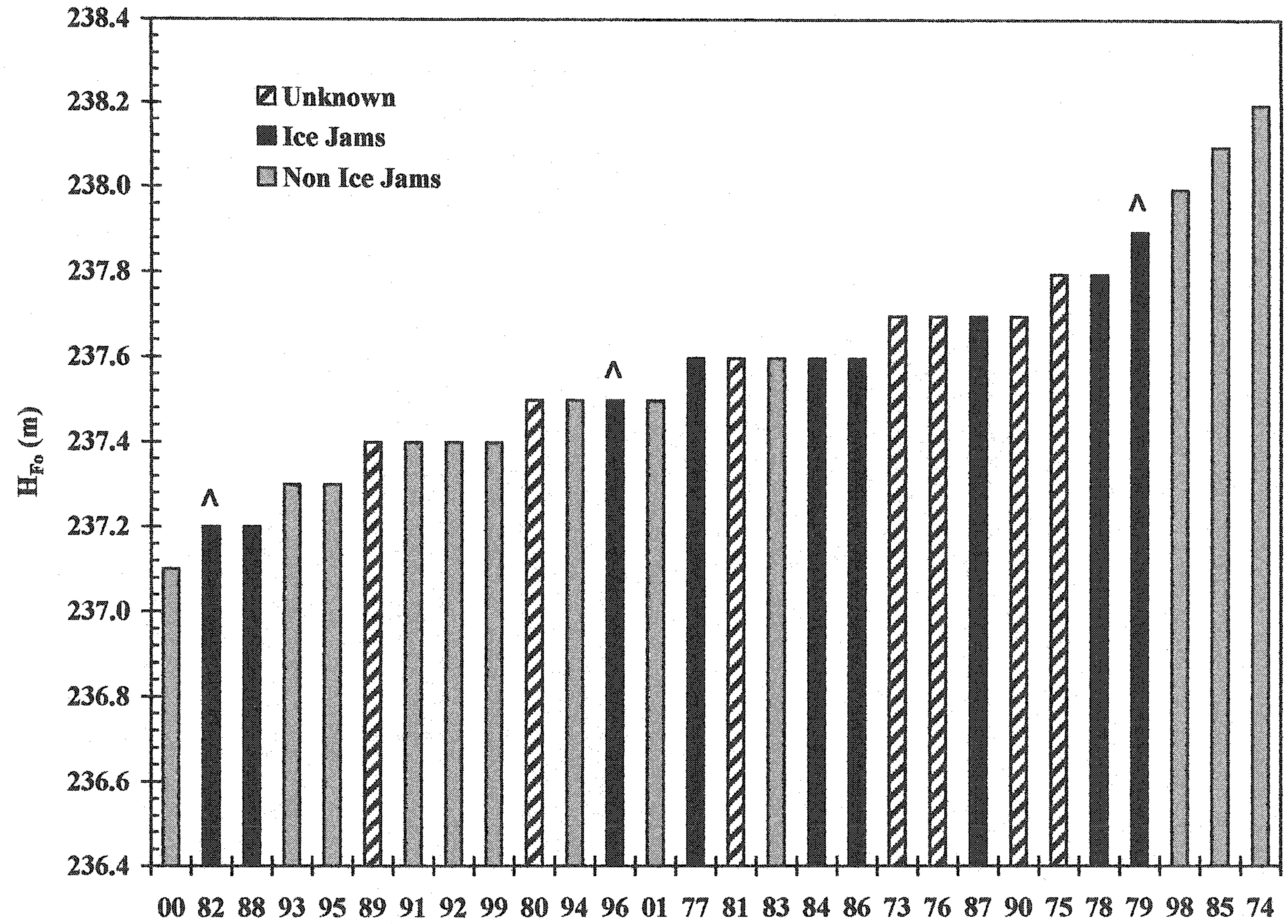

Figure 4.19 H_{Fo} (m) during jam, no jam and unknown years.

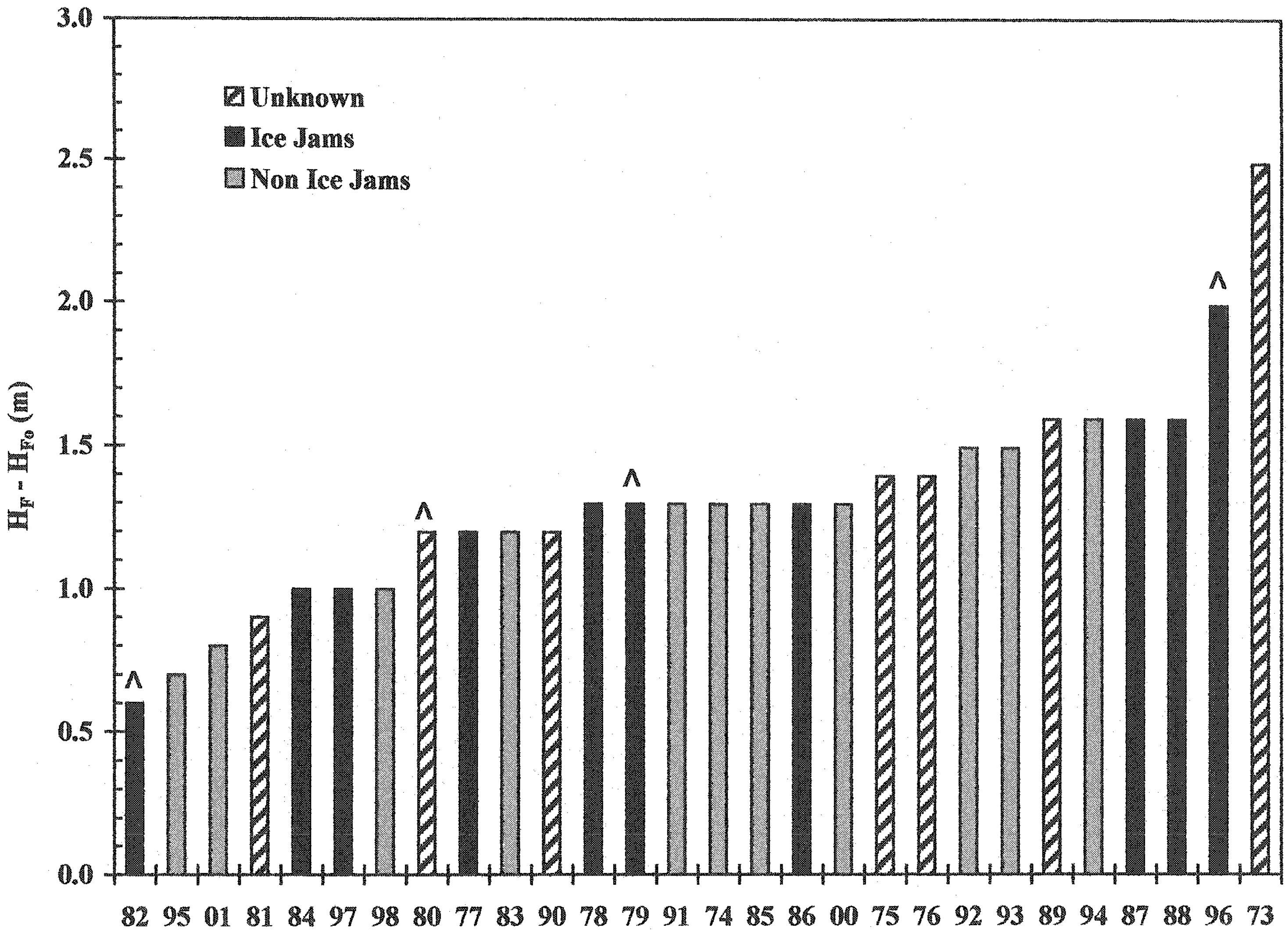

Figure 4.20 **Difference between H_F and H_{Fo} (m) during jam, no jam and unknown years.**

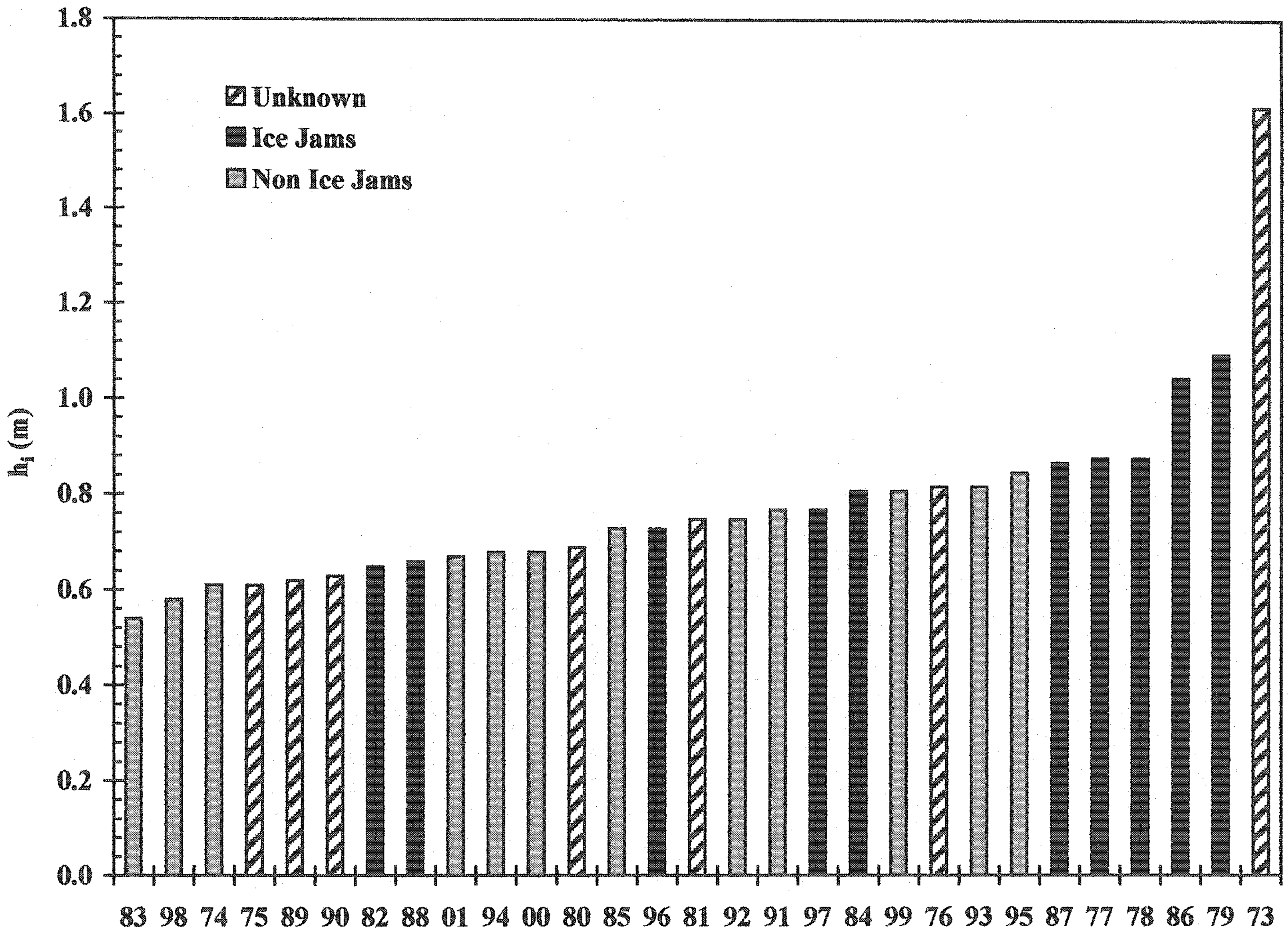

Figure 4.21 h_i (m) during jam, no jam and unknown years.

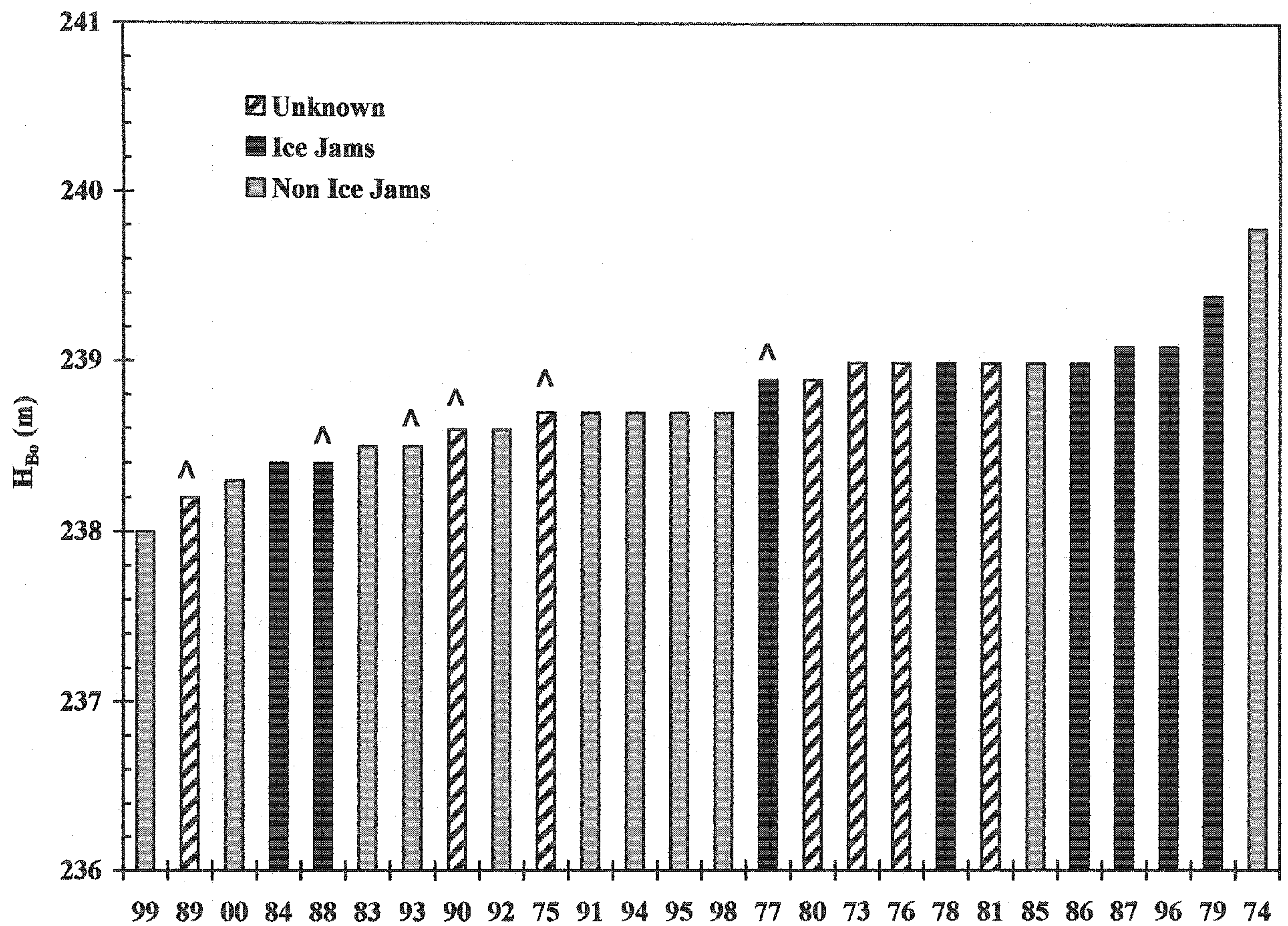

Figure 4.22 H_{Bo} (m) during jam, no jam and unknown years.

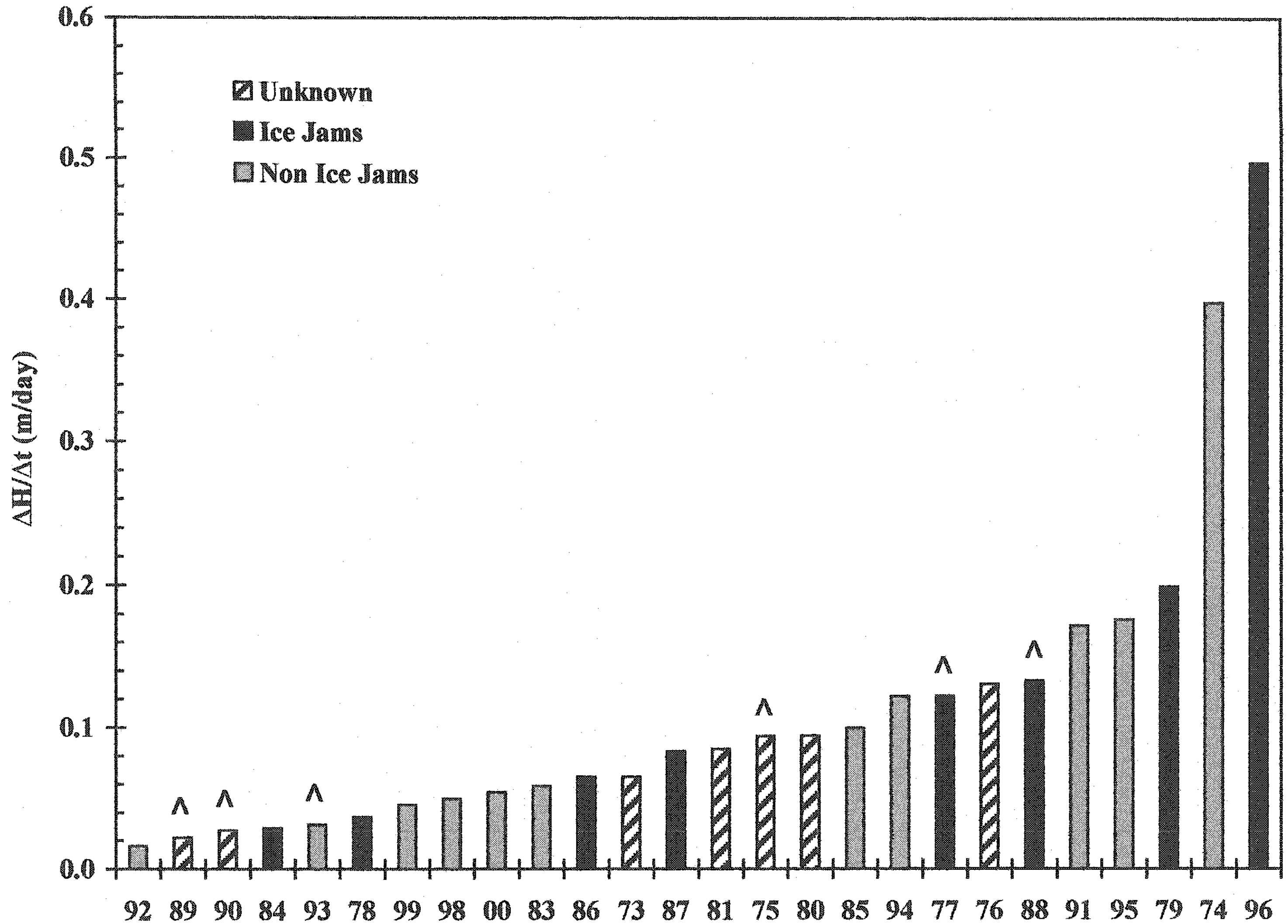

Figure 4.23 The ratio of ΔH (m) and Δt (day) during jam, no jam and unknown years.

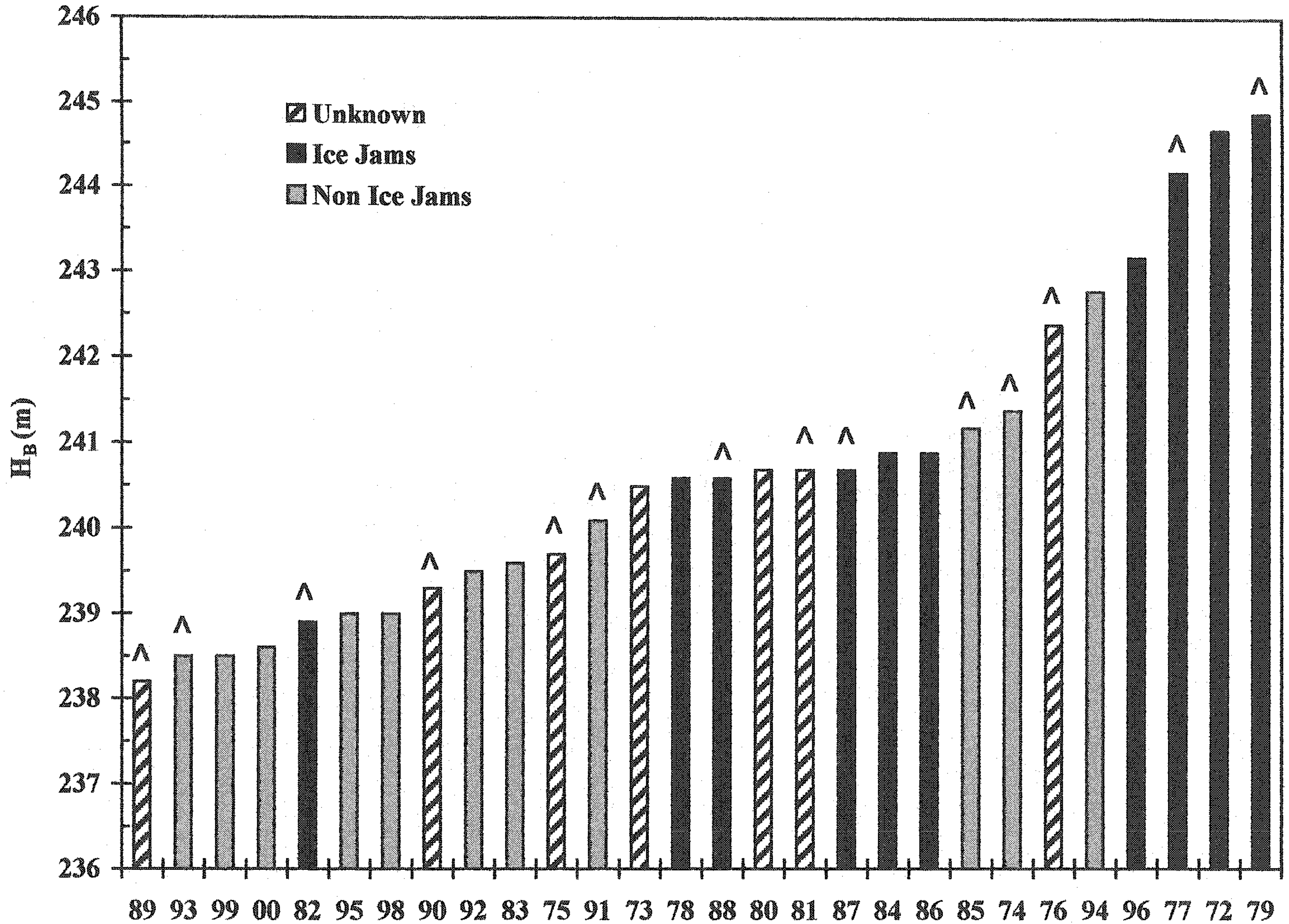

Figure 4.24 H_B (m) during jam, no jam and unknown years.

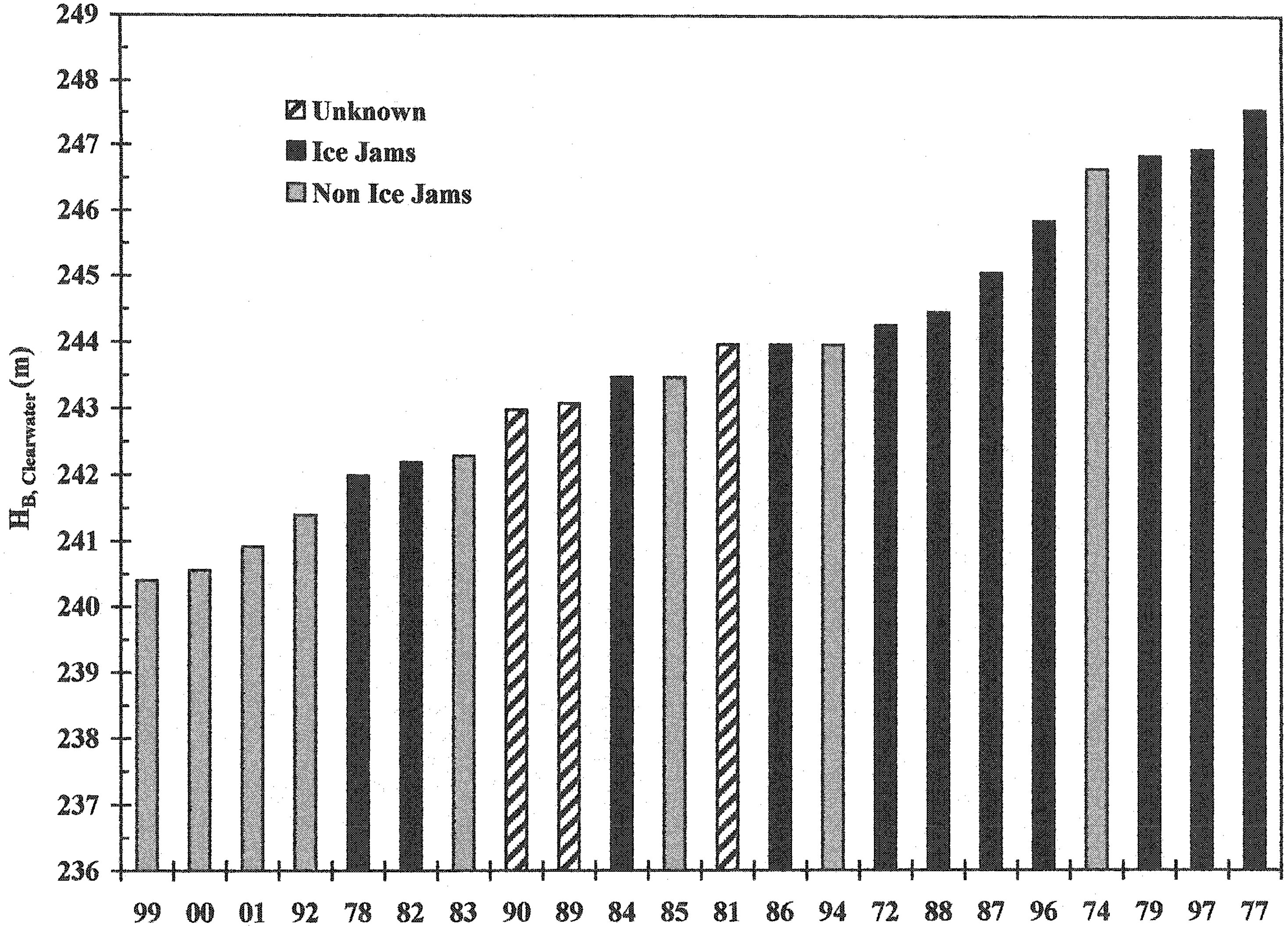

Figure 4.25 $H_{B,\,Clearwater}$ (m) during jam, no jam and unknown years.

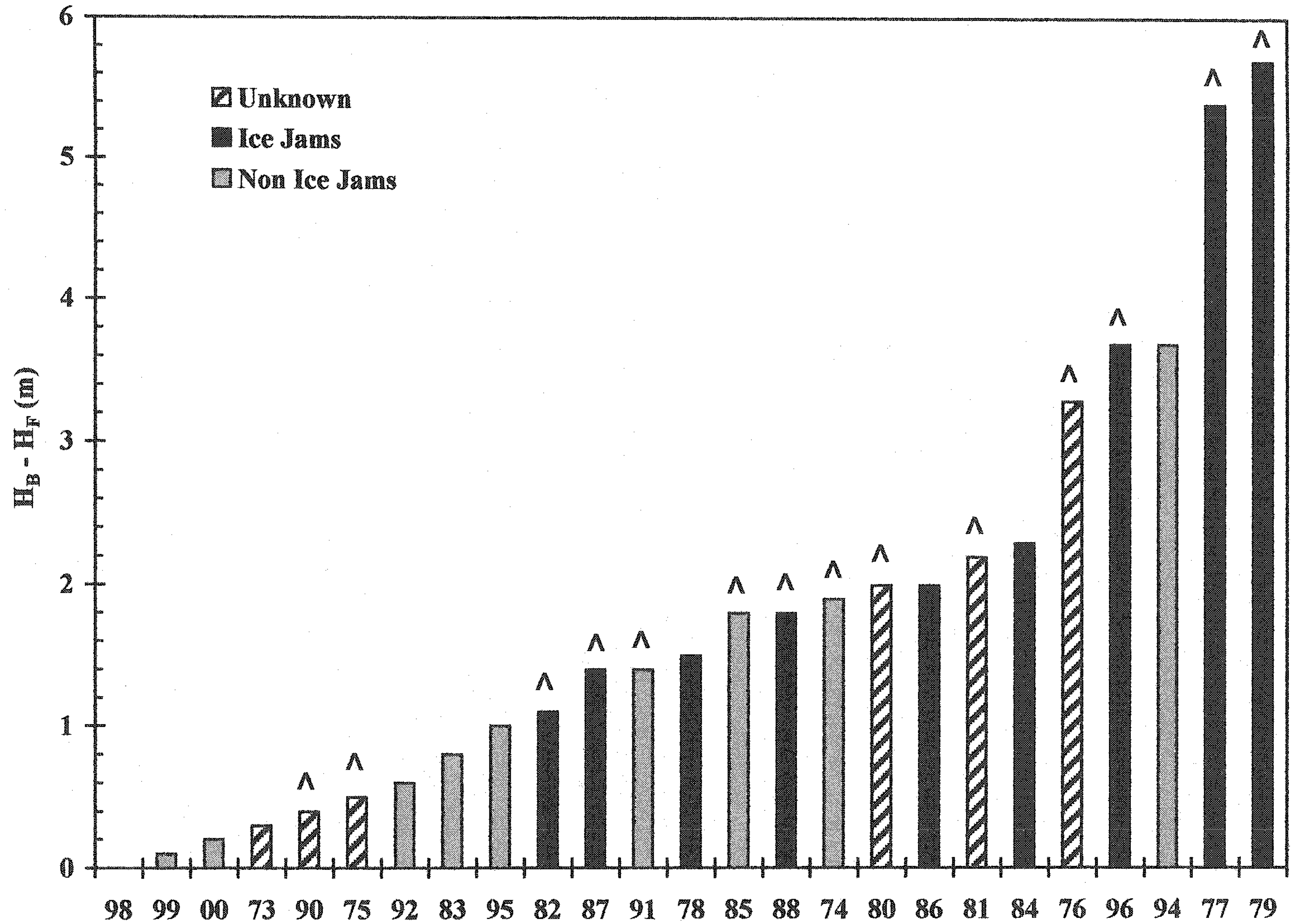

Figure 4.26 Difference between H_B and H_F (m) during jam, no jam and unknown years.

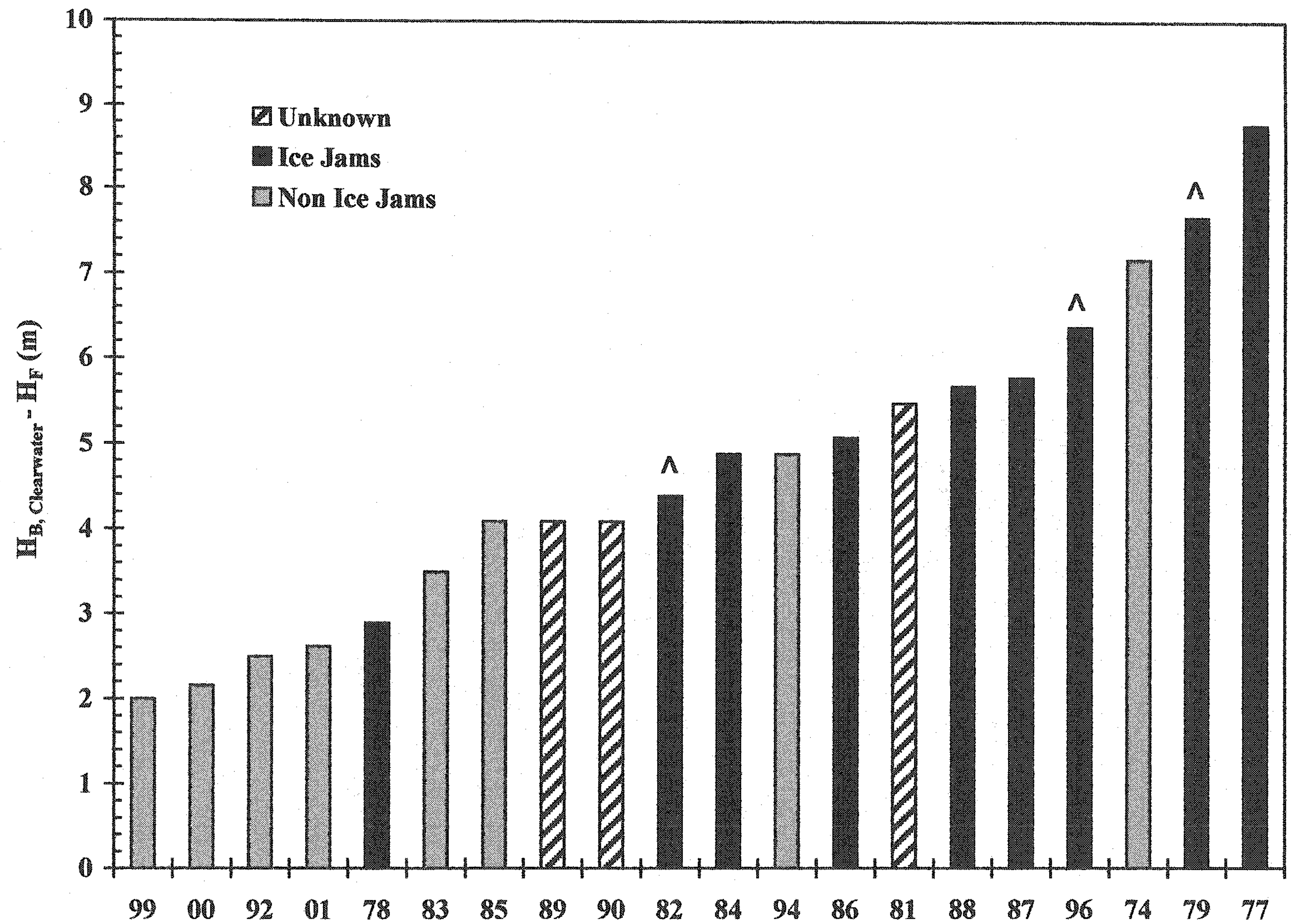

Figure 4.27 Difference between $H_{B, Clearwater}$ and H_F (m) during jam, no jam and unknown years.

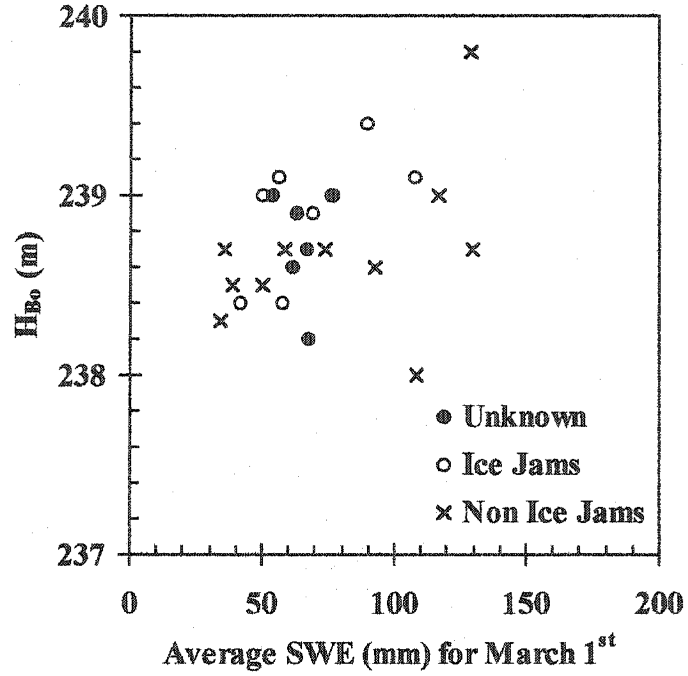

Figure 4.28 H_{Bo} (m) versus average SWE (mm) for March 1st during jam, no jam and unknown years.

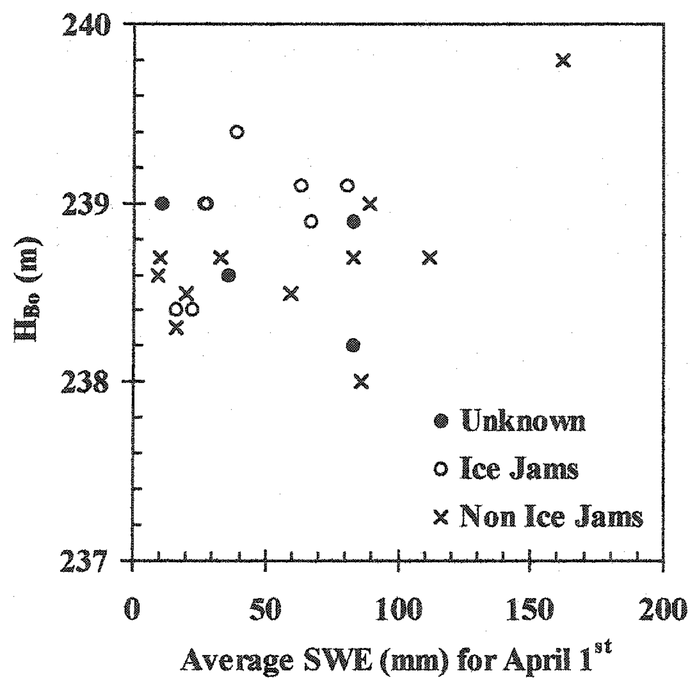

Figure 4.29 H_{Bo} (m) versus average SWE (mm) for April 1st during jam, no jam and unknown years.

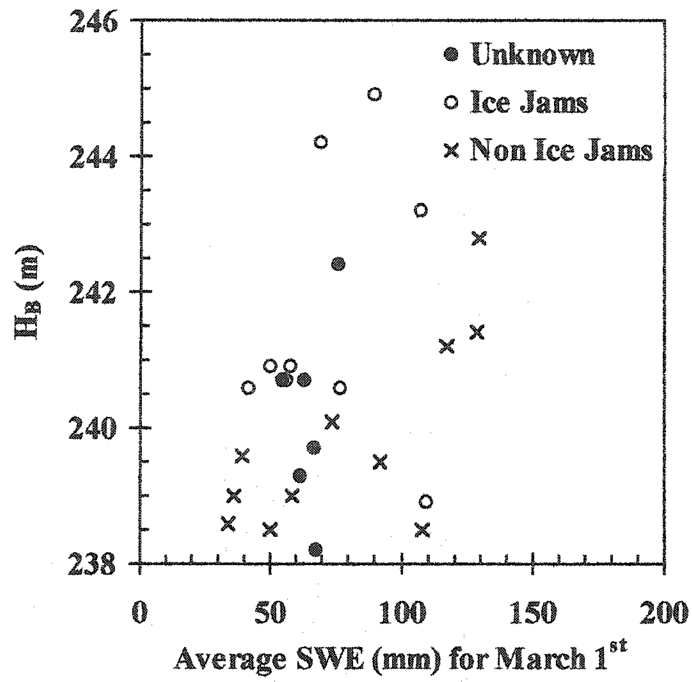

Figure 4.30 H_B (m) versus average SWE (mm) for March 1st during jam, no jam and unknown years.

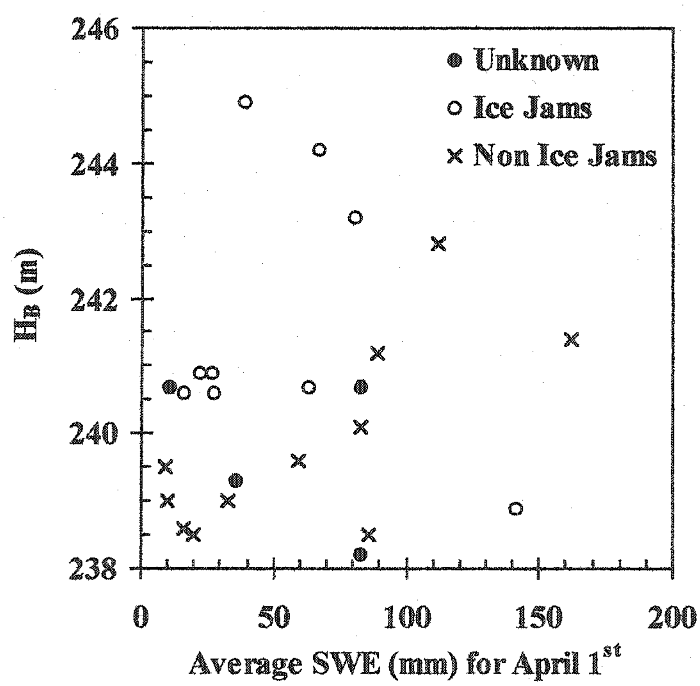

Figure 4.31 H_B (m) versus average SWE (mm) for April 1st during jam, no jam and unknown years.

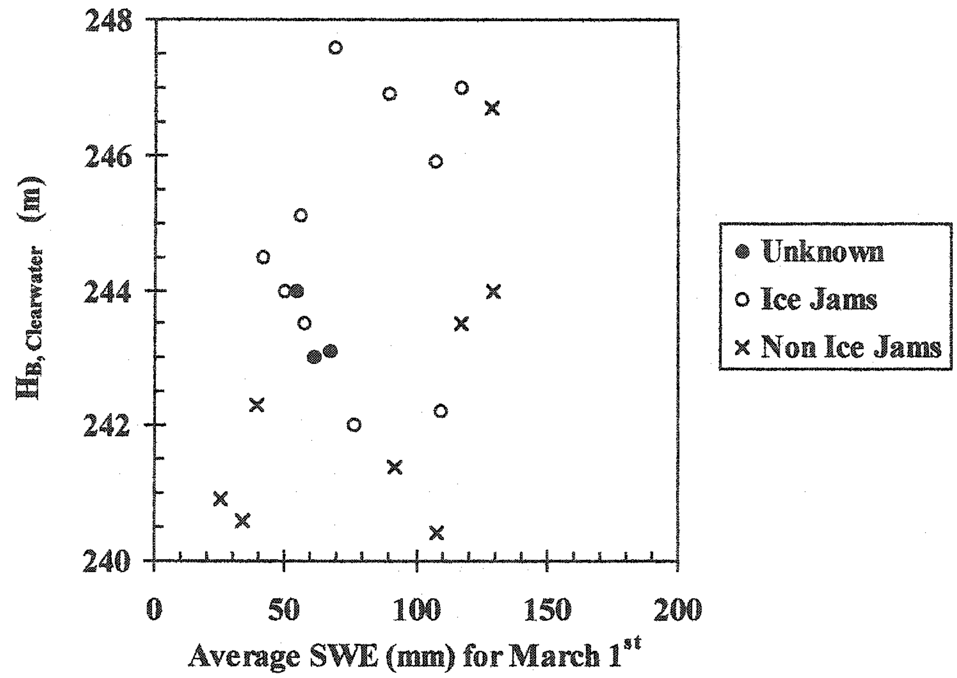

Figure 4.32 $H_{B,\ Clearwater}$ (m) versus average SWE (mm) for March 1st during jam, no jam and unknown years.

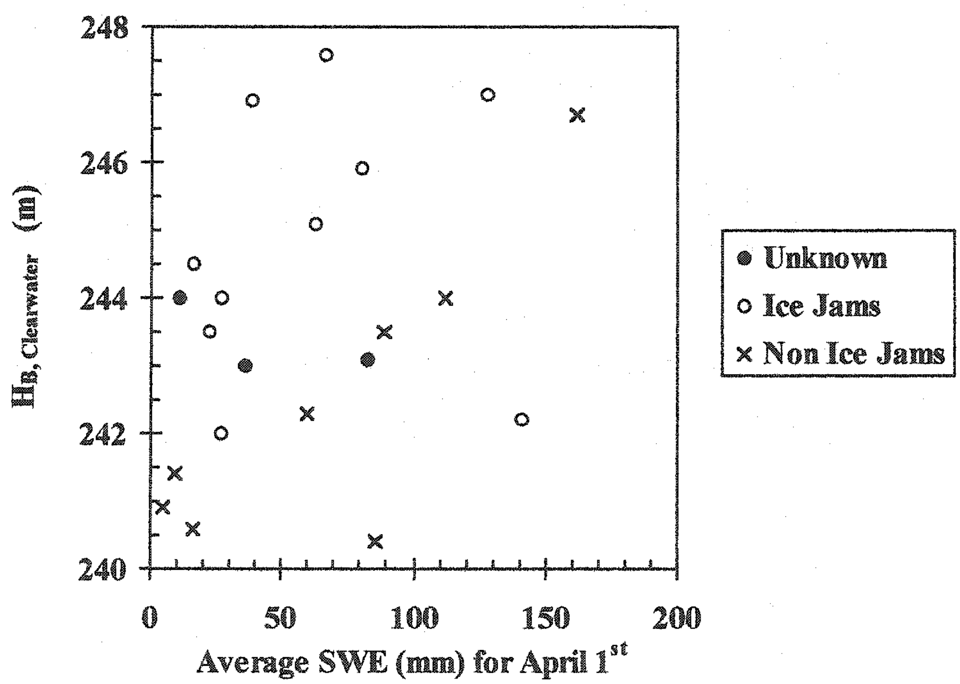

Figure 4.33 $H_{B,\ Clearwater}$ (m) versus average SWE (mm) for April 1st during jam, no jam and unknown years.

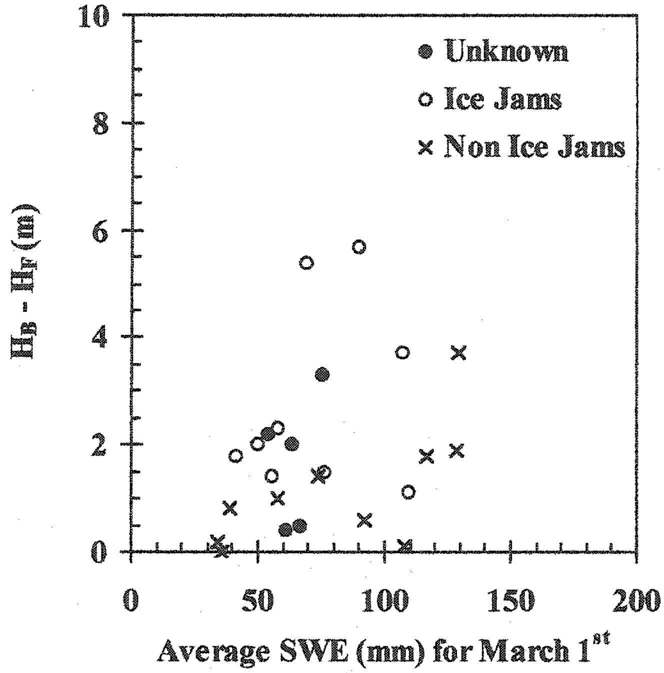

Figure 4.34 H_B - H_F (m) versus average SWE (mm) for March 1st during jam, no jam and unknown years.

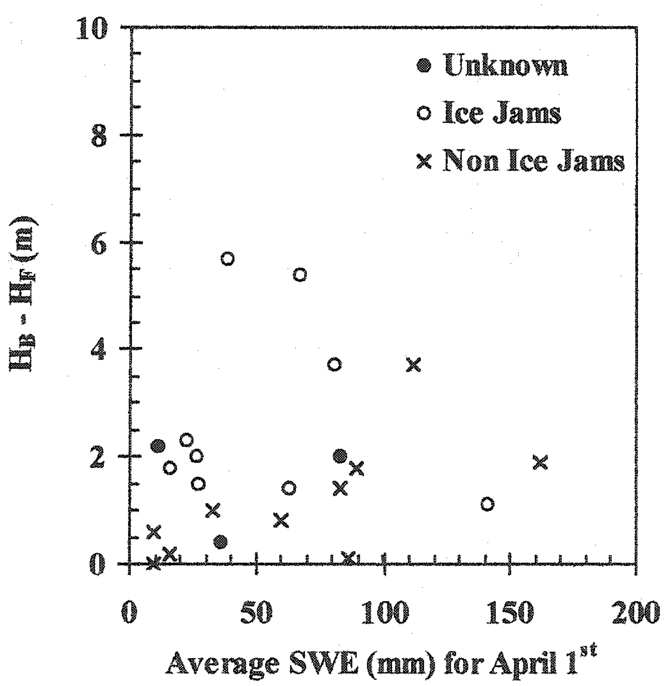

Figure 4.35 H_B - H_F (m) versus average SWE (mm) for April 1st during jam, no jam and unknown years.

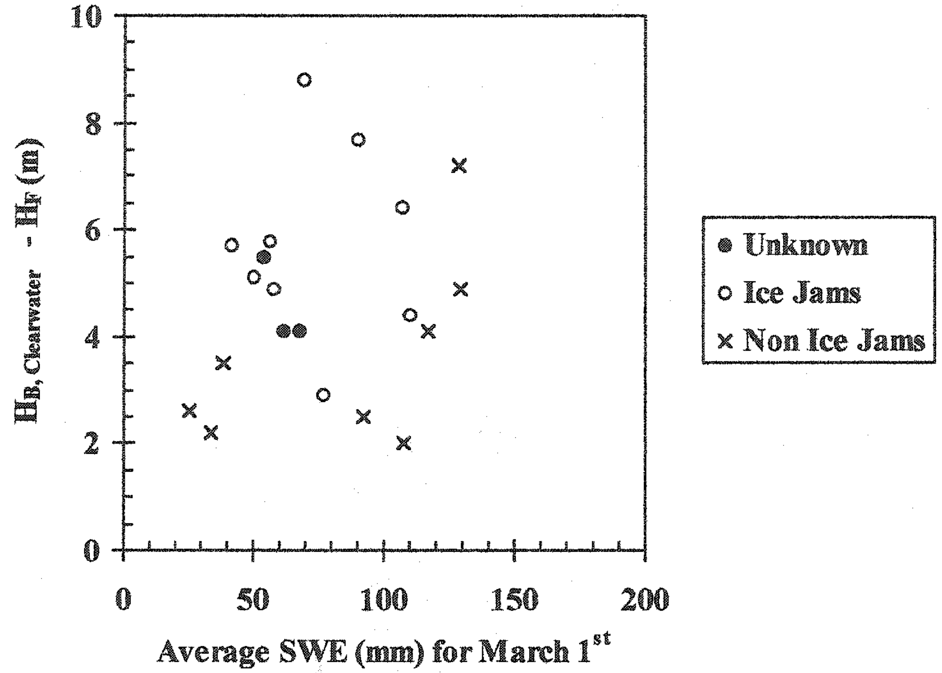

Figure 4.36 $H_{B, Clearwater}$ - H_F (m) versus average SWE (mm) for March 1st during jam, no jam and unknown years.

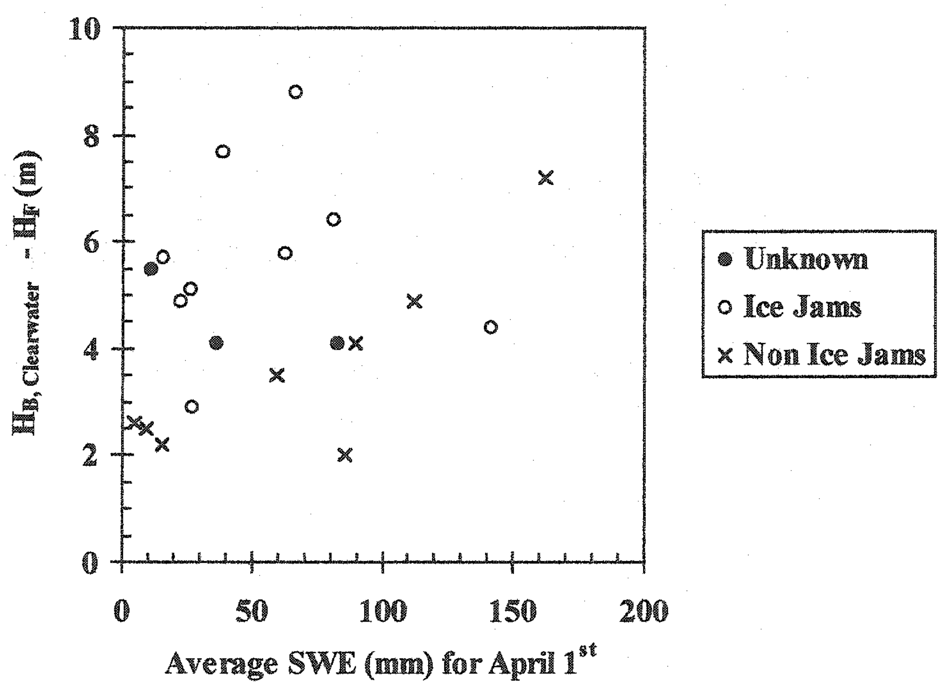

Figure 4.37 $H_{B, Clearwater}$ - H_F (m) versus average SWE (mm) for April 1st during jam, no jam and unknown years.

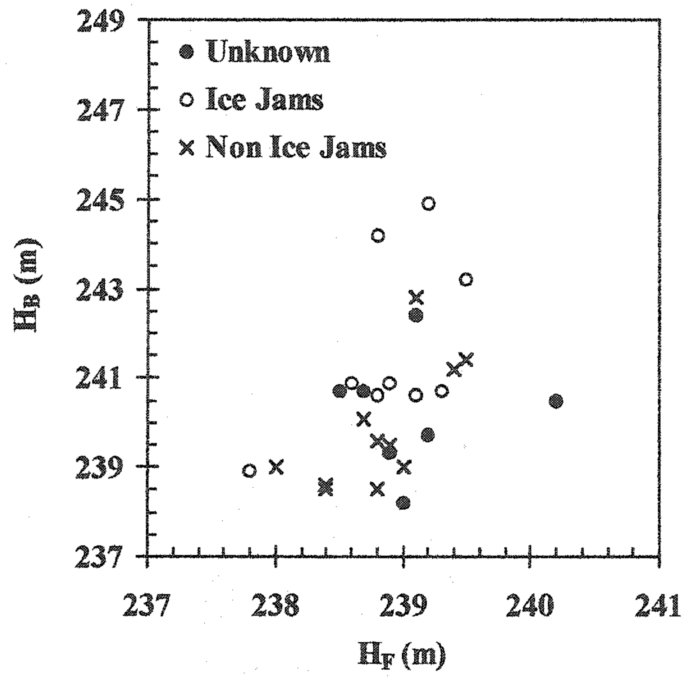

Figure 4.38 H_B (m) versus H_F (m) during jam, no jam and unknown years.

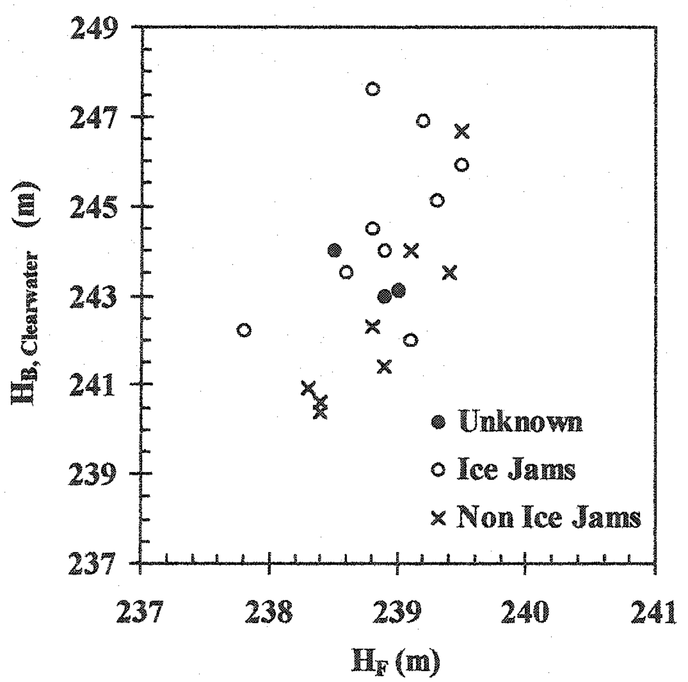

Figure 4.39 $H_{B,\ Clearwater}$ (m) versus H_F (m) during jam, no jam and unknown years.

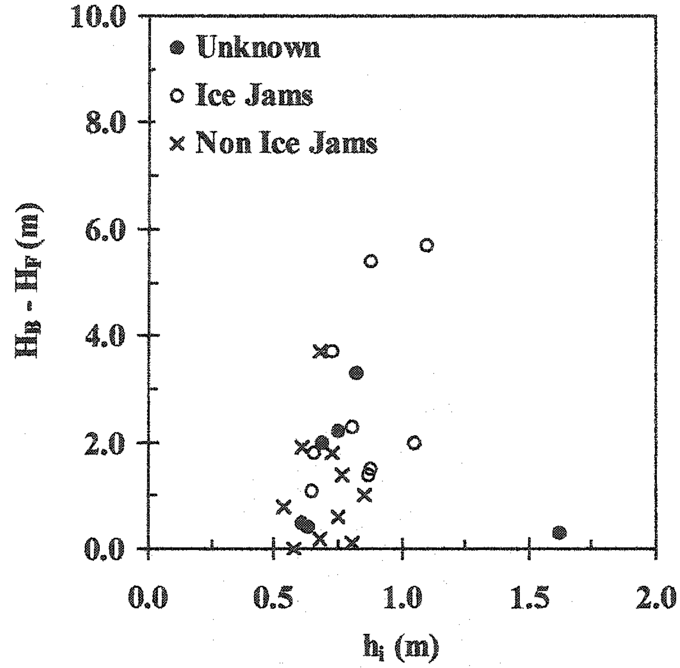

Figure 4.40 H_B - H_F (m) versus h_i (m) during jam, no jam and unknown years.

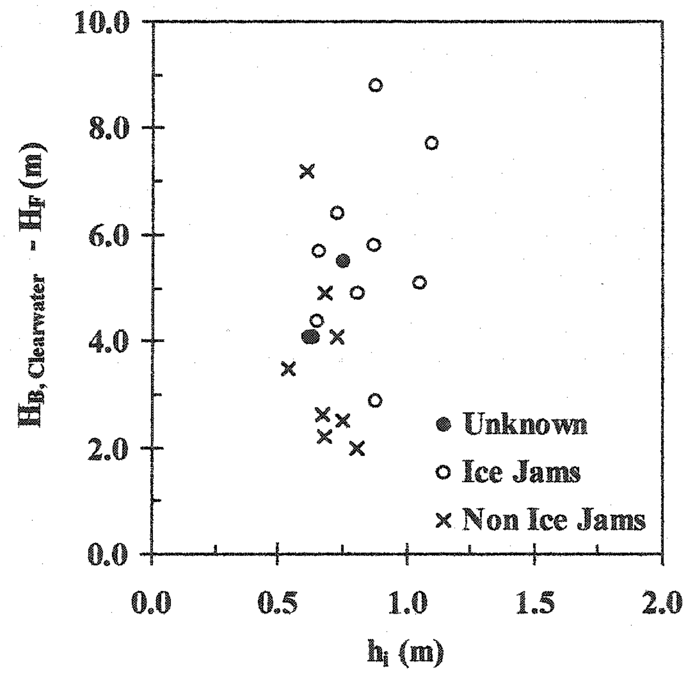

Figure 4.41 $H_{B, Clearwater}$ - H_F (m) versus average h_i (m) during jam, no jam and unknown years.

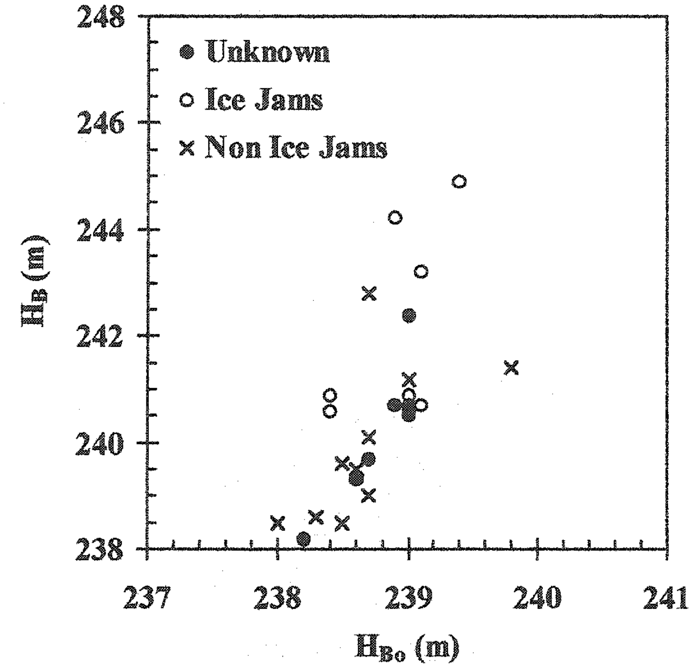

Figure 4.42 H_B (m) versus H_{Bo} (m) during jam, no jam and unknown years.

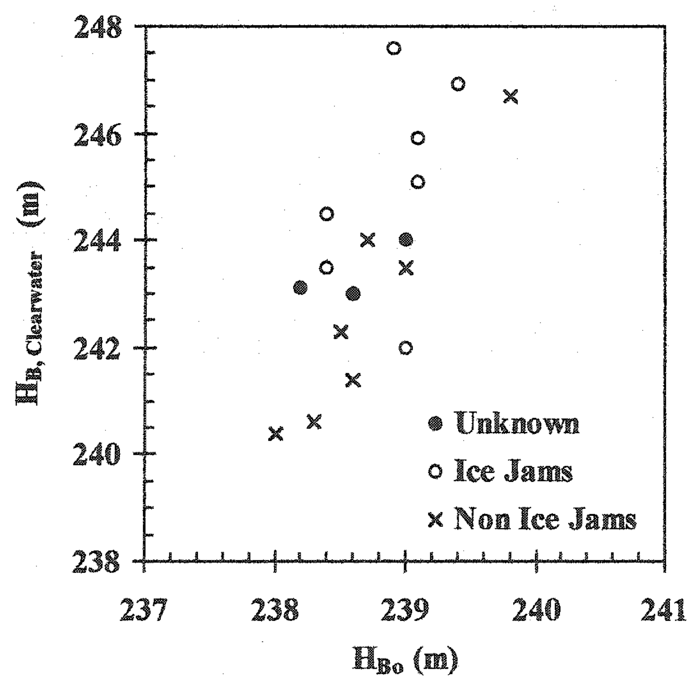

Figure 4.43 $H_{B, Clearwater}$ versus average H_{Bo} (m) during jam, no jam and unknown years.

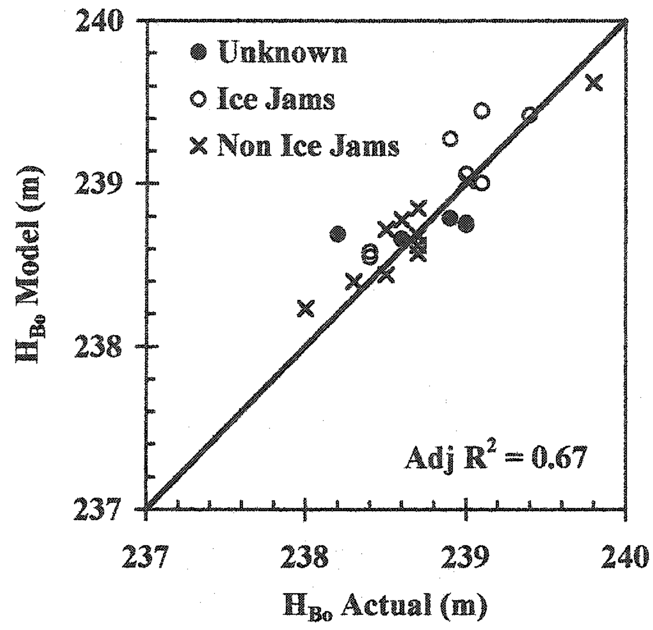

Figure 4.44 H_{Bo} model (m) versus H_{Bo} actual (m) during jam, no jam and unknown years.

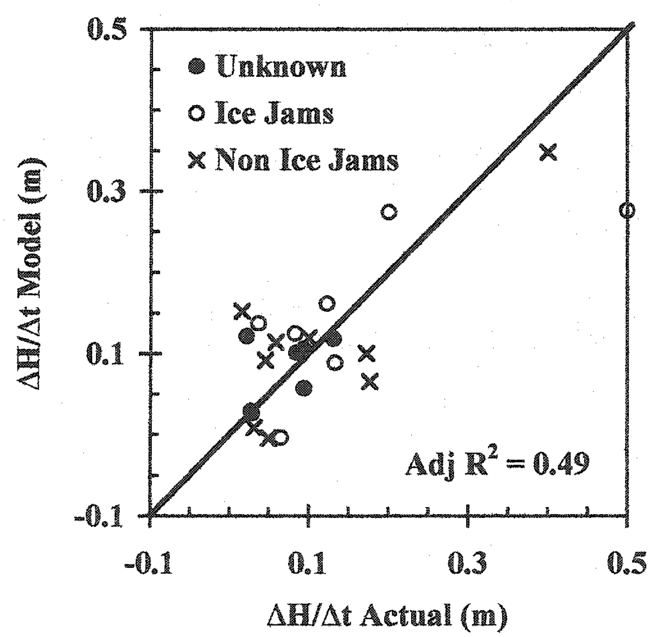

Figure 4.45 $\Delta H/\Delta t$ model (m/day) versus $\Delta H/\Delta t$ actual (m/day) during jam, no jam and unknown years.

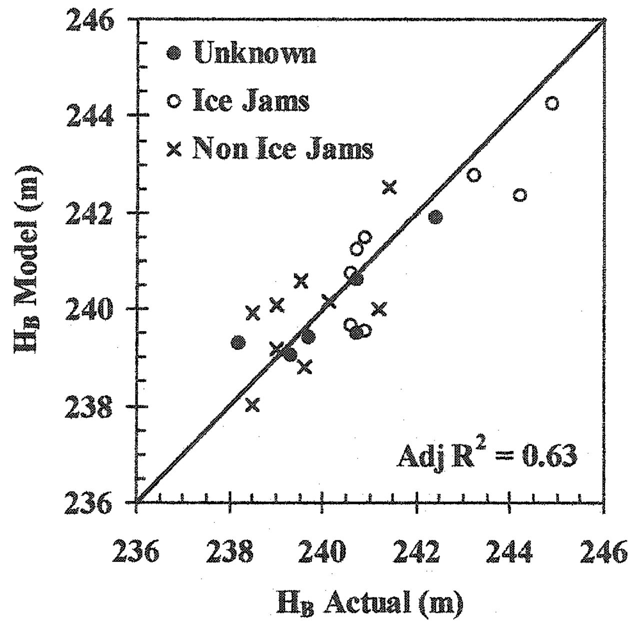

Figure 4.46 H_B model (m) versus H_B actual (m) during jam, no jam and unknown years.

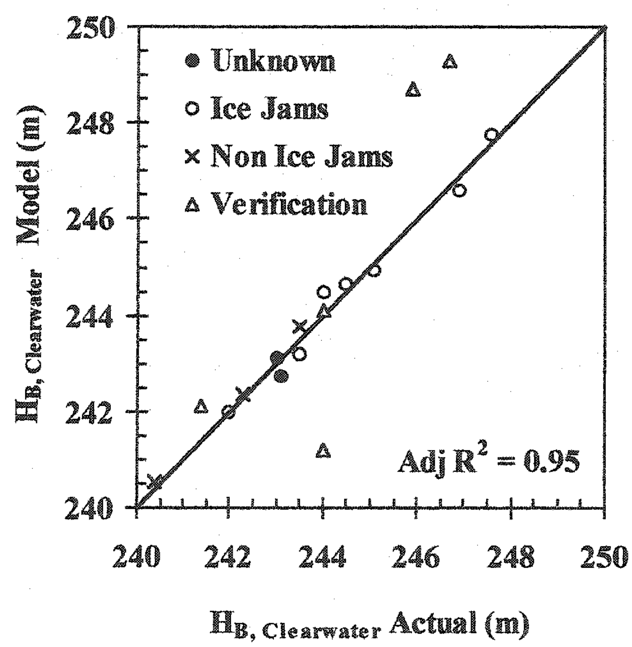

Figure 4.47 $H_{B,\ Clearwater}$ model (m) versus $H_{B,\ Clearwater}$ actual (m) during jam, no jam and unknown years.

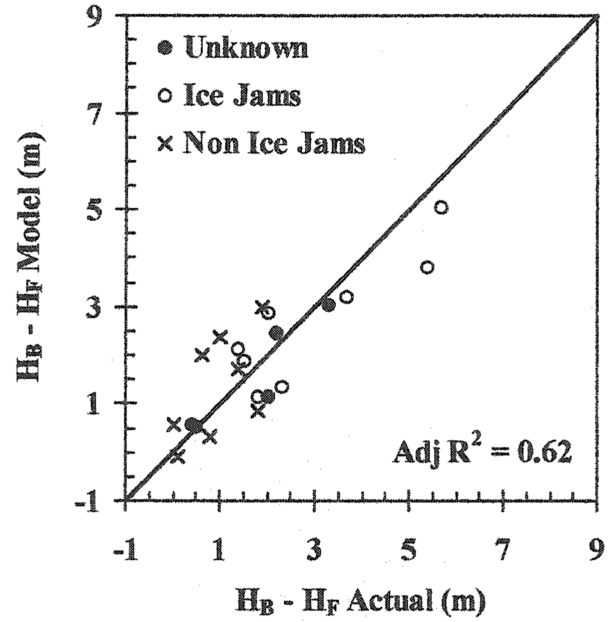

Figure 4.48 H_B - H_F model (m) versus H_B - H_F actual (m) during jam, no jam and unknown years.

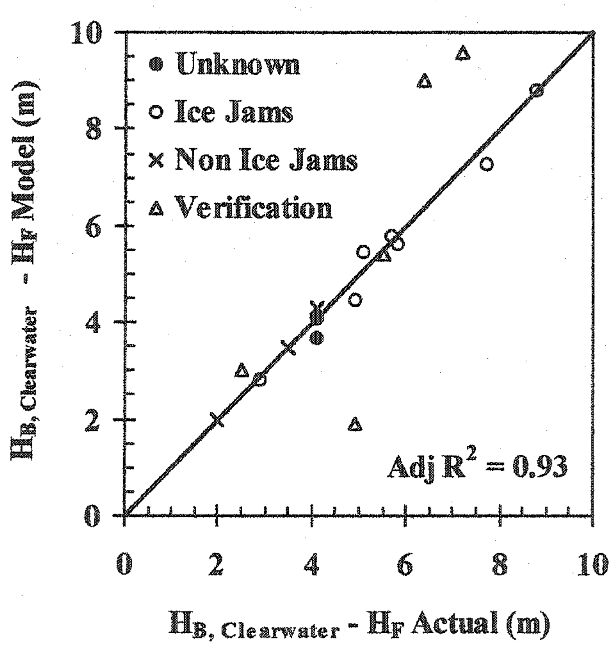

Figure 4.49 $H_{B, Clearwater}$ - H_F model (m) versus $H_{B, Clearwater}$ - H_F actual (m) during jam, no jam and unknown years.

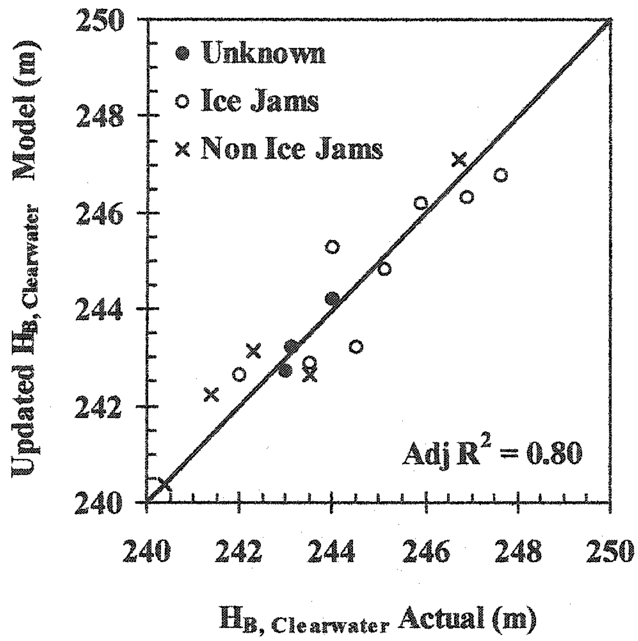

Figure 4.50 Updated $H_{B, Clearwater}$ model (m) versus $H_{B, Clearwater}$ actual (m) during jam, no jam and unknown years.

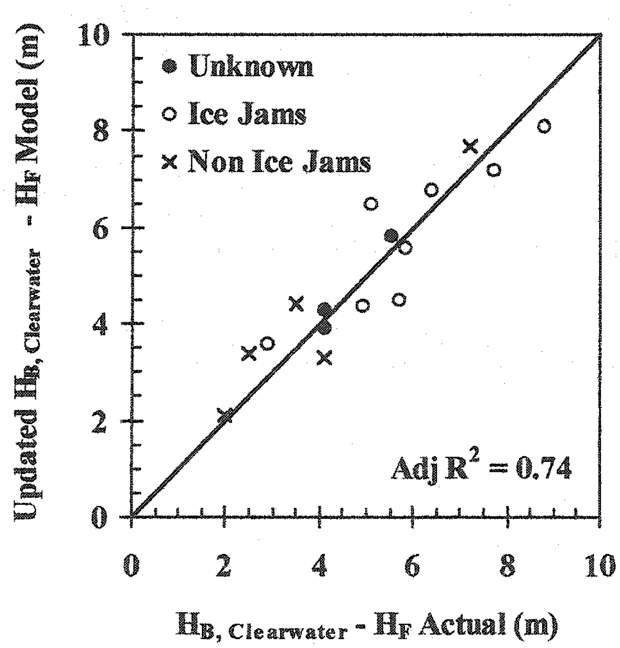

Figure 4.51 Updated $H_{B, Clearwater} - H_F$ model (m) versus $H_{B, Clearwater} - H_F$ actual (m) during jam, no jam and unknown years.

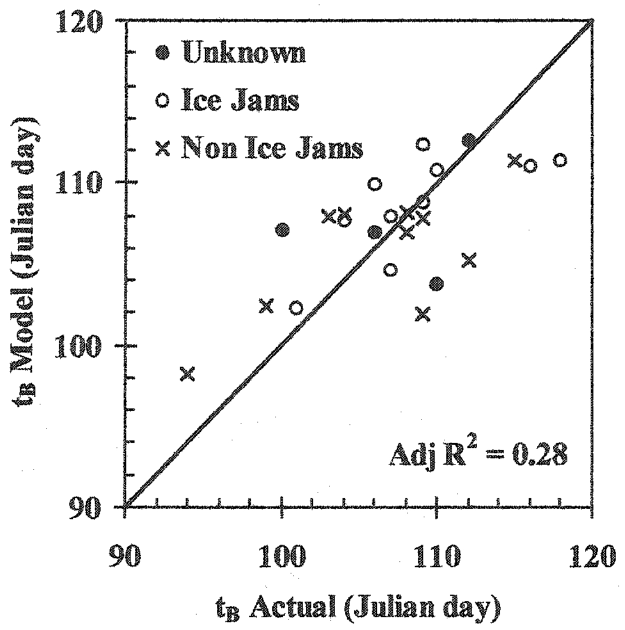

Figure 4.52 t_B model (Julian day) versus t_B actual (Julian day) during jam, no jam and unknown years.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

This chapter will first present a summary of the hydrometeorological database established and the results obtained during this research. Recommendations will then be discussed to help determinate reliable forecasting models at Fort McMurray, Alberta.

5.1 CONCLUSIONS

River ice jams are a natural phenomenon, which can cause serious flood damages and may result in the loss of human life. Although researchers have been studying this subject for years, the forecasting models currently developed are site-specific and are usually not transferable to other locations. The first ice jam ever documented at Fort McMurray occurred in spring 1875. Since then, ice jams have been frequently observed on the Athabasca River in the vicinity of Fort McMurray. To date, no forecasting model is available to predict the potential occurrence or severity of ice jams at the studied reach.

In order to better understand the breakup process of the Athabasca River in the vicinity of Fort McMurray, data on historic ice jam events were compiled. It was observed from the available information that the river ice breakup on the Athabasca River at Fort McMurray can be triggered by an ice run which may be caused by the release of an ice jam upstream of town. Flooding occurs when a severe ice jam forms downstream of the Clearwater River confluence, which generates high backwater levels along the Clearwater River. It has been documented that during a significant ice run on the Athabasca River, the ice from the Athabasca River will likely be pushed upstream into the Clearwater River. When breakup is mainly governed by thermal effects, the Clearwater River may break before the Athabasca River.

A hydrometeorological database was established during this research in order to investigate the likelihood of ice jam formation and severity at Fort McMurray. The meteorological record was built with air temperature, solar radiation, and basin snow water equivalent (SWE) in late winter, which was documented from the 1972 to 2001 spring breakup. The hydraulic database is based on ice thickness, and variables related to the water level during river ice freeze-up and breakup. This record contains information from the 1973 to 2001 breakup. The meteorological data for the 1972 breakup were added to this research after discovering that an ice jam occurred that year. This information was only received at the end of this study. Therefore, the hydraulic data for the 1972 breakup were not included since this information is very labor-intensive to process, which was not the case for the meteorological data.

The air temperature factors considered in this research were the accumulated degree-days of thaw up to the breakup date (ADDT), the degree-days accumulated in the 10 days prior to breakup date (T_{10}), and the number of days with maximum temperatures greater than 0°C prior to breakup (T_{max}) calculated from the ADDT starting date. Solar radiation was considered as the accumulated daily average radiation flux received from the date degree-days of thaw accumulation was started up to the breakup date (S), and as the accumulated daily average radiation flux received in the 4 days prior to breakup (S_4). SWE was investigated for March 1st and April 1st. An antecedent soil moisture index was also considered in this study.

Six aspects of the hydraulic record were investigated: the freeze-up water level (H_F) that represents the highest stage during freeze-up; the pre freeze-up water level (H_{Fo}); the river ice thickness prior to breakup (h_i); the fairly steady increase in water level preceding breakup ($\Delta H/\Delta t$); the stage immediately before breakup (H_{Bo}); and, the maximum stage observed during breakup (H_B). The values of H_F, H_{Fo}, $\Delta H/\Delta t$, H_B, and H_{Bo} were measured at the Water Survey Canada (WSC) gauge below Fort McMurray while h_i was measured in the vicinity of Fort McMurray. The maximum water level during breakup at the Clearwater River confluence ($H_{B,\,Clearwater}$) was also used in this research as well as the following three parameters: (H_F - H_{Fo}); (H_B - H_F); and ($H_{B,\,Clearwater}$ - H_F).

Threshold models were first investigated in order to assess their ability to identify the occurrence of ice jams at Fort McMurray. The first step of this section was to identify if general weather tendencies occur that define a distinction between 'ice jam' and 'no ice jam' years. In this context, the air temperature and the solar radiation were first studied separately. No significant correlations or patterns were obtained with this analysis, nor did the results improve when these two meteorological factors were considered together. Other threshold models were investigated in this research using histograms. All of the variables previously listed were studied individually, except for the daily air temperature and solar radiation variables, which were combined in order to estimate the total heat input. None of the threshold models studied provided any information on the likelihood of ice jam formation at the studied site.

Finally, regression models were studied in the form of linear and multiple linear regressions. Linear regressions were first performed. These linear relationships did not provide any patterns on the occurrence of ice jams. On the other hand, the results of the multiple linear regressions were very promising with the dependent variables $H_{B,\ Clearwater}$ and ($H_{B,\ Clearwater}$ - H_F), yielding Adjusted R^2 (Adj R^2) values equal to 0.95 and 0.93, respectively. The results showed that the following dependent variables are important to estimated $H_{B,\ Clearwater}$: T_{10}; S_4; average SWE for March 1st and April 1st; antecedent soil moisture; $\Delta H/\Delta t$; and h_i. Meanwhile, T_{10}, S_4, average SWE for March 1st and April 1st, antecedent soil moisture, $\Delta H/\Delta t$, h_i, and H_F were significant in estimating ($H_{B,\ Clearwater}$ - H_F).

The $H_{B,\ Clearwater}$ and ($H_{B,\ Clearwater}$ - H_F) regression models were evaluated using five additional breakup water levels which became available later in the study. The results obtained with the models were not consistent with the observations for all five events; therefore, the multiple regressions were recalculated to include these additional data. The results obtained with the expanded data set resulted in Adj R^2 equal to 0.80 for $H_{B,\ Clearwater}$ and 0.74 for ($H_{B,\ Clearwater}$ - H_F). Although these Adj R^2 values are significantly smaller than the ones obtained in the models which did not include the five additional years of data, these results are still acceptable when considering the complexity of ice jam formation. Furthermore, they are expected to produce a model which is more consistent with actual occurrences, than that which would be provided by the models which were based on fewer events. The independent variables for the updated $H_{B,\, Clearwater}$ model are S, average SWE for March 1st and April 1st, antecedent soil moisture index, $\Delta H/\Delta t$, and h_i. The following variables were used in the updated ($H_{B,\, Clearwater}$ - H_F) model: S; average SWE for March 1st and April 1st; antecedent soil moisture; $\Delta H/\Delta t$; h_i; and H_F.

It can be concluded from these results that river ice breakup on the Athabasca River in the vicinity of Fort McMurray is very complex. Factors, which are believed to influence the occurrence of ice jams need to be studied together in order to identify the likelihood of ice jam occurrence.

5.2 RECOMMENDATIONS

The first recommendation is to update (yearly) the established database in order to validate the updated multiple linear regression models of $H_{B,\, Clearwater}$ and $H_{B,\, Clearwater}$ - H_F. It is also suggested to install a remote water level station at the Clearwater River confluence since promising results were obtained at this location and the water level at this site is an indication of the flood severity during ice jam events at Fort McMurray. Presently the water level at the Clearwater River confluence is measured manually during spring, which does not provide a continuous record of the stage. Since breakup can occur very quickly, this means that the peak water level is not always recorded. Consequently, high water marks must be used to estimate the maximum stage at breakup.

The next step in forecasting ice jams at Fort McMurray is to use logistic models such as fuzzy logic to determine a long term forecast of the likelihood of ice jam (Mahabir *et al.*, 2002). A long term forecast model would be used in late winter to identify if the following spring breakup has a low or high risk for ice jam formation. Finally, this research has demonstrated that simple forecasting models such as multiple linear regressions can be used to forecast ice jam occurrence on a short time basis (does not provide the severity of breakup before it occurs). This technique may be applicable at other sites if relevant information on the variables believed to influence breakup is available.

CHAPTER 6 REFERENCES

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APPENDIX A

Appendix A1 Freeze-up water level at the Water Survey Canada gauge on the Athabasca River below Fort McMurray for the years of 1972 to 2000

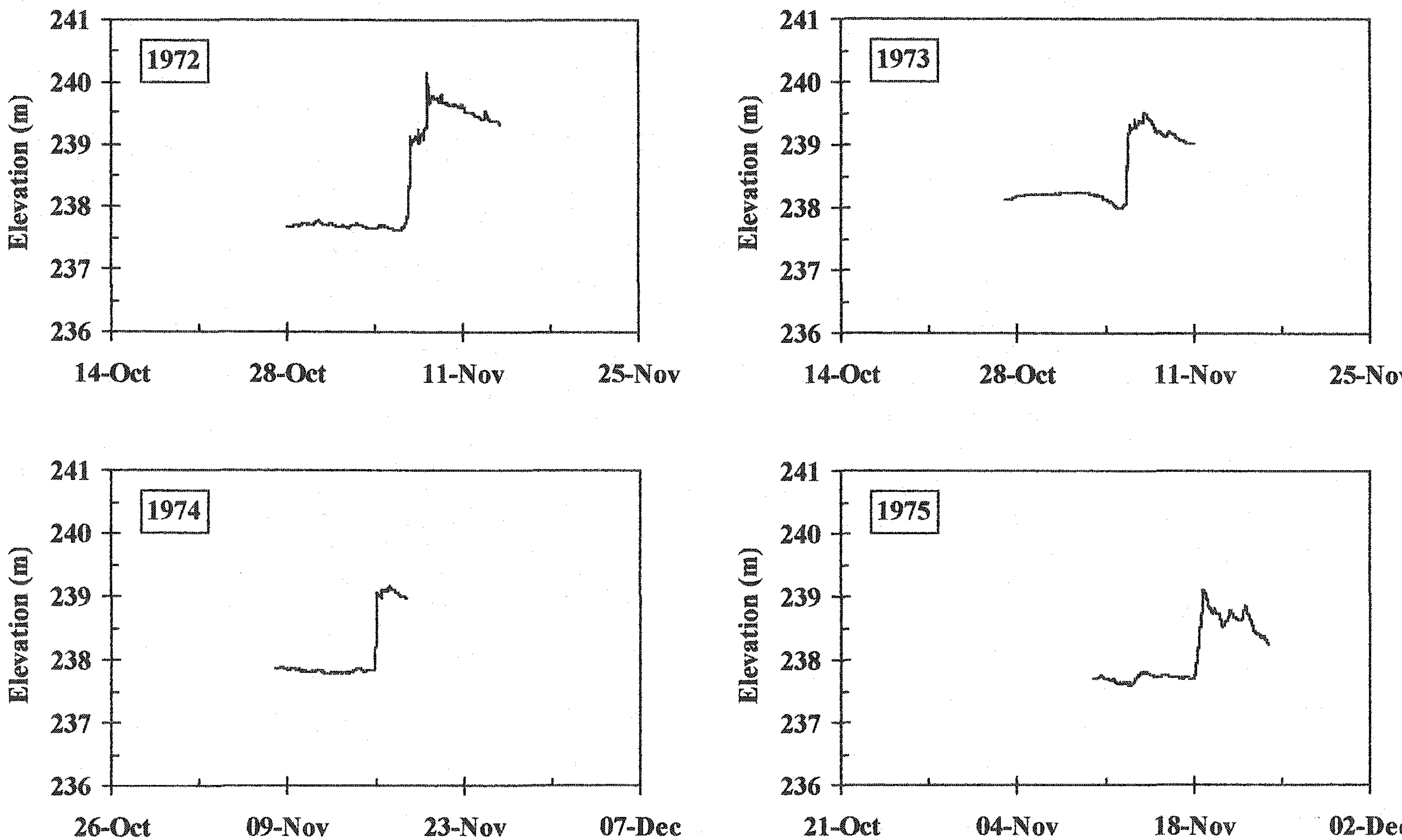


Figure A1.1: Water elevation during freeze-up for the years of 1972 to 1975 at the Water Survey Canada gauge below Fort McMurray.

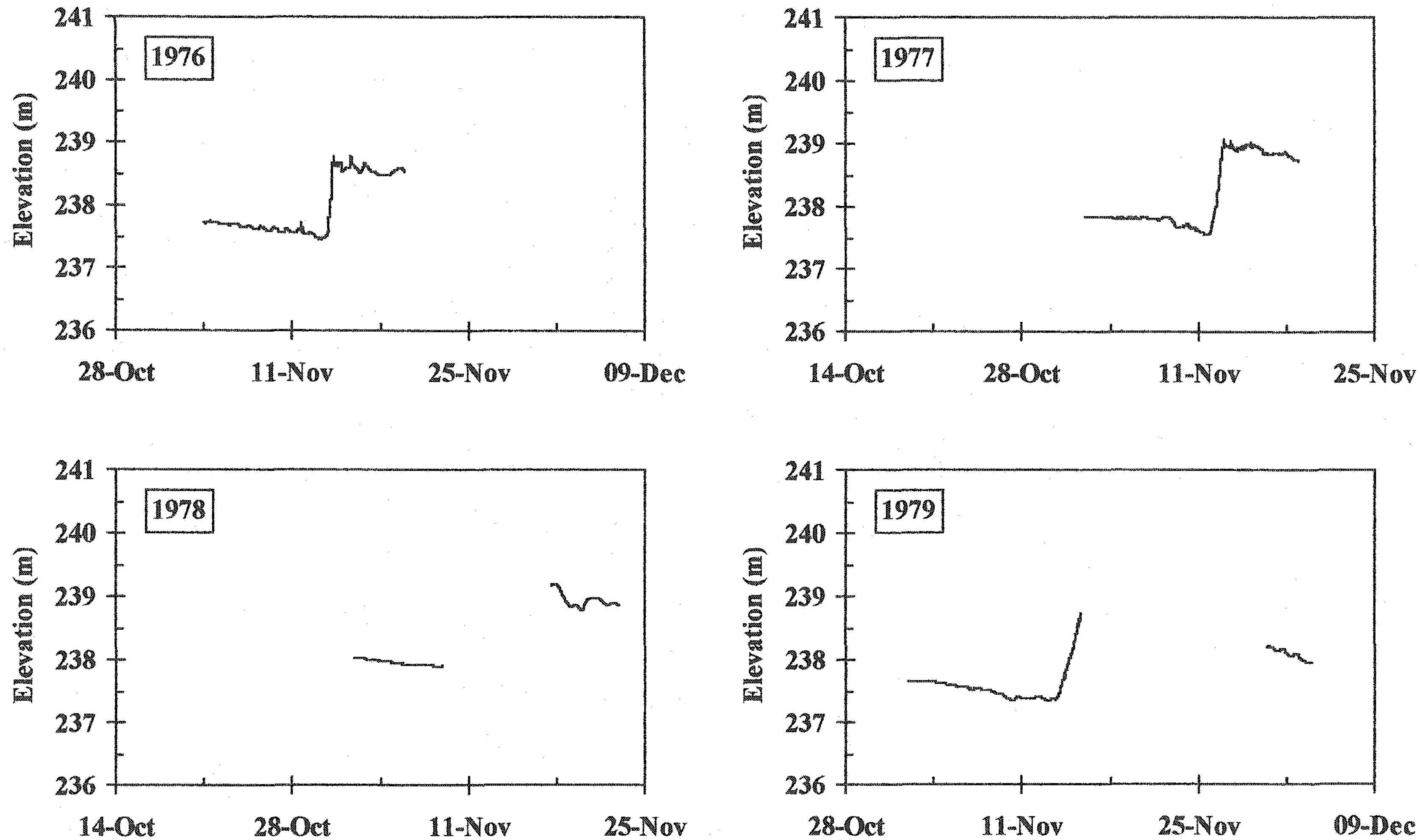


Figure A1.2: Water elevation during freeze-up for the years of 1976 to 1979 at the Water Survey Canada gauge below Fort McMurray.

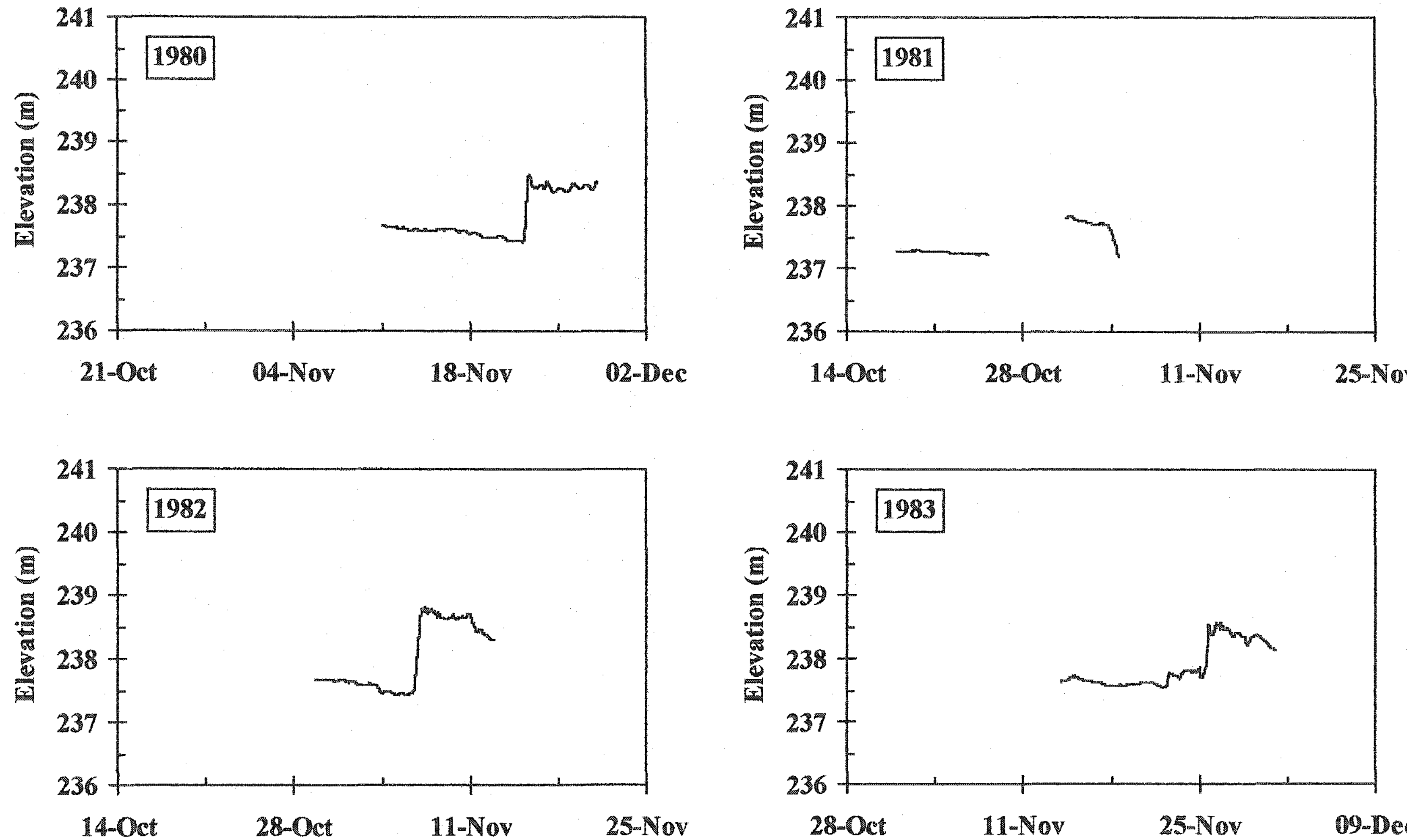


Figure A1.3: Water elevation during freeze-up for the years of 1980 to 1983 at the Water Survey Canada gauge below Fort McMurray.

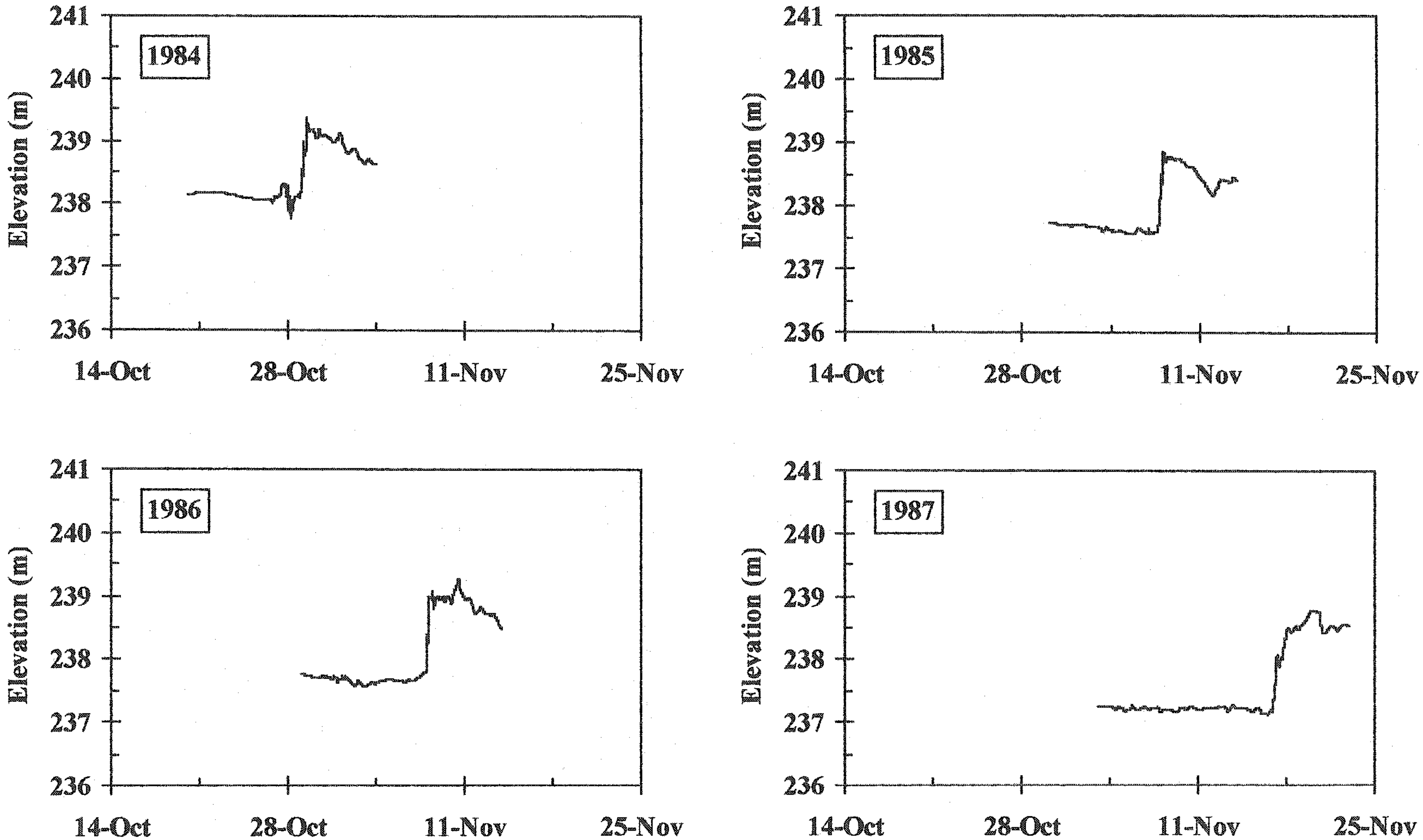


Figure A1.4: Water elevation during freeze-up for the years of 1984 to 1987 at the Water Survey Canada gauge below Fort McMurray.

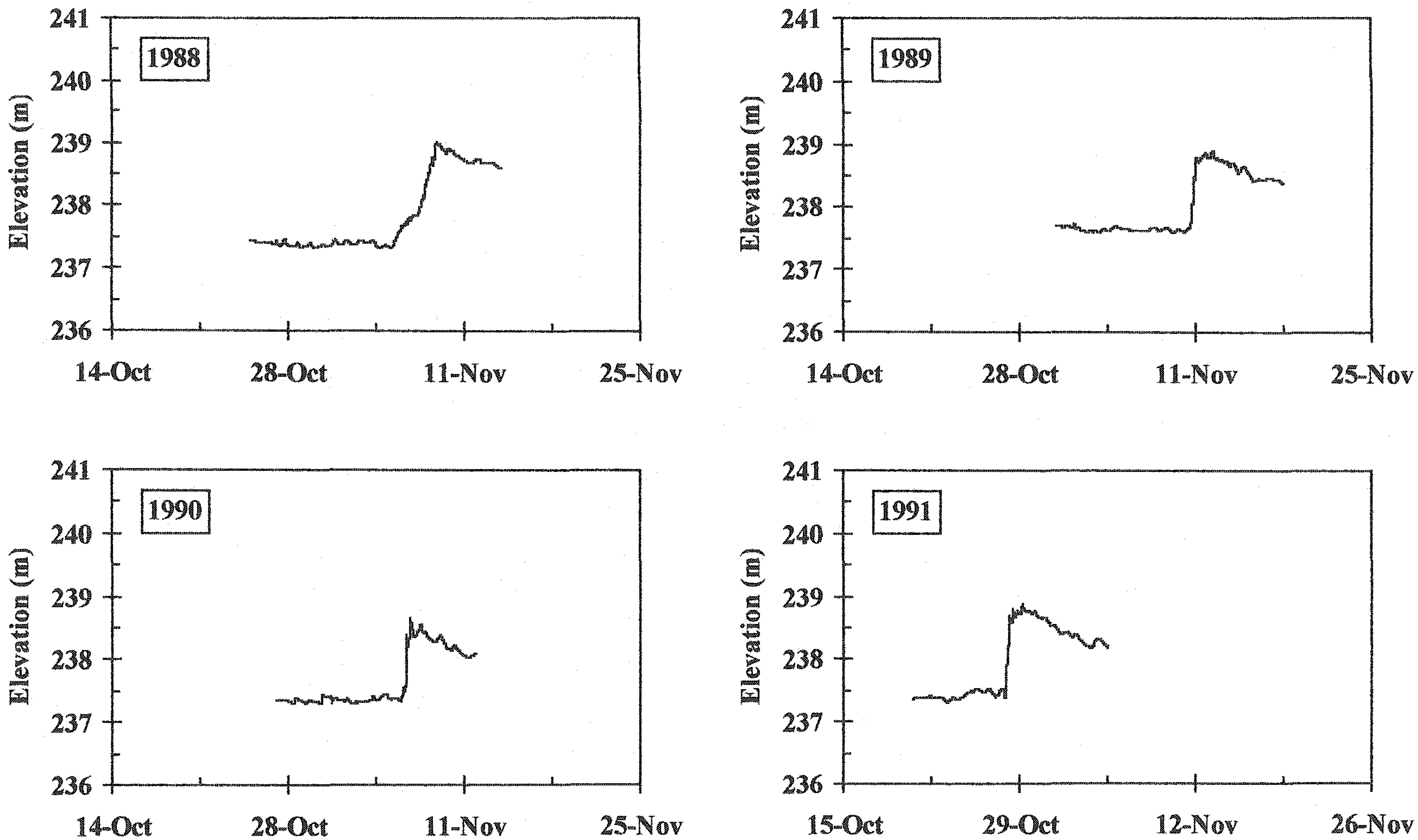


Figure A1.5: Water elevation during freeze-up for the years of 1988 to 1991 at the Water Survey Canada gauge below Fort McMurray.

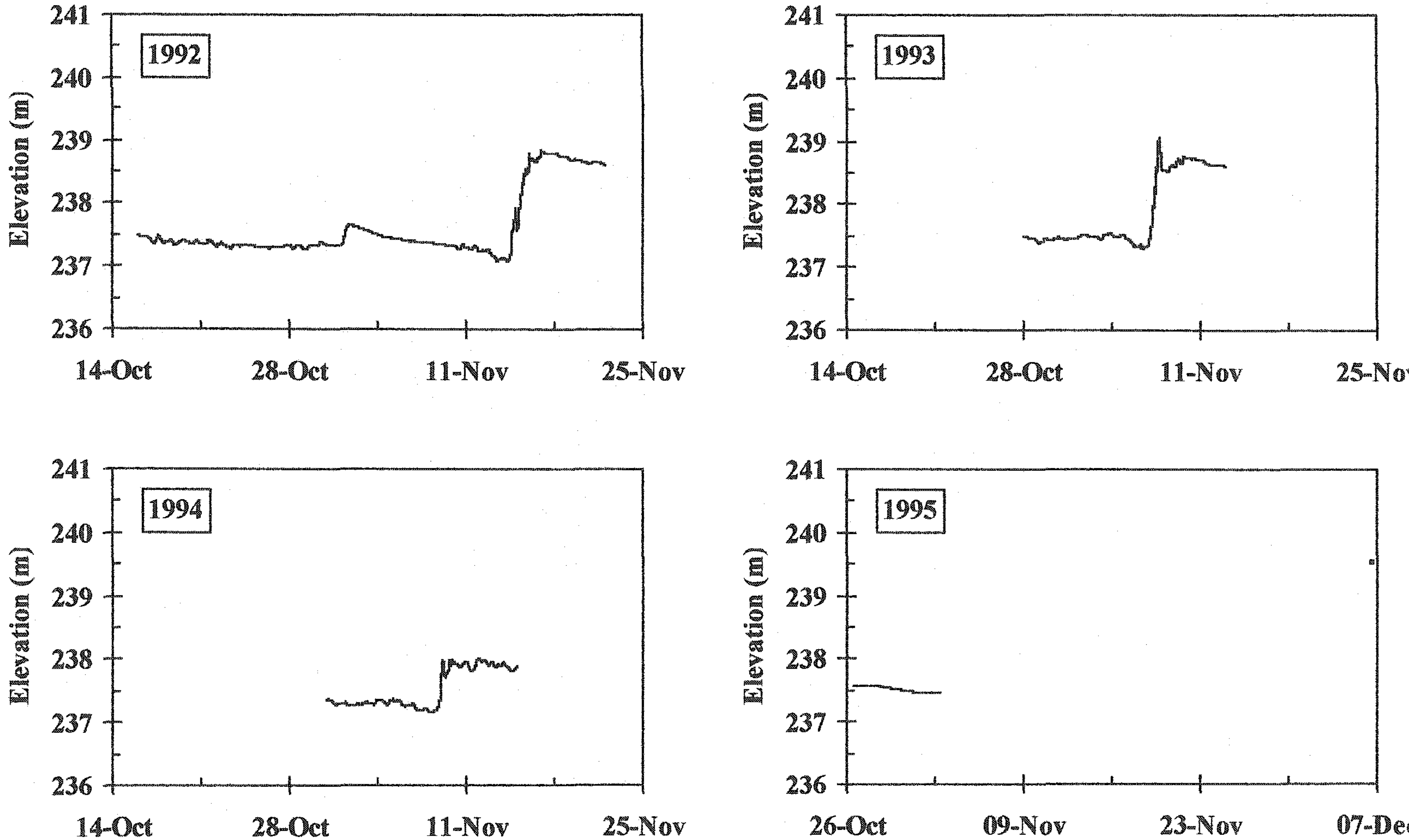


Figure A1.6: Water elevation during freeze-up for the years of 1992 to 1995 at the Water Survey Canada gauge below Fort McMurray.

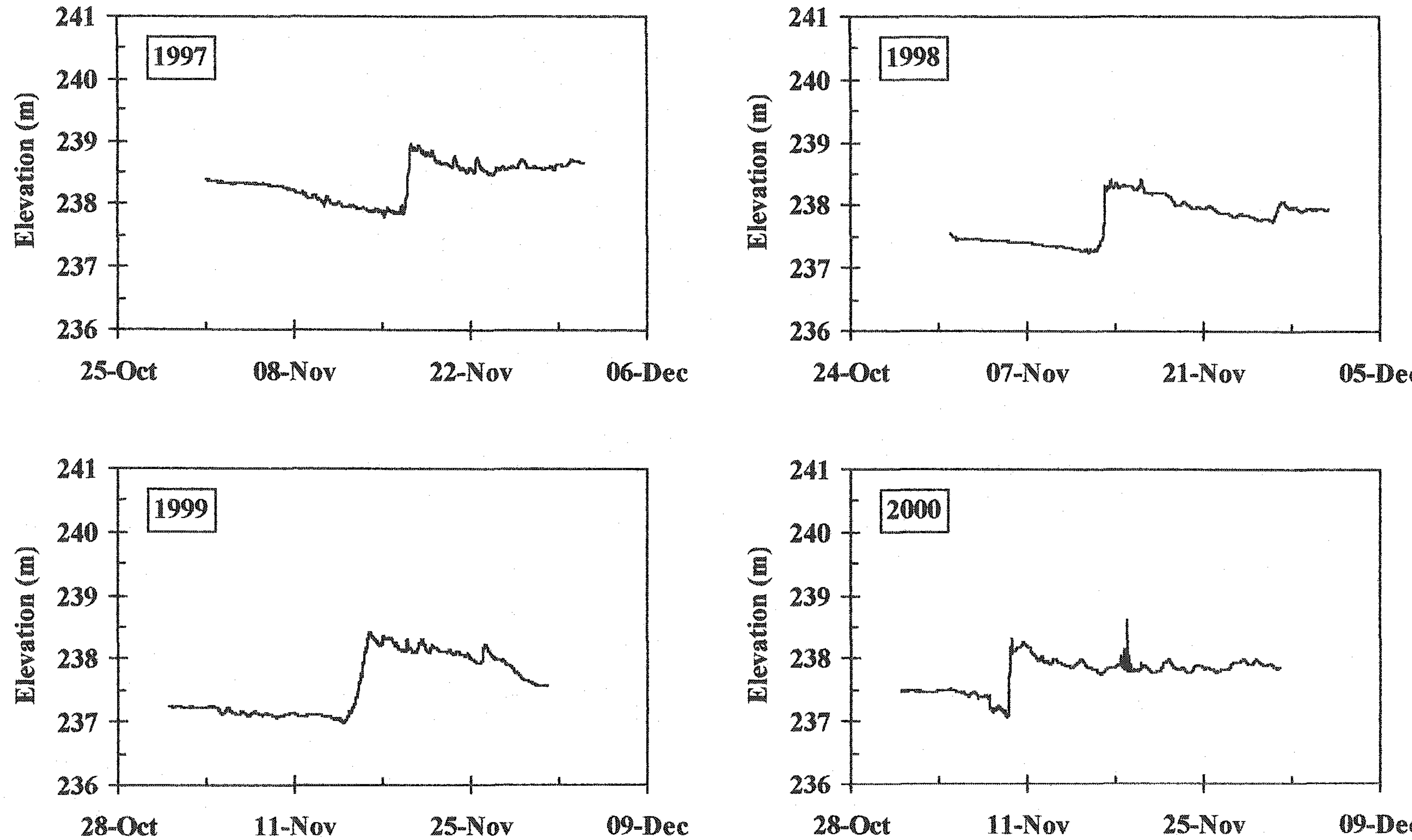


Figure A1.7: Water elevation during freeze-up for the years of 1997 to 2000 at the Water Survey Canada gauge below Fort McMurray.

Appendix A2 Breakup water level at the Water Survey Canada gauge on the Athabasca River below Fort McMurray for the years of 1972 to 2001

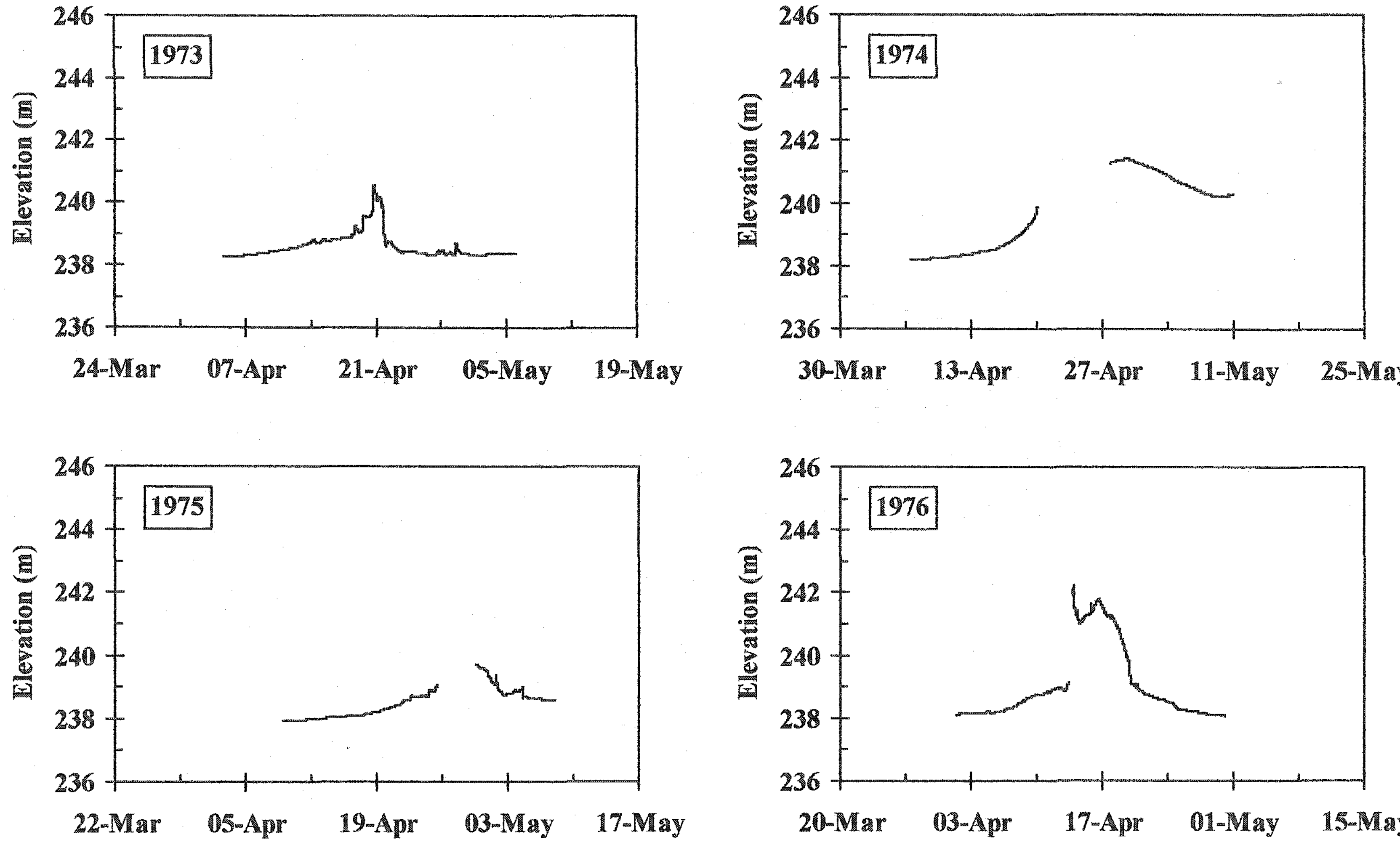


Figure A2.1: Water elevation during breakup for the years of 1973 to 1976 at the Water Survey Canada gauge below Fort McMurray.

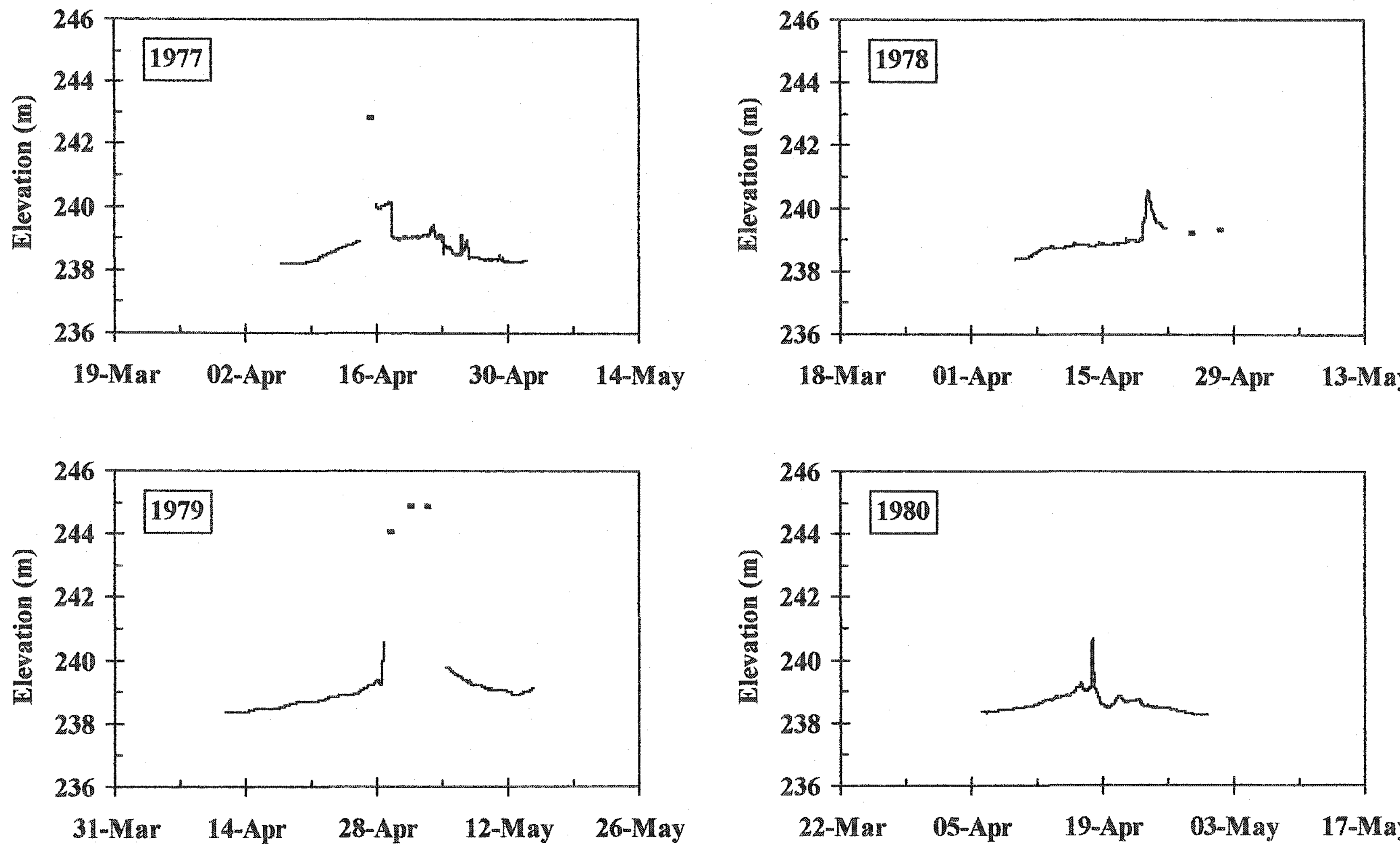


Figure A2.2: Water elevation during breakup for the years of 1977 to 1980 at the Water Survey Canada gauge below Fort McMurray.

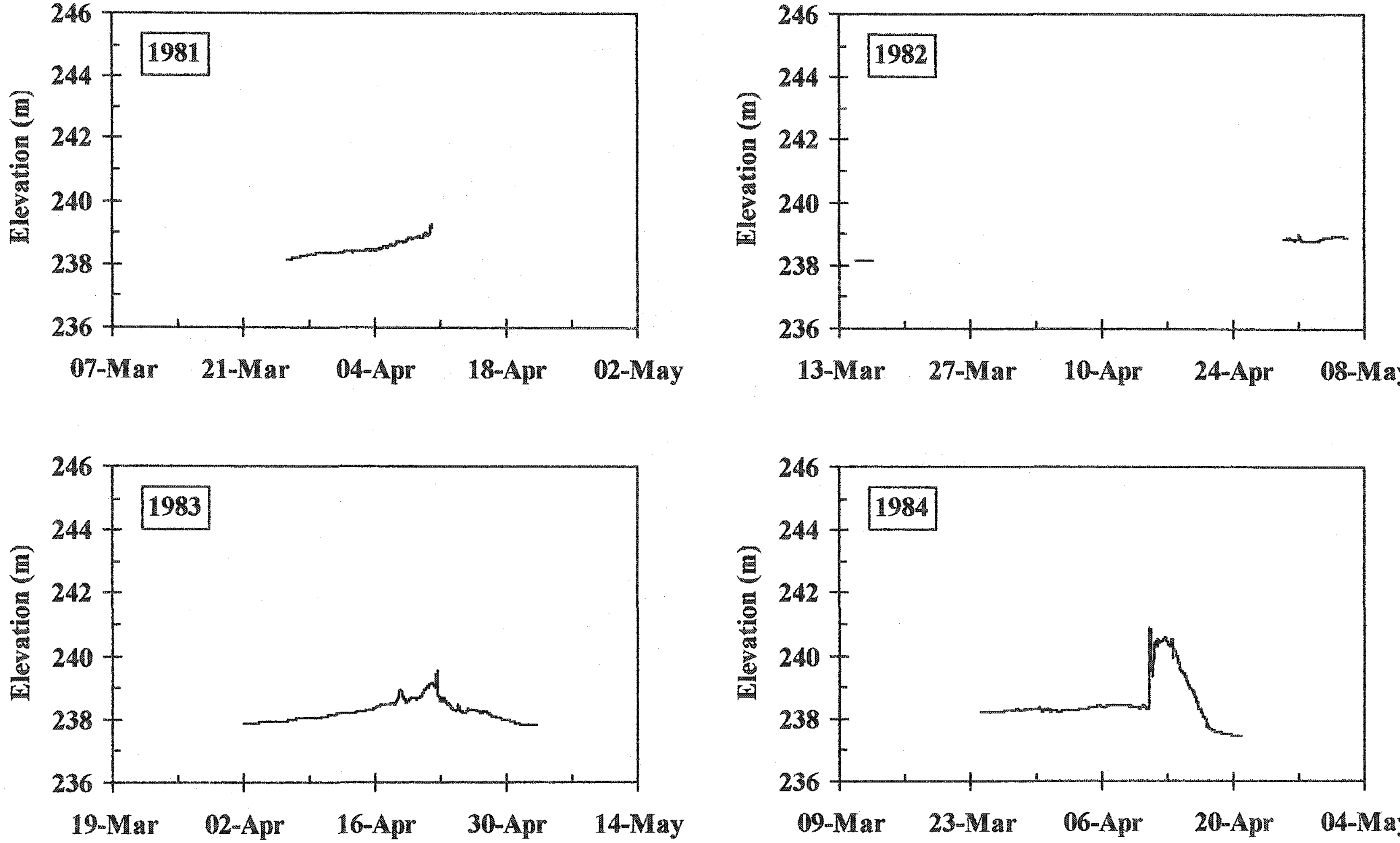


Figure A2.3: Water elevation during breakup for the years of 1981 to 1984 at the Water Survey Canada gauge below Fort McMurray.

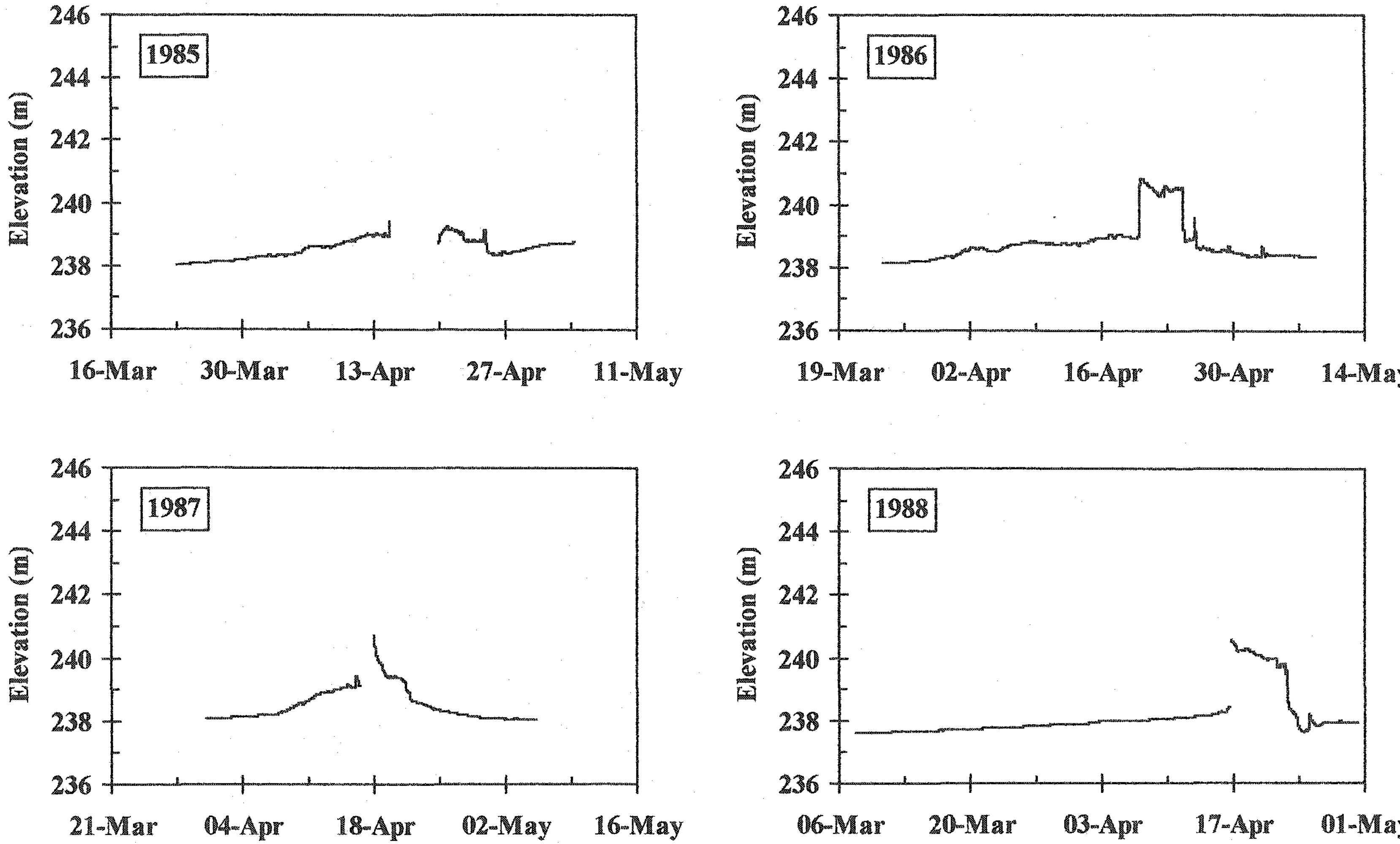


Figure A2.4: Water elevation during breakup for the years of 1985 to 1988 at the Water Survey Canada gauge below Fort McMurray.

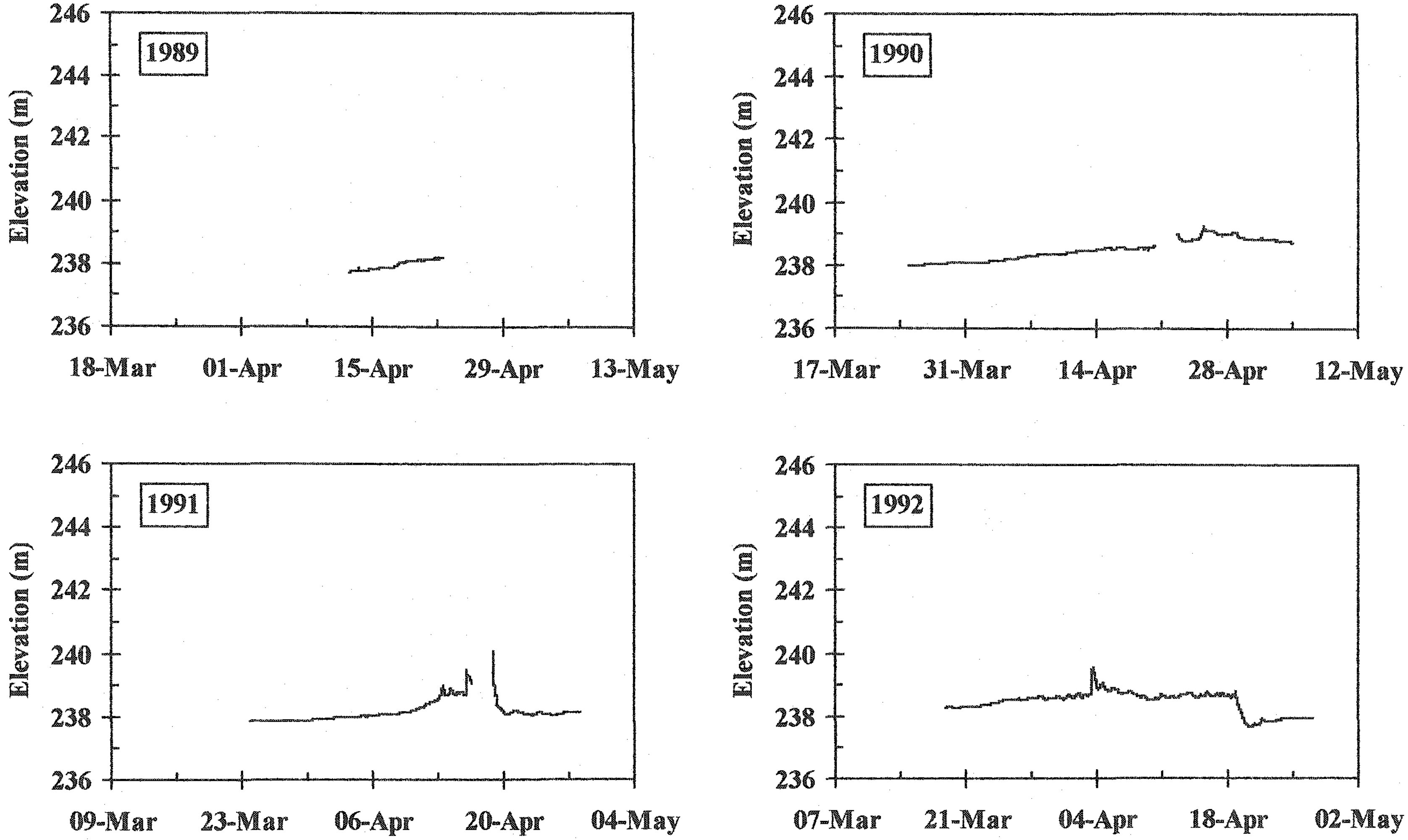


Figure A2.5: Water elevation during breakup for the years of 1989 to 1992 at the Water Survey Canada gauge below Fort McMurray.

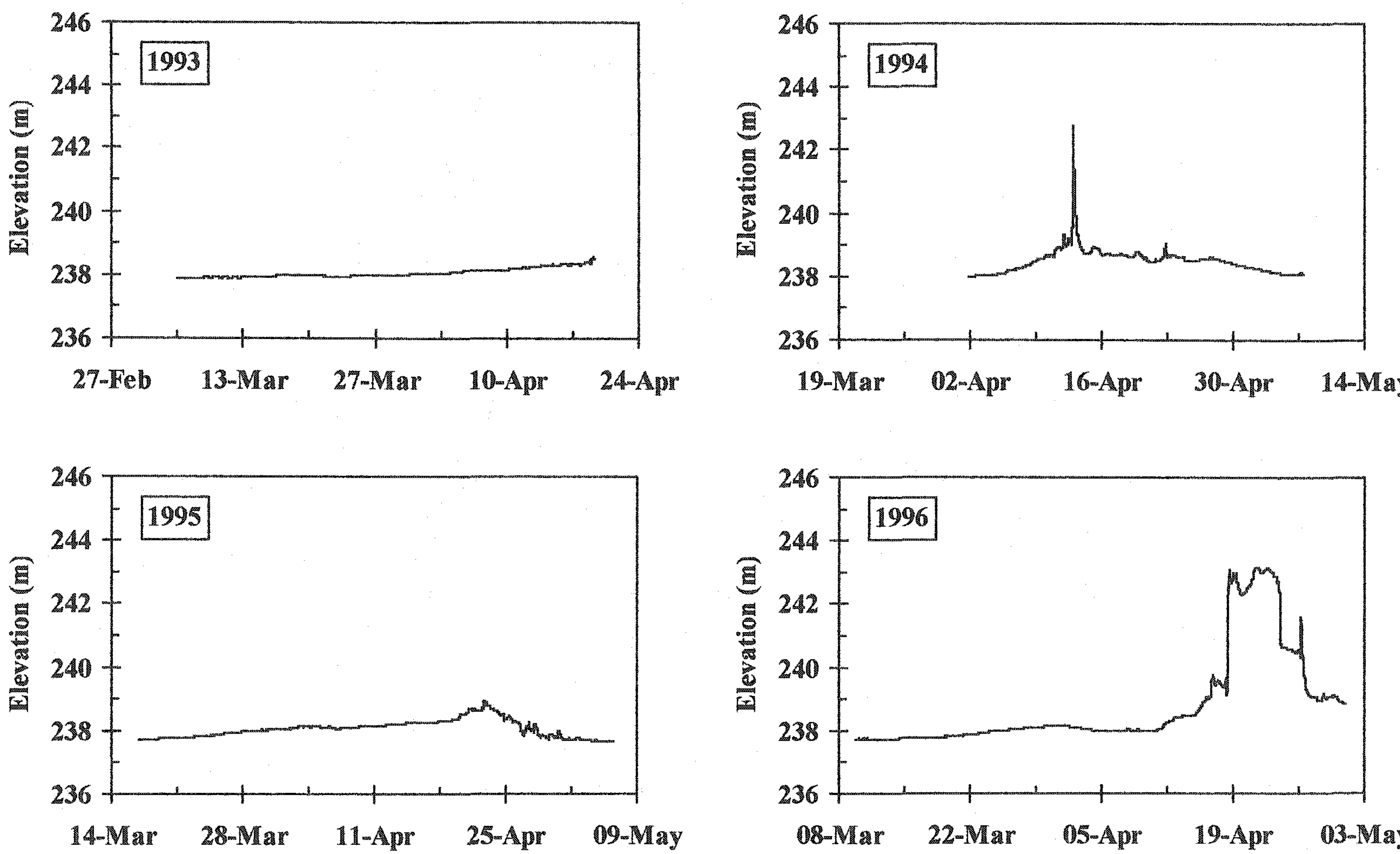


Figure A2.6: Water elevation during breakup for the years of 1993 to 1996 at the Water Survey Canada gauge below Fort McMurray.

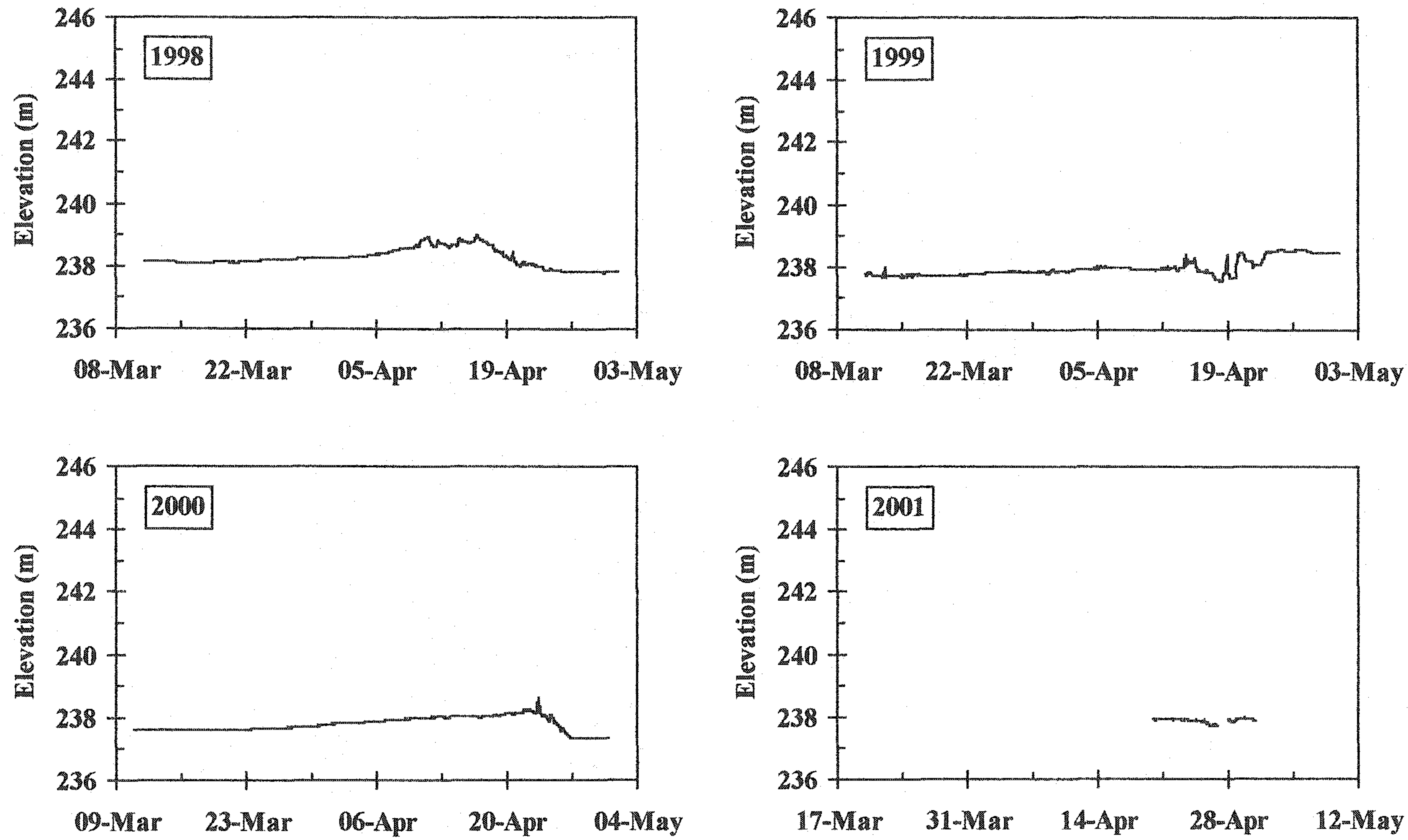


Figure A2.7: Water elevation during breakup for the years of 1998 to 2001 at the Water Survey Canada gauge below Fort McMurray.

Appendix A3 Ice thickness on the Athabasca River near Fort McMurray from Water Survey Canada winter survey

Year	Day	Ice Thickness (m)	Location	WSC Comments
1972	Oct. 17	-	-	Very little ice in river
	Nov. 24	Slush can not be separated from ice thickness	46 m upstream of MacEwan Bridge, 6.4 km above gauge	Ice cover, river surface very rough and large amount of slush found in cross-section (7 readings out of 22), approximately 27 m of cross-section with slush to bottom of riverbed
	Dec. 20	-	-	River surface very rough
1973	Jan. 10	Slush can not be separated from ice thickness	Measurement made at MacEwan Bridge, 9.7 km above gauge	Ice cover, snow cover light (0.61 m), approximately 0.76 m of ice with slush, slush (4 readings out of 26), approximately 4.6 m of cross-section with slush to bottom of riverbed
	Feb. 26	1.19 (11) [a,c]	18 m upstream side of MacEwan Bridge, 4.8 km above gauge	Ice cover, slush (6 readings out of 21)
	Apr. 2	1.62 (20)	4.8 km above gauge, measurement made upstream of MacEwan Bridge	Ice cover, ice thickness about 1.22 m, river surface rough and icy with pools of water forming on surface
	Apr. 4	-	-	River surface soft, partly frozen overflow, rough, pools of water forming
	Apr. 19	-	-	Open water at Fort MacKay and at GCOS Plant, very little ice flowing, a relatively small amount of ice piled on edges, ice not broken at bridge and gauge
	Apr. 24	-	-	Ice still not broken at bridge, open water along right edge and some overflow in center of river

Year	Day	Ice Thickness (m)	Location	WSC Comments
1973	May 2	-	-	Some ice piled on sandbars near gauge and a little bit along shore in places
	May 7	-	0.8 km below gauge	No ice
	Oct. 12	-	Below gauge	No ice
1974	Jan. 19	0.46 (16)	-	Ice cover, snow cover on section drifted and packed 0.15 to 0.30 m deep, section fairly smooth, no slush ice in storage under ice, ice thickness about 0.46 m
	Feb. 18	0.61 (19) c	30 m below gauge	Ice cover, average ice thickness 0.61 m, snow on river deep and becoming packed, slush (3 readings out of 22)
	Mar. 18	0.64 (19)	At gauge	Complete ice cover
	Apr. 15	0.61 (22)	At gauge	Ice cover, some snow remains on river, 2 open sections observed above gauge
	Dec. 9	0.30 (12) a	At gauge	Ice cover, some open leads
1975	Jan. 28	0.55 (18) c	At gauge	Complete ice cover, slush (1 reading out of 19)
	Mar. 15	0.73 (18)	At gauge	Ice cover
	Apr. 19	0.61 (19)	At gauge	Ice cover, open leads above measurement section
	Apr. 26	-	-	River in process of breaking up
	Apr. 29	-	-	River flowing heavy ice
	Oct. 7	-	0.3 km below gauge	No ice
	Dec. 18	0.64 (17)	-	Ice cover, slush (8 readings out of 25), approximately 43 m of cross-section with slush to bottom of riverbed

Year	Day	Ice Thickness (m)	Location	WSC Comments
1976	Jan. 16	0.76 (19) [a,c]	At gauge	Complete ice cover, slush (1 reading out of 21)
	Feb. 20	0.82 (20) [c]	At gauge	Complete ice cover, slush (1 reading out of 21), approximately 6 m of cross-section with slush to bottom of riverbed
	Mar. 8	0.85 (21)	At gauge	Complete ice cover
	Apr. 1	0.82 (21)	-	Ice cover, some overflow present
	Apr. 10	-	-	Ice broken out in places, open holes all across channel
	Apr. 17	-	-	Ice on sandbars and on banks below gauge, probably 0.30 to 0.46 m of backwater, also ice flowing in stream
	May 7	-	0.8 km below gauge	No ice
	Dec. 4	0.55 (12) [a,c]	0.8 km below gauge at summer section	Complete ice cover, slush (5 readings out of 21), approximately 61 m of cross-section with slush to bottom of riverbed
	Dec. 17	0.67 (17) [c]	0.8 km below gauge	Complete ice cover, slush (4 readings out of 21)
1977	Jan. 21	0.85 (20)	0.4 km below gauge	Complete ice cover, average ice thickness 0.85 m
	Feb. 18	0.91 (20)	0.8 km below gauge	Complete ice cover, average ice thickness 0.91 m
	Mar. 30	0.88 (21) [a]	0.8 km below gauge	Complete ice cover, average ice thickness 0.94 m
	Apr. 15	-	-	Lots of ice in area above and below gauge, large ice jam at mouth of Clearwater

Year	Day	Ice Thickness (m)	Location	WSC Comments
1977	Apr. 17	-	-	Large ice jam above gauge, ice on edge below gauge, very little velocity on right bank, high velocity on left bank, this is the opposite of normal
	Apr. 21	-	-	Ice jam above gauge
	Apr. 26	-	-	Some ice flowing, large jam above gauge blocking right channel of river, no ice below gauge, channel conditions severely changed due to ice jam, the sandbar that was located in front of the gauge has moved downstream
	Oct. 27	-	0.8 km below gauge	No ice
	Dec. 19	0.73 (23)	0.4 km below gauge	Complete ice cover
1978	Jan. 16	0.79 (26)	0.8 km below gauge	Complete ice cover, average ice thickness 0.79 m
	Feb. 4	0.82 (25)	1.6 km below gauge	Complete ice cover
	Mar. 8	0.91 (17)	-	Complete ice cover
	Apr. 2	0.88 (28)	0.4 km below gauge	Complete ice cover, some open leads
	Apr. 12	-	-	Open hole in ice at gauge
	Apr. 18	-	-	Ice cover, open hole at gauge and an open channel below gauge
	Apr. 24	-	-	Ice has not moved out, open channel out from gauge
	Apr. 27	-	-	Ice jam at bridge in Fort McMurray, ice jammed at gauge
	Nov. 17	-	-	Open area at gauge, but jammed everywhere else

Year	Day	Ice Thickness (m)	Location	WSC Comments
1978	Dec. 5	0.37 (6) $_{ac}$	0.4 km below gauge	Complete ice cover, slush (6 readings out of 22), approximately 15 m of cross-section with slush to bottom of riverbed
	Dec. 18	0.43 (7) $_{ac}$	0.4 km below gauge	Complete ice cover, slush (9 readings out of 24), approximately 76 m of cross-section with slush to bottom of riverbed
1979	Jan. 11	0.61 (15) $_{ac}$	0.4 km below gauge	Complete ice cover, slush (7 readings out of 24), approximately 69 m of cross-section with slush to bottom of riverbed
	Feb. 14	0.67 (18) $_{ac}$	0.4 km below gauge	Complete ice cover, slush (5 readings out of 24), approximately 130 m of cross-section with slush to bottom of riverbed
	Mar. 8	0.85 (19) $_{c}$	0.5 km below gauge	Complete ice cover, slush (5 readings out of 24), approximately 114 m of cross-section with slush to bottom of riverbed
	Apr. 3	0.88 (18) $_{ac}$	0.8 km below gauge	Complete ice cover, some overflow on ice, open hole above gauge, slush (2 readings out of 24)
	Apr. 21	1.10 (19) $_{c}$	61 m below MacEwan Bridge	Ice cover, open holes along left bank at gauge, slush (1 readings out of 21)
	Apr. 25	-	-	Ice has open leads above and below gauge, ice has lifted but not moved
	Apr. 29	-	-	Ice jam 8.0 km below gauge
	May 1	-	-	Ice still jammed at gauge and at town, high water mark 244.969
	May 3	-	-	Ice jammed at gauge and above
	May 5	-	-	Lots of ice flowing, still some backwater
	May 14	-	-	Some ice on banks and islands, probably normal

Year	Day	Ice Thickness (m)	Location	WSC Comments
1979	May 24	-	-	No ice
	Oct. 22	-	1.6 km below gauge	No ice
	Nov. 15	-	-	Slush pans flowing, back channels are frozen
	Nov. 30	0.31 (16) [a,c]	-	Ice cover, open channel 20 m below gauge, measuring conditions poor, slush (14 readings out of 35), approximately 185 m of cross-section with slush to bottom of riverbed
1980	Jan. 11	0.59 (21) [a,c]	0.5 km below gauge	Ice cover, slush (5 readings out of 28), approximately 25 m of cross-section with slush to bottom of riverbed, approximately 5 m of ice to bottom of riverbed on left bank
	Feb. 7	0.90 (15) [a,c]	1 km below gauge	Ice cover, slush (4 readings out of 26), approximately 60 m of cross-section with ice to bottom of riverbed
	Mar. 6	0.80 (21) [c]	1 km below gauge	Ice cover, slush (3 readings out of 26), approximately 60 m of cross-section with ice to bottom of riverbed
	Apr. 2	0.80 (17) [a,c]	0.5 km below gauge	Ice cover, slush (3 readings out of 27), approximately 75 m of cross-section with ice to bottom of riverbed
	Apr. 11	0.69 (20) [a,c]	0.5 km below gauge	Complete ice cover at gauge, open water along left bank at measurement section, slush (3 readings out of 27), approximately 55 m of cross-section with ice to bottom of riverbed

Year	Day	Ice Thickness (m)	Location	WSC Comments
1980	Apr. 22	-	-	Ice pans flowing and ice piled along banks
	May 21	-	1 km below gauge	No ice, river very low for May
	Dec. 13	0.57 (28) $_{a c}$	0.5 km below gauge	Complete ice cover, slush (10 readings out of 39), approximately 15 m of cross-section with slush to bottom of riverbed
1981	Jan. 23	0.71 (19) $_{a}$	1 km below gauge	Complete ice cover, some slush in measurement section
	Feb. 18	0.73 (15) $_{a c}$	1 km below gauge	Complete ice cover, slush (2 readings out of 20), approximately 75 m of cross-section with ice to bottom of riverbed
	Mar. 25	0.75 (19) $_{a}$	Below gauge	Ice cover
	Apr. 16	-	-	Complete ice cover at gauge
	Oct. 31	-	-	Complete ice cover at gauge, open leads upstream and downstream
	Dec. 10	0.30 (8) $_{c}$	0.1 km below gauge	Compete ice cover at gauge, slush at measurement section (12 readings out of 20), no flow on left side of sandbar (left bank)
1982	Jan. 15	0.57 (9) $_{a c}$	0.5 km above MacEwan Bridge	Ice cover, slush (17 readings out of 32), approximately 110 m of cross-section with slush to bottom of riverbed
	Feb. 19	0.58 (24) $_{c}$	Below gauge at summer boat measurement site	Ice cover, slush (5 readings out of 29), approximately 40 m of cross-section with slush to bottom of riverbed
	Mar. 27	0.65 (26) $_{a c}$	1 km below gauge at boat measurement section	Ice cover, slush (2 readings out of 29)
	Apr. 24	-	-	Complete ice cover at gauge

Year	Day	Ice Thickness (m)	Location	WSC Comments
1982	Apr. 29	-	-	Some ice pans flowing, ice piled along edges
	Oct. 29	-	-	Slush flowing
	Dec. 16	0.46 (12) [c]	0.1 km below gauge	Ice cover, slush (6 readings out of 18)
1983	Jan. 19	0.53 (11) [a c]	-	Ice cover, slush (1 reading out of 18)
	Mar. 12	0.54 (11) [a b]	0.1 km below gauge	Ice cover
	Apr. 19	-	-	¾ of ice cover at gauge
	Dec. 12	0.37 (15) [c]	50 m below gauge	Complete ice cover at gauge, slush (5 readings out of 20)
1984	Jan. 12	0.71 (15)	60 m below gauge	Complete ice cover
	Mar. 6	0.81 (15)	80 m below gauge	Ice cover
	Apr. 6	-	-	River starting to open up on sides
	Apr. 12	-	-	River went out at Fort McMurray at 00:26 Apr. 11th according to H. Rickert from Alberta Environment, ice jammed up at gauge
	Apr. 16	-	-	Could not level, ice piled high on banks
	Dec. 13	0.58 (18)	80 m below gauge	Complete ice cover
1985	Jan. 14	0.68 (19)	75 m below gauge	Full ice cover
	Mar. 14	0.79 (24)	75 m below gauge	Complete ice cover
	Apr. 2	0.73 (20)	Below gauge	Full ice cover
	Apr. 10	-	-	Open lead upstream of gauge
	Apr. 25	-	-	Light ice flowing
	Nov. 1	-	-	Slush starting to flow, likely no backwater due to ice

Year	Day	Ice Thickness (m)	Location	WSC Comments
1986	Jan. 9	0.96 (31)	30 m below gauge	Ice cover
	Mar. 7	1.01 (31)	At gauge	Complete ice cover
	Apr. 12	-	-	Ice unsafe (80% ice cover), open leads everywhere
	Apr. 15	1.05 (17)	Above gauge, upstream of MacEwan Bridge	Ice cover
	May 11	-	2 km below gauge	No ice
	Nov. 1	-	-	Ice flowing
1987	Jan. 14	0.62 (28) [a]	At gauge	Ice cover, approximately 20 m of cross-section with ice to bottom of riverbed
	Mar. 7	0.78 (21)	At gauge	Complete ice cover at gauge
	Mar. 8	-	-	Complete ice cover at gauge
	Mar. 9	0.87 (22)	1 km above MacEwan Bridge	Ice cover
	Apr. 7	0.87 (22)	1 km above MacEwan Bridge	Ice cover, water pooling on ice, some open holes
	Apr. 9	-	-	Complete ice cover at gauge, open leads just downstream of gauge, stage rising
	Apr. 29	-	Below gauge	No ice
	Nov. 3	-	1 km below gauge	No ice
1988	Jan. 5	0.42 (21)	5 km above gauge	Complete ice cover, very little slush
	Jan. 6	-	-	Complete ice cover at gauge
	Mar. 4	-	-	Complete ice cover at gauge
	Mar. 6	0.63 (20)	At water treatment plant	Complete ice cover
	Apr. 10	-	-	Complete ice cover at gauge, some open leads
	Apr. 12	0.66 (25)	2 km above gauge	Complete ice cover throughout and some open leads along left edge

Year	Day	Ice Thickness (m)	Location	WSC Comments
1988	May 8	-	1 km below gauge	No ice
	Nov. 4	-	-	Ice along both edges, steady flowing ice pans
	Dec. 13	0.46 (17) $_{a c}$	5 km above gauge at water treatment plant	Complete ice cover, slush (3 readings out of 21)
	Dec. 14	-	-	Complete ice cover at gauge
1989	Jan. 9	0.50 (19) $_{a c}$	5 km above gauge	Ice cover, slush (4 readings out of 24), approximately 20 m of cross-section with slush to bottom of riverbed
	Jan. 10	-	-	Complete ice cover at gauge
	Feb. 8	0.60 (24)	Fort McMurray	Ice cover, slush (7 readings out of 24)
	Mar. 6	0.76 (24)	5 km above gauge	Complete ice cover at gauge, slush (5 readings out of 24)
	Apr. 11	0.83 (24) $_{c}$	5 km above gauge	Complete ice cover at measurement section and throughout, slush (2 readings out of 26)
	Apr. 12	0.62 (22)	1 km below gauge	Complete ice cover at gauge and measurement section
	Oct. 24	-	2 km below gauge	No ice
	Dec. 5	0.37 (6) $_{a c}$	1 km below gauge	Complete ice cover at gauge, lots of slush ice, slush (17 readings out of 24), approximately 80 m of cross-section with slush to bottom of riverbed
1990	Jan. 9	0.54 (12) $_{a c}$	1 km below gauge	99% complete ice cover, open lead just below gauge, slush (9 readings out of 22), approximately 20 m of cross-section with slush to bottom of riverbed

Year	Day	Ice Thickness (m)	Location	WSC Comments
1990	Mar. 4	0.69 (26) [c]	1 km below gauge	Complete ice cover at gauge and throughout, lots of snow (0.5 to 0.7m), slush (2 readings out of 28)
	Apr. 7	0.63 (26)	1 km below gauge	Complete ice cover at gauge and throughout
	May 6	-	1 km below gauge	No ice
	Oct. 26	-	-	Ice along both edges with ice pans flowing
	Dec. 4	0.38 (8) [a,c]	1 km below gauge	Complete ice cover at gauge, slush (15 readings out of 24)
1991	Jan. 9	0.66 (20) [c]	1 km below gauge	Complete ice cover at gauge and throughout, slush (5 readings out of 25), approximately 20 m of cross-section with slush to bottom of riverbed
	Feb. 27	0.77 (23) [c]	1 km below gauge	Complete ice cover, slush (1 reading out of 24)
	Apr. 5	0.77 (26)	1.5 km below gauge	Complete ice cover at and below gauge
	May 5	-	1 km below gauge	No ice
	Dec. 4	0.64 (21)	1 km below gauge at boat measurement site	Ice cover, no slush
1992	Jan. 8	0.74 (21)	1 km below gauge	Complete ice cover, slush (1 reading out of 21)
	Mar. 8	0.83 (26)	1 km below gauge at open water site	Ice cover, slush
	Apr. 1	0.75 (25)	1 km below gauge	Complete ice cover, no slush
	May 5	-	1.5 km below gauge	No ice
	Oct. 15	-	1 km below gauge	No ice

Year	Day	Ice Thickness (m)	Location	WSC Comments
1993	Jan. 7	0.76 (24)	1 km below gauge	Complete ice cover, lots of ice ridges, slush (1 reading out of 24)
	Mar. 5	0.96 (25)	1 km below gauge	Ice cover, lots of melt water on ice, no slush
	Apr. 2	0.82 (25) [b]	1 km below gauge	Complete ice cover
	May 1	-	-	Steady stream, mini bergs in middle of river
	May 3	-	1 km below gauge	No ice flowing
	Oct. 14	-	1 km below gauge	No ice
	Dec. 16	0.51 (21)	1 km below gauge	Complete ice cover, slush (6 readings out of 21)
1994	Jan. 6	0.57 (23)	1 km below gauge	Ice cover, slush (2 readings out of 23)
	Mar. 6	0.81 (26)	1 km below gauge	Complete ice cover, 0.8% of slush area at cross-section (1 reading out of 26)
	Apr. 9	0.68 (25)	1 km below gauge at open water site	Ice cover, small open lead, right bank at gauge, no slush
	May 15	-	1 km below gauge	No ice
	Oct. 16	-	0.5 km below gauge	No ice
	Dec. 14	0.60 (24)	1 km below gauge	Complete ice cover, 16.4% of slush area at cross-section (3 readings out of 24)
1995	Jan. 4	0.70 (25)	1 km below gauge	Ice cover, 4.0% of slush area at cross-section (4 readings out of 25)
	Mar. 7	0.83 (25)	1 km below gauge at summer section	Complete ice cover, no slush
	Mar. 31	0.85 (24)	1 km below gauge at summer section	Complete ice cover, no slush
	May 13	-	1 km below gauge	No ice
	Oct. 29	-	1 km below gauge	No ice

Year	Day	Ice Thickness (m)	Location	WSC Comments
1995	Dec. 6	0.47 (28)	1 km below gauge at summer section	Complete ice cover, 23.8% of slush area at cross-section (11 readings out of 28)
1996	Jan. 4	0.63 (24)	1 km below gauge	Complete ice cover, no slush
	Mar. 9	0.75 (27)	1 km below gauge	Complete ice cover, no slush
	Apr. 16	0.73 (25)	1 km below gauge	Ice cover, large open lead at gauge in middle and along right bank, very little snow cover, no slush
	Dec. 11	0.48 (11) [a]	1 km below gauge	Complete ice cover at gauge and throughout, no slush
1997	Mar. 12	0.77 (24)	-	Complete ice cover, 8.5% of slush area at cross-section (3 readings out of 24)
1998	Jan. 29	0.69 (19)	5 km below gauge	Ice cover, no slush, little flow on left edge
	Mar. 12	0.58 (23)	1.6 km below gauge	Ice cover, 0.7 m of ice at gauge, 2.4% of slush area at cross-section (1 reading out of 23), river has a lot of flow through bridge channel at measurement site, poor velocity distribution, very low discharge, some panels with no discharge
	Apr. 21	-	-	River clear of ice except pans flowing, spare ice on west bank above confluence of Clearwater
	Oct. 23	-	0.8 km below gauge	No ice
	Dec. 15	0.45 (24)	5 km below gauge	Complete ice cover, very little slush, some open leads
1999	Jan. 28	0.56 (22)	Below gauge	Complete ice cover, no slush

Year	Day	Ice Thickness (m)	Location	WSC Comments
1999	Mar. 11	-	Approximately 5 km below gauge, 2 km below sawmill	Ice cover
	Apr. 8	0.81 (20)	10 to 12 km below gauge at winter road crossing	Ice cover, ice is rotting away, ice is saturated and candled, numerous holes, no slush
	May 5	-	-	No ice
	May 7	-	Downstream side of bridge, 5.6 km above gauge, above confluence of Clearwater	No ice
	Dec. 20	0.40 (20)	Downstream side of MacEwan Bridge above confluence of Clearwater	Complete ice cover, ice cover very irregular, a lot of slush in cross-sections (13 readings out of 20), approximately 60 m of cross-section with slush to bottom of riverbed
	Dec. 21	-	-	Complete ice cover at gauge
2000	Dec. 13	0.40 (25)	Athabasca River below Fort McMurray	Ice cover, 6.1% of slush area at cross-section (3 readings out of 25)
2001	Jan. 23	0.54 (24)	-	Complete ice cover at gauge
	Mar. 8	0.64 (23)	8 km below gauge	Ice cover, some open leads, flow in 2 channels
	Mar. 28	0.67 (24)	Approximately 8 km below gauge	Complete ice cover at gauge, water pooling on ice, cracks appearing, measured total ice thickness of 0.72 m
	May 7	-	-	No ice left

[a] Omitted ice thickness values that are believed to be affected by slush
[b] It appears that the ice was melting on left bank
[c] Omitted ice thickness measurements affected by slush

Note: When slush was believed to affect the ice thickness measurements, a value of at least 10 cm was used to separate the readings affected by slush from the ones with no slush.

Appendix A4 Breakup date, maximum water elevations during breakup, and location of ice jams available from 1875 to 2001

Year	Breakup Date	Source	Maximum Water Elevation (m)	Location of Ice Jam	Other Elevations	Comments
1875	Apr. 20	1. Hudson's Bay Co. archives as referred to in Blench and Associates Ltd. (1964) 2. Moberly and Cameron (1929) as referred to in Blench and Associates Ltd. (1964)	251.5 – 253.0 at Hudson's Bay Co. post on Apr. 20	Jammed on Apr. 20	252.0 [a]	Largest flood on record
1881	Apr. 21	Hudson's Bay Co. archives as referred to in Blench and Associates Ltd. (1964)	< 250 at Hudson's Bay Co. post on Apr. 21	Between MacDonald Island and the little island opposite to the Hudson's Bay Co. post, formed on Apr. 21	249.0 [a]	Flood
1885	Apr. 9	Hudson's Bay Co. archives as referred to in Blench and Associates Ltd. (1964)	249.0 at Hudson's Bay Co. post	Jammed on Apr. 9	248.1 [a]	Flood
1925		Northern Alberta Railways Co. as referred to in Blench and Associates Ltd. (1964)	247.4 at Waterways	Ice jam		Flood

Year	Breakup Date	Source	Maximum Water Elevation (m)	Location of Ice Jam	Other Elevations	Comments
1928		Northern Alberta Railways Co. as referred to in Blench and Associates Ltd. (1964)	248.6 at Waterways	Ice jam		Flood
1936	Apr. 21	Northern Alberta Railways Co. as referred to in Blench and Associates Ltd. (1964)	250.1 at Waterways on Apr. 22	Ice jam		Flood
1938	Apr. 27	D.O.T. Canada (1959)				
1939	Apr. 21	D.O.T. Canada (1959)				
1940	Apr. 25	D.O.T. Canada (1959)				
1941	Apr. 14	D.O.T. Canada (1959)				
1948	May 1	D.O.T. Canada (1959)				
1949	Apr. 15	D.O.T. Canada (1959)				

Year	Breakup Date	Source	Maximum Water Elevation (m)	Location of Ice Jam	Other Elevations	Comments
1950	Apr. 28	D.O.T. Canada (1959)				
1953	Apr. 21	D.O.T. Canada (1959)				
1954	May 9 [b]	D.O.T. Canada (1959)				
1955	Apr. 17	D.O.T. Canada (1959)				
1956	Apr. 20	D.O.T. Canada (1959)				
1957	Prior to May 3	D.O.T. Canada (1959)				
1958	Apr. 15	D.O.T. Canada (1959)				
		Department of Northern Affairs and National Resources as referred to in Blench and Associates Ltd. (1964)	244.9 at WSC gauge below Fort McMurray	Ice jam		No flood damage at Fort McMurray
1959	Apr. 13	McMurray office, D.O.T., as referred to in Blench and Associates Ltd. (1964)				

Year	Breakup Date	Source	Maximum Water Elevation (m)	Location of Ice Jam	Other Elevations	Comments
1960	Apr. 12	McMurray office, D.O.T., as referred to in Blench and Associates Ltd. (1964)				
	Apr. 15 [f]	Doyle (1987)				
1961	May 8 [b]	McMurray office, D.O.T., as referred to in Blench and Associates Ltd. (1964)				
	Apr. 28 [f]	Doyle (1987)				
1962	Apr. 24	McMurray office, D.O.T., as referred to in Blench and Associates Ltd. (1964)				
		Department of Northern Affairs and National Resources as referred to in Blench and Associates Ltd. (1964)	246.2 high water marks	Ice jam		Flood
	Apr. 17 [f]	Doyle (1987)	242.7 [h] at WSC gauge below Fort McMurray			

Year	Breakup Date	Source	Maximum Water Elevation (m)	Location of Ice Jam	Other Elevations	Comments
1963	Apr. 20	McMurray office, D.O.T., as referred to in Blench and Associates Ltd. (1964)				
		Department of Northern Affairs and National Resources as referred to in Blench and Associates Ltd. (1964)	247.5 on Athabasca River at the Snye and at the Northern Transportation Co. Ltd. Docks from high water marks	Across the Athabasca River just downstream of the Snye		Flood
		Doyle (1987)	244.1 [ch] at WSC gauge below Fort McMurray			
1964	Apr. 24	Blench and Associated Ltd. (1964)		Ice jam		Flood not severe
	Apr. 21 [f]	Doyle (1987)				
1965	Apr. 14 [f]	Doyle (1987)				
1966	Apr. 15 [f]	Doyle (1987)	239.6 [i] at WSC gauge below Fort McMurray			

Year	Breakup Date	Source	Maximum Water Elevation (m)	Location of Ice Jam	Other Elevations	Comments
1967	Apr. 28 [f]	Doyle (1987)	238.8 [g,i] at WSC gauge below Fort McMurray			
1968	Apr. 27 [f]	Doyle (1987)	238.4 [i] at WSC gauge below Fort McMurray			Thermal breakup
1969	Apr. 14 [f]	Doyle (1987)	239.0 [g,i] at WSC gauge below Fort McMurray			
1970	Apr. 7 [f]	Doyle (1987)	238.4 [i] at WSC gauge below Fort McMurray			
1971	Apr. 20 [f]	Doyle (1987)	239.0 [i] at WSC gauge below Fort McMurray			
1972	Apr. 22 [f]	Doyle (1987)	244.7 [i] at WSC gauge below Fort McMurray		244.3 [a,b]	
		Northwest Hydraulic Consultant Ltd. Report (1978)	245.3 likely at MacEwan Bridge	Ice jam		

Year	Breakup Date	Source	Maximum Water Elevation (m)	Location of Ice Jam	Other Elevations	Comments
1973	Apr. 18 [f]	Doyle (1987)	240.4 [i] at WSC gauge below Fort McMurray			
	Apr. 18	WSC gauge below Fort McMurray strip chart	240.5 at WSC gauge below Fort McMurray on Apr. 20			
1974	Apr. 19 [f]	Doyle (1987)	243.8 [b,i] at WSC gauge below Fort McMurray			
	Apr. 19	WSC gauge below Fort McMurray strip chart	241.4 [g] at WSC gauge below Fort McMurray on Apr. 29			
	Apr. 20	Northwest Hydraulic Consultants Ltd. (1974)	247.2 at MacEwan Bridge on Apr. 20		246.7 about 5 km upstream of Clearwater River confluence on Apr. 21	Uneventful breakup
1975	Apr. 25 [f]	Doyle (1987)	238.7 [g,i] at WSC gauge below Fort McMurray			

Year	Breakup Date	Source	Maximum Water Elevation (m)	Location of Ice Jam	Other Elevations	Comments
1975	Apr. 25 [c]	WSC gauge below Fort McMurray strip chart	239.7 [g] at WSC gauge below Fort McMurray on Apr. 29			
1976	Apr. 12 [f]	Doyle (1987)	242.4 [j] at WSC gauge below Fort McMurray			
	Apr. 13	WSC gauge below Fort McMurray strip chart	242.2 [g] at WSC gauge below Fort McMurray on Apr. 13			
1977	Apr. 15 [f]	Doyle (1987)	244.2 [j] at WSC gauge below Fort McMurray			
	Apr. 14 [c]	WSC gauge below Fort McMurray strip chart	242.8 [g] at WSC gauge below Fort McMurray on Apr. 15			
		Alberta Environment (personal communication)	247.4			

Year	Breakup Date	Source	Maximum Water Elevation (m)	Location of Ice Jam	Other Elevations	Comments
1977	Apr. 14	Alberta Research Council (1977)	248.7 at MacEwan Bridge on Apr. 14	Original jam toe at the upstream end of Poplar Island (9 km downstream of bridges) to 14 km upstream of the bridges (1.6 km upstream of Mountain Rapids), formed on Apr. 14 Subsequent jam toe downstream of the Clearwater mouth among the group of islands, formed on Apr. 15	248.0 at Waterways on Apr. 15 247.8 at Clearwater school on Apr. 15 247.9 at Clearwater River side of MacDonald Island at the confluence on Apr. 15 247.6 at Athabasca River side of MacDonald Island at the confluence on Apr. 15	Flood
1978		Doyle (1987)	238.7 [b,j] at WSC gauge below Fort McMurray			

Year	Breakup Date	Source	Maximum Water Elevation (m)	Location of Ice Jam	Other Elevations	Comments
1978	Apr. 19	WSC gauge below Fort McMurray strip chart	240.6 at WSC gauge below Fort McMurray on Apr. 19			
	Apr. 19	Alberta Research Council (1978)	242.0 at Clearwater River confluence	At MacEwan Bridge (22 km long), jammed on Apr. 19		
1979	Apr. 28 [f]	Doyle (1987)	242.7 [b j] at WSC gauge below Fort McMurray			
	Apr. 28	WSC gauge below Fort McMurray strip chart	244.9 [g] at WSC gauge below Fort McMurray on May 3			
	Apr. 28	Alberta Research Council (1979)	247.5 at MacEwan Bridge on Apr. 29	At island 16 km downstream of MacEwan Bridge to 2km downstream of Mountain Rapids, jammed on Apr. 28	246.9 on Athabasca River immediately upstream of the Clearwater River mouth on Apr. 29	Minor flood compare to 1977 event

Year	Breakup Date	Source	Maximum Water Elevation (m)	Location of Ice Jam	Other Elevations	Comments
1979		Alberta Research Council (1979)			246.5 on Clearwater River immediately upstream of the confluence 246.8 at Grimshaw Trucking terminal on Apr. 30 246.9 at WSC gauge at Draper	
1980	Apr. 14 [f]	Doyle (1987)	240.7 [j] at WSC gauge below Fort McMurray			
	Apr. 15	WSC gauge below Fort McMurray strip chart	240.7 at WSC gauge below Fort McMurray on Apr. 17			

Year	Breakup Date	Source	Maximum Water Elevation (m)	Location of Ice Jam	Other Elevations	Comments
1981	Apr. 10 [f]	Doyle (1987)	240.7 [j] at WSC gauge below Fort McMurray			
	Apr. 10	WSC gauge below Fort McMurray strip chart	239.3 [g] at WSC gauge below Fort McMurray on Apr. 10			
1982	Apr. 25 [f]	Doyle (1987)	238.9 [j] at WSC gauge below Fort McMurray			
	Apr. 26	Alberta Environment (1982)	246.8 at MacEwan Bridge on Apr. 26	Between MacEwan Bridge and Clearwater River confluence	242.2 at Clearwater River confluence on Apr. 26	
1983	Apr. 18 [f]	Doyle (1987)	237.7 [b j] at WSC gauge below Fort McMurray			
	Apr. 18	WSC gauge below Fort McMurray strip chart	239.6 at WSC gauge below Fort McMurray on Apr. 22			

Year	Breakup Date	Source	Maximum Water Elevation (m)	Location of Ice Jam	Other Elevations	Comments
1983	Apr. 25	Alberta Research Council (1984)	239.5 at WSC gauge below Fort McMurray on Apr. 22		242.0 at MacEwan Bridge on Apr. 21 242.3 [b] at N.T.C.L .Dock on Apr. 21	Uneventful breakup
1984	Apr. 10 [f]	Doyle (1987)	240.2 [j] at WSC gauge below Fort McMurray			
	Apr. 10	WSC gauge below Fort McMurray strip chart	240.9 at WSC gauge below Fort McMurray on Apr. 11			
	Apr. 11	Alberta Research Council (1985)	244.5 at MacEwan Bridge on Apr. 11	Jam toe 0.8 km upstream of MacEwan Bridge (9.4 km long), jammed on Apr. 10	241.0 at WSC gauge below Fort McMurray on Apr. 11 243.5 [d b]	No serious flooding

Year	Breakup Date	Source	Maximum Water Elevation (m)	Location of Ice Jam	Other Elevations	Comments
1984		Alberta Research Council (1985)		Subsequent jam toe downstream of WSC gauge below Fort McMurray formed on Apr. 11		
1985		Doyle (1987)	241.2 [j] at WSC gauge below Fort McMurray			
	Apr. 14	WSC gauge below Fort McMurray strip chart	239.4 [g] at WSC gauge below Fort McMurray on Apr. 14			
	Apr. 18	Alberta Research Council (1985)	243.5 at Clearwater River confluence			Uneventful breakup
1986	Apr. 19	WSC gauge below Fort McMurray strip chart	240.9 at WSC gauge below Fort McMurray on Apr. 20			

Year	Breakup Date	Source	Maximum Water Elevation (m)	Location of Ice Jam	Other Elevations	Comments
1986	Apr. 19	Alberta Research Council (1988)	244.0 at Clearwater River confluence	Jam toe 0.8 km upstream of the mouth of Parsons Creek, head of jam just downstream of Mountain Rapids, formed on Apr. 19		
1987	Apr. 16	WSC gauge below Fort McMurray strip chart	240.7 $_g$ at WSC gauge below Fort McMurray on Apr. 17			
	Apr. 16	Regional Municipality of Wood Buffalo				
	Apr. 16	Alberta Research Council (1988)	246.5 at MacEwan Bridge on Apr. 16	Jam toe just downstream of Poplar Island, head of jam some 5 km upstream of MacEwan Bridge, formed on Apr. 16	244.5 at Clearwater River confluence on Apr. 16	

Year	Breakup Date	Source	Maximum Water Elevation (m)	Location of Ice Jam	Other Elevations	Comments
1987	Apr. 16	Alberta Environment (1988)	246.5 at MacEwan Bridge on Apr. 16	Jam toe in vicinity of Poplar Island, formed on Apr. 16 Subsequent jam toe just below Stony Island (approximately 17 km downstream of MacEwan Bridge), head of jam just downstream of Mountain Rapids (some 11 km upstream of MacEwan Bridge), formed on Apr. 16	244.9 at Clearwater River confluence on Apr. 16 245.1 at Clearwater River confluence on Apr. 17	
1988	Apr. 16 [e]	WSC gauge below Fort McMurray strip chart	240.6 [g] at WSC gauge below Fort McMurray on Apr. 16			
	Apr. 18	Regional Municipality of Wood Buffalo				

Year	Breakup Date	Source	Maximum Water Elevation (m)	Location of Ice Jam	Other Elevations	Comments
1988	Apr. 16	Alberta Environment (1989): Draft	244.8 at MacEwan Bridge on Apr. 16	Jam toe just upstream of Poplar Island, head of jam just downstream of Mountain Rapids, formed on Apr. 16	244.5 at Clearwater River confluence on Apr. 16 243.1 at N.T.C.L .Dock and Waterways on Apr. 16	No flooding reported
1989	Apr. 22 $_e$	WSC gauge below Fort McMurray strip chart	238.2 $_g$ at WSC gauge below Fort McMurray on Apr. 22			
		City of Fort McMurray as referred to in Alberta Environmental Protection (1993)	243.1 at Clearwater River confluence			
	Apr. 22	Regional Municipality of Wood Buffalo				
1990	Apr. 20 $_e$	WSC gauge below Fort McMurray strip chart	239.3 $_g$ at WSC gauge below Fort McMurray on Apr. 25			

Year	Breakup Date	Source	Maximum Water Elevation (m)	Location of Ice Jam	Other Elevations	Comments
1990		City of Fort McMurray as referred to in Alberta Environmental Protection (1993)	243.0 at Clearwater River confluence			
	Apr. 21	Regional Municipality of Wood Buffalo				
1991	Apr. 13	WSC gauge below Fort McMurray strip chart	240.1 $_{g}$ at WSC gauge below Fort McMurray on Apr. 18			
	Apr. 18	Regional Municipality of Wood Buffalo				
		Alberta Environment (personal communication)				Uneventful breakup
1992	Apr. 3	WSC gauge below Fort McMurray strip chart	239.5 at WSC gauge below Fort McMurray on Apr. 3			
	Apr. 17	Regional Municipality of Wood Buffalo				

Year	Breakup Date	Source	Maximum Water Elevation (m)	Location of Ice Jam	Other Elevations	Comments
1992		Alberta Environment (personal communication)				Uneventful breakup
1993	Apr. 19 [c]	WSC gauge below Fort McMurray strip chart	238.5 [g] at WSC gauge below Fort McMurray on Apr. 19			
	Apr. 19	Regional Municipality of Wood Buffalo				
		Alberta Environment (personal communication)				Uneventful breakup
1994	Apr. 11	WSC gauge below Fort McMurray strip chart	242.8 at WSC gauge below Fort McMurray on Apr. 12			
	Apr. 12	Regional Municipality of Wood Buffalo				
		Alberta Environment (personal communication)				Uneventful breakup

Year	Breakup Date	Source	Maximum Water Elevation (m)	Location of Ice Jam	Other Elevations	Comments
1995	Apr. 22	WSC gauge below Fort McMurray strip chart	239.0 at WSC gauge below Fort McMurray on Apr. 22			
	Apr. 22 to Apr. 28	Regional Municipality of Wood Buffalo				
		Alberta Environment (personal communication)				Uneventful breakup
1996	Apr. 16	WSC gauge below Fort McMurray strip chart	243.2 at WSC gauge below Fort McMurray on Apr. 21			
	Apr. 16	Regional Municipality of Wood Buffalo				
		Alberta Environment (personal communication)		Ice jam below Clearwater River confluence		

Year	Breakup Date	Source	Maximum Water Elevation (m)	Location of Ice Jam	Other Elevations	Comments
1997	Apr. 20	Regional Municipality of Wood Buffalo				
		Alberta Environment (personal communication)	247.0	Ice Jam		
1998	Apr. 9	WSC gauge below Fort McMurray strip chart	239.0 at WSC gauge below Fort McMurray on Apr. 15			
	Apr. 19	Regional Municipality of Wood Buffalo (2002)	243.0 at Water Treatment Plant on Apr. 15			
		Alberta Environment (personal communication)				Uneventful breakup
1999	Apr. 14	WSC gauge below Fort McMurray strip chart	238.5 at WSC gauge below Fort McMurray on Apr. 20			
	Apr. 18	Regional Municipality of Wood Buffalo (2002)	242.7 at Water Treatment Plant on Apr. 18			

Year	Breakup Date	Source	Maximum Water Elevation (m)	Location of Ice Jam	Other Elevations	Comments
1999		University of Alberta	242.0 at Water Intake I		242.1 at Water Intake II 241.2 at MacEwan Bridge 240.8 at MacDonald Island 240.4 at Clearwater River side of MacDonald Island at the confluence	Thermal breakup
2000	Apr. 23	WSC gauge below Fort McMurray strip chart	238.6 at WSC gauge below Fort McMurray on Apr. 23			
	Apr. 25	Regional Municipality of Wood Buffalo (2002)	241.9 at Water Treatment Plant on Apr. 23			

Year	Breakup Date	Source	Maximum Water Elevation (m)	Location of Ice Jam	Other Elevations	Comments
2000		University of Alberta	240.6 at Clearwater River side of MacDonald Island at the confluence			Uneventful breakup
2001	Apr. 26	Regional Municipality of Wood Buffalo (2002)	242.9 at Water Treatment Plant on Apr. 26		241.8 at Waterways on Apr. 24	
	Apr. 25	University of Alberta	239.5 $_e$ at Lagoon		236.9 $_e$ at Sawmill 243.2 $_e$ at Water Intake I 242.7 $_e$ Water Intake II 242.1 $_e$ at Bridges 240.9 at Clearwater River side of MacDonald Island at the confluence	Small ice run

a Adjusted to the Clearwater River confluence, Northwest Hydraulic Consultant Ltd. Report (1978)
b Questionable
c WSC gauge below Fort McMurray malfunctioning
d Adjusted to the Clearwater River confluence, Alberta Environmental Protection (1993)
e High water mark observed on Apr. 28
f End of discharge increase prior to breakup from WSC chart as referred to in Doyle (1987)
g Highest measurement from WSC strip charts at the gauge below Fort McMurray, discontinued record during breakup
h T. Blench and Associates Ltd. (1964) as referred to in Doyle (1987)
i Strip charts from WSC gauge below Fort McMurray as referred to in Doyle (1987)
j Personal communication with D. Andres, Alberta Research Council, as referred to in Doyle (1987)

Note: Ice jams were documented if they were located in the vicinity of Fort McMurray from the Golf Course (approximately 4 km upstream of the MacEwan Bridge) to downstream of the Clearwater River confluence where it affects the Clearwater River stage. If no jams occurred in this reach, it was specified as an uneventful year.

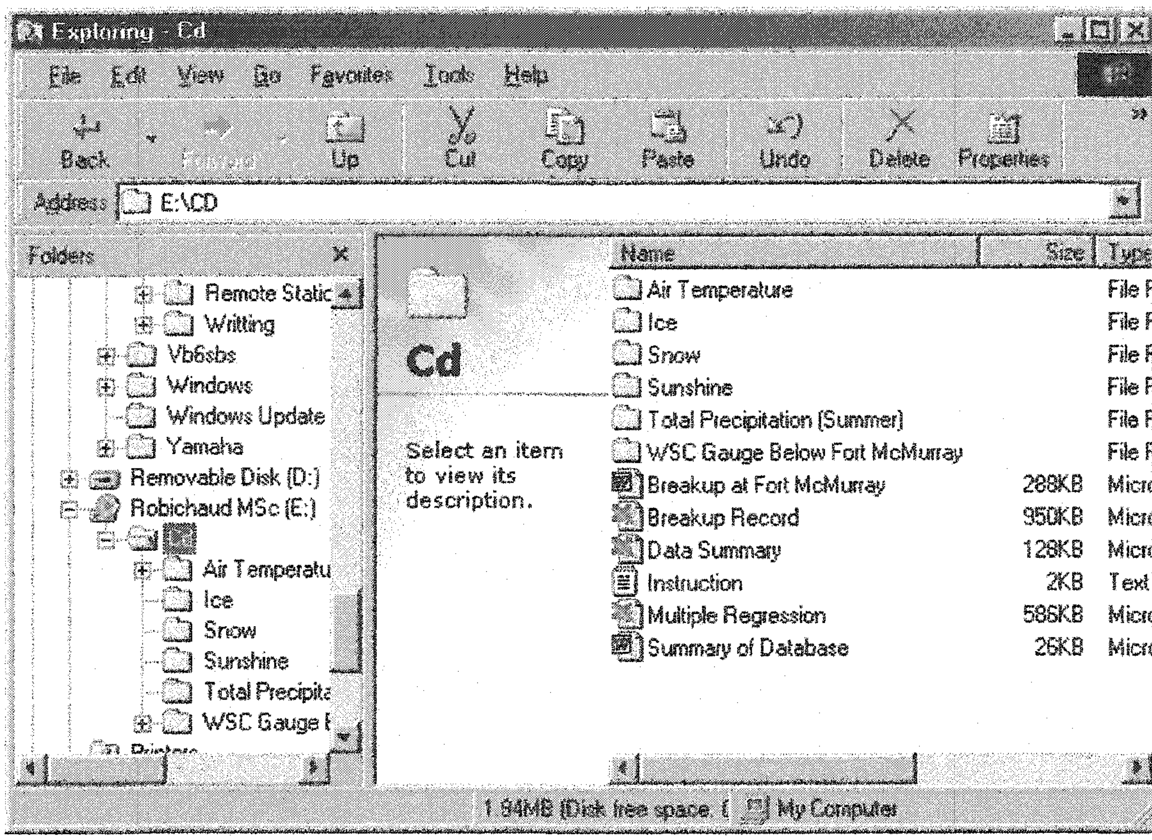
General Information:

- The Water Treatment Plant represents the same location as the Water Intake # 1 and is approximately located 1.6 km upstream of MacEwan Bridge.
- Water Intake #2 is around 0.4 km upstream of the bridges in Fort McMurray.
- The Lagoon station is approximately 3.8 km downstream of the MacEwan Bridge.
- The Sawmill is located around 15.8 km downstream of the bridges in Fort McMurray.

APPENDIX B

Appendix B1 Hydrometeorological Database (CD)

The attached CD contains all the hydrometeorological data gathered during this research. The following screen appears when the CD is first opened:



Instructions on how to find specific data on this CD are provided in the file "Instruction".

APPENDIX C

Appendix C1 Filling Missing Snow Record for March 1st

There were 18 stations in the Athabasca River basin considered in this research which 8 of them had missing values in their record for March 1st. Linear regressions were done with each incomplete station with the help of the surrounding stations. Multiple linear regressions were also calculated for the stations with missing records. The period of study was 1974 to 2001.

Edson #2 Station (Stn 3): Missing 1974

Linear Regression:

Paddle River H.W. (Stn 13)	No data for 1974.	
Lodgepole (Stn 9)	$R^2 = 0.78$	1975 to 2001
Obed (Stn 12)	No data for 1974.	
Brazeau Res. (Stn 21)	No data for 1974.	
Whitecourt (Stn 19)	$R^2 = 0.65$	1975 to 2001
Mayerthorpe S.P. (Stn 10)	No data for 1974.	
Sturgeon Heights (Stn 16)	No data for 1974.	
Little Smoky (Stn 24)	No data for 1974.	

Multiple Linear Regression:

Stn 9, and 19	Adj Rsqr = 0.777	1975 to 2001

Mayerthorpe S.P. Station (Stn 10): Missing 1974 and 1975

Linear Regression:

Paddle River H.W. (Stn 13)	No data for 1974, 1975	
Lodgepole (Stn 9)	$R^2 = 0.73$	1976 to 2001
Whitecourt (Stn 19)	$R^2 = 0.90$	1976 to 2001
Twin Lakes (Stn 17)	No data for 1974, 1975	
Meadowview (Stn 11)	$R^2 = 0.84$	1976 to 2001, omitting 1992
Barrhead West (Stn 2)	$R^2 = 0.78$	1976 to 2001
Edson #2 (Stn 3)	No data for 1974	
Onoway (Stn 23)	$R^2 = 0.87$	1976 to 2001

Multiple Linear Regression:

Stn 9, 19, 11, 2, and 23	Adj Rsqr = 0.916	1976 to 2001, omitting 1992
Stn 9, 19, 11, and 23	Adj Rsqr = 0.920	1976 to 2001, omitting 1992
Stn 9, 19, and 23	Adj Rsqr = 0.919	1976 to 2001
Stn 19, and 23	Adj Rsqr = 0.915	1976 to 2001

Meadowview Station (Stn 11): Missing 1992

Linear Regression:

Twin Lakes (Stn 17)	$R^2 = 0.91$	1982 to 2001, omitting 1992
Whitecourt (Stn 19)	$R^2 = 0.85$	1974 to 2001, omitting 1992

Barrhead West (Stn 2)	$R^2 = 0.90$	1974 to 2001, omitting 1992
Mayerthorpe S.P. (Stn 10)	$R^2 = 0.84$	1976 to 2001, omitting 1992
Barrhead North (Stn 1)	$R^2 = 0.88$	1974 to 2001, omitting 1992
Westlock (Stn 18)	No data for 1992	
Onoway (Stn 23)	$R^2 = 0.88$	1974 to 2001, omitting 1992
Paddle River H.W. (Stn 13)	No data for 1992	

Multiple Linear Regression:

Stn 17, 19, 2, 10, 1, and 23	Adj Rsqr = 0.944	1982 to 2001, omitting 1992
Stn 17, 19, 2, 1, and 23	Adj Rsqr = 0.948	1982 to 2001, omitting 1992
Stn 17, 2, 1, and 23	Adj Rsqr = 0.952	1982 to 2001, omitting 1992
Stn 17, 2, and 1	Adj Rsqr = 0.951	1982 to 2001, omitting 1992
Stn 17, and 2	Adj Rsqr = 0.952	1982 to 2001, omitting 1992

Obed Station (Stn 12): Missing 1974

Linear Regression:

Sturgeon Heights (Stn 16)	No data for 1974	
Edson #2 (Stn 3)	No data for 1974	
Lodgepole (Stn 9)	$R^2 = 0.62$	1975 to 2001
Brazeau Res. (Stn 21)	No data for 1974	
Whitecourt (Stn 19)	$R^2 = 0.57$	1975 to 2001
Paddle River H.W. (Stn 13)	No data for 1974	
Mayerthorpe S.P. (Stn 10)	No data for 1974	
Little Smoky (Stn 24)	No data for 1974	

Multiple Linear Regression:

Stn 9, and 19	Adj Rsqr = 0.628	1975 to 2001

Paddle River H.W. Station (Stn 13): Missing 1974 to 1992

Linear Regression:

Mayerthorpe S.P. (Stn 10)	No data for 1974, 1975	
Whitecourt (Stn 19)	$R^2 = 0.98$	1993 to 2001
Twin Lakes (Stn 17)	No data for 1974 to1981	
Meadowview (Stn 11)	No data for 1992	
Barrhead West (Stn 2)	$R^2 = 0.94$	1993 to 2001
Lodgepole (Stn 9)	$R^2 = 0.87$	1993 to 2001
Edson #2 (Stn 3)	No data for 1974	
Onoway (Stn 23)	$R^2 = 0.95$	1993 to 2001

Multiple Linear Regression:

Stn 19, 2, 9, and 23	Adj Rsqr = 0.966	1993 to 2001
Stn 19, 9, and 23	Adj Rsqr = 0.972	1993 to 2001
Stn 19, and 9	Adj Rsqr = 0.975	1993 to 2001

Sturgeon Heights Station (Stn 16): Missing 1974 to 1987

Linear Regression:

Obed (Stn 12)	No data for 1974	
Edson #2 (Stn 3)	No data for 1974	
Brazeau Res. (Stn 21)	No data for 1974 to 1976	
Lodgepole (Stn 9)	$R^2 = 0.75$	1988 to 2001

Multiple Linear Regression:
None

Twin Lakes Station (Stn 17): Missing 1974 to 1981

Linear Regression:

Barrhead West (Stn 2)	No data for 1974	
Mayerthorpe S.P. (Stn 10)	No data for 1974, 1975	
Meadowview (Stn 11)	$R^2 = 0.91$	1982 to 2001, omitting 1992
Barrhead North (Stn 1)	$R^2 = 0.90$	1982 to 2001
Westlock (Stn 18)	$R^2 = 0.77$	1982 to 2001, omitting 1992
Onoway (Stn 23)	$R^2 = 0.90$	1982 to 2001
Paddle River H.W. (Stn 13)	No data for 1974 to 1992	
Whitecourt (Stn 19)	$R^2 = 0.91$	1982 to 2001

Multiple Linear Regression:

Stn 11, 1, 18, 23, and 19	Adj Rsqr = 0.939	1982 to 2001, omitting 1992
Stn 11, 1, 23, and 19	Adj Rsqr = 0.944	1982 to 2001, omitting 1992
Stn 11, 1, and 19	Adj Rsqr = 0.947	1982 to 2001, omitting 1992
Stn 1, and 19	Adj Rsqr = 0.948	1982 to 2001

Westlock Station (Stn 18): Missing 1992

Linear Regression:

Barrhead North (Stn 1)	$R^2 = 0.80$	1974 to 2001, omitting 1992
Meadowview (Stn 11)	No data for 1992	
Onoway (Stn 23)	$R^2 = 0.74$	1974 to 2001, omitting 1992
Twin Lakes (Stn 17)	$R^2 = 0.77$	1982 to 2001, omitting 1992
Barrhead West (Stn 2)	$R^2 = 0.74$	1974 to 2001, omitting 1992
Perryvale (Stn 14)	$R^2 = 0.70$	1974 to 2001, omitting 1992

Multiple Regression:

Stn 1, 23, 17, 2, and 14	Adj Rsqr = 0.790	1982 to 2001, omitting 1992
Stn 1, 23, 17, and 14	Adj Rsqr = 0.805	1982 to 2001, omitting 1992
Stn 1, 17, and 14	Adj Rsqr = 0.816	1982 to 2001, omitting 1992
Stn 1, and 14	Adj Rsqr = 0.817	1982 to 2001, omitting 1992

Appendix C2 Linear Regression Results for March 1st

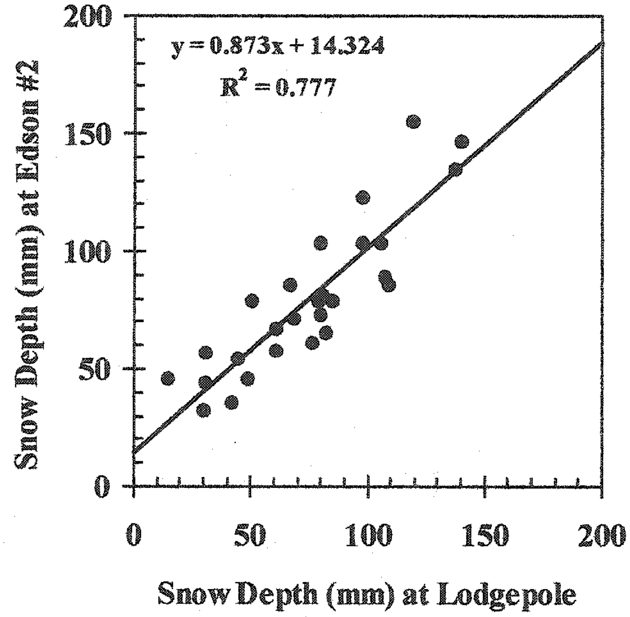


Figure C2.1 Water equivalent snow depth (mm) for Edson #2 versus Lodgepole during March 1st for the years of 1975 to 2001.

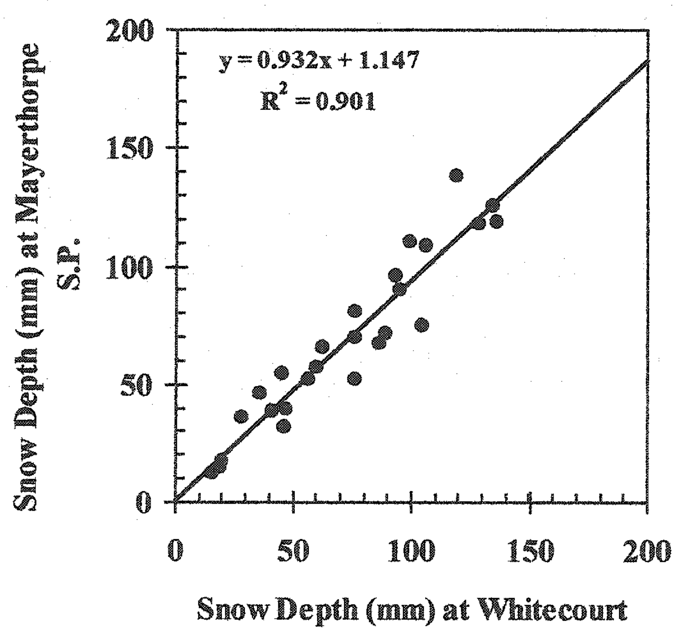


Figure C2.2 Water equivalent snow depth (mm) for Mayerthorpe S.P. versus Whitecourt during March 1st for the years of 1976 to 2001.

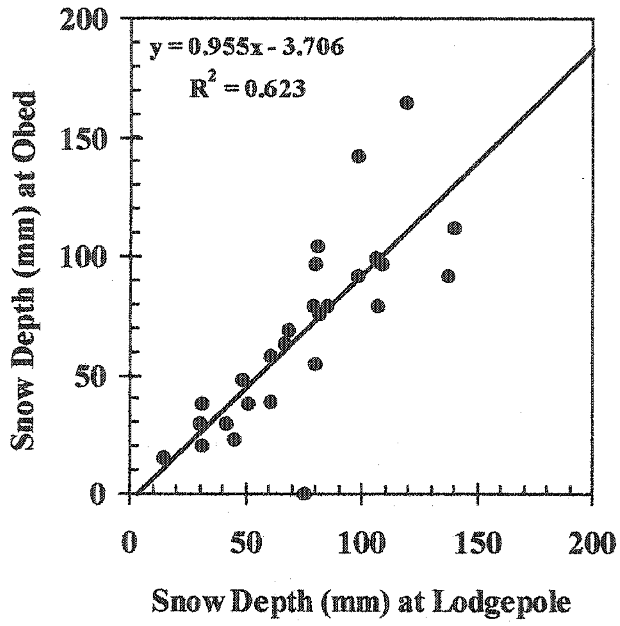


Figure C2.3 Water equivalent snow depth (mm) for Obed versus Lodgepole during March 1st for the years of 1975 to 2001.

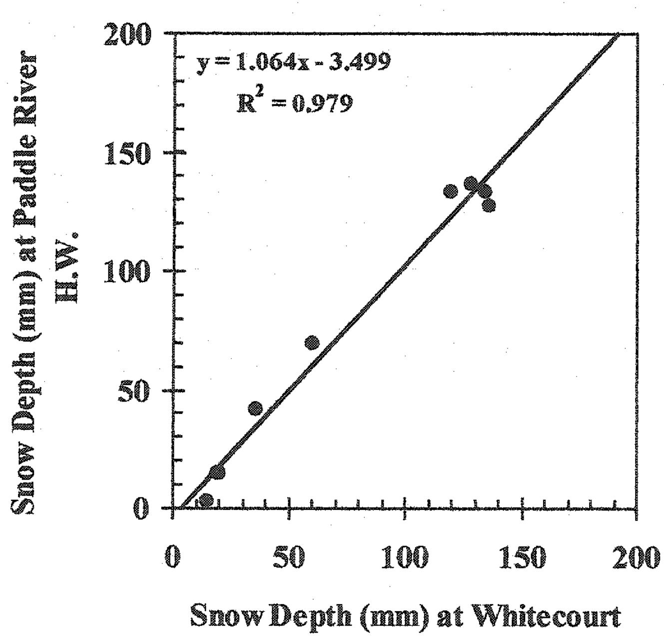


Figure C2.4 Water equivalent snow depth (mm) for Paddle River H.W. versus Whitecourt during March 1st for the years of 1993 to 2001.

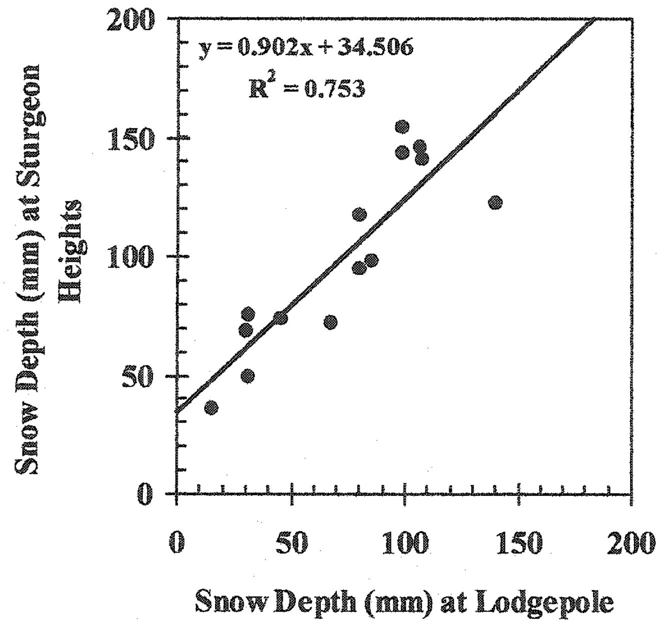


Figure C2.5 Water equivalent snow depth (mm) for Sturgeon Heights versus Lodgepole during March 1st for the years of 1988 to 2001.

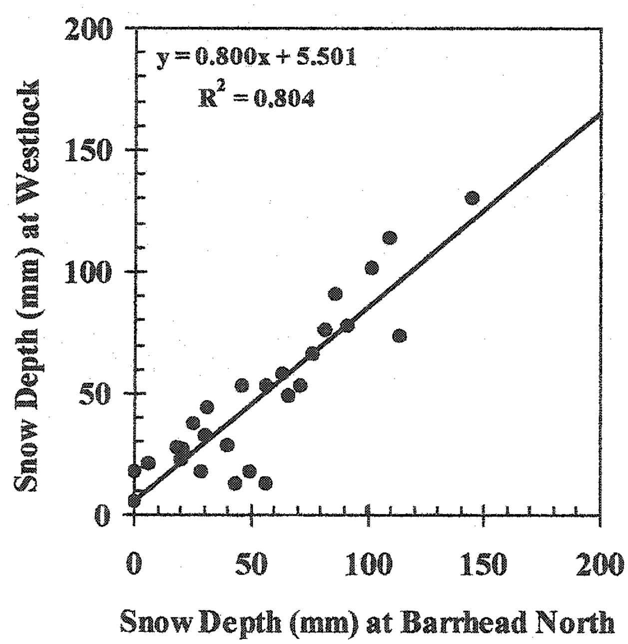


Figure C2.6 Water equivalent snow depth (mm) for Westlock versus Barrhead North during March 1st for the years of 1974 to 2001, omitting 1992.

Appendix C3 Multiple Regression Results for the Average SWE of March 1st

March 1st Multiple Linear Regression for Meadowview (Station 11)

Station 11 = 7.037 + (0.374 * Station 17) + (0.670 * Station 2)

N = 19.000 Missing Observations = 9

R = 0.978 Rsqr = 0.957 Adj Rsqr = 0.952

Standard Error of Estimate = 8.796

	Coefficient	**Std. Error**	**t**	**P**	**Std. Coeff.**	**VIF**
Constant	7.037	3.721	1.891	0.077		
Station 17	0.374	0.156	2.397	0.029	0.362	8.511
Station 2	0.670	0.160	4.178	<0.001	0.631	8.511

Warning: Multicollinearity is present among the independent variables. The variables with the largest values of VIF are causing the problem. Consider getting more data or eliminating one or more variables from the equation. The likely candidates for elimination are: Station 17, Station 2

Analysis of Variance:

	DF	**SS**	**MS**	**F**	**P**
Regression	2	27669.254	13834.627	178.814	<0.001
Residual	16	1237.904	77.369		
Total 18	28	907.158	1605.953		

Column	**SSIncr**	**SSMarg**
Station 17	26318.911	444.640
Station 2	1350.342	1350.342

The dependent variable Station 11 can be predicted from a linear combination of the independent variables:

	P
Station 17	0.029
Station 2	<0.001

All independent variables appear to contribute to predicting Station 11 (P < 0.05).

PRESS = 2043.419

Durbin-Watson Statistic = 1.752

Normality Test: Passed (P = 0.824)

Constant Variance Test: Passed (P = 0.726)

Power of performed test with alpha = 0.050: 1.000

Regression Diagnostics:

Row	Predicted	Residual	Std. Res.	Stud. Res.	Stud. Del. Res.
1	91.792	12.208	1.388	1.499 <	1.565 <
2	26.228	3.772	0.429	0.461	0.449
3	47.110	-1.110	-0.126	-0.132	-0.128

March 1st Multiple Linear Regression for Twin Lakes (Station 17)

Station 17 = 0.393 + (0.503 * Station 1) + (0.481 * Station 19)

N = 20.000 Missing Observations = 8

R = 0.976 Rsqr = 0.953 Adj Rsqr = 0.948

Standard Error of Estimate = 8.675

	Coefficient	**Std. Error**	**t**	**P**	**Std. Coeff.**	**VIF**
Constant	0.393	4.055	0.0970	0.924		
Station 1	0.503	0.126	4.008	<0.001	0.488	5.409
Station 19	0.481	0.114	4.216	<0.001	0.513	5.409

Warning: Multicollinearity is present among the independent variables. The variables with the largest values of VIF are causing the problem. Consider getting more data or eliminating one or more variables from the equation. The likely candidates for elimination are: Station 1 , Station 19

Analysis of Variance:

	DF	**SS**	**MS**	**F**	**P**
Regression	2	26201.533	13100.767	174.067	<0.001
Residual	17	1279.467	75.263		
Total	19	27481.000	1446.368		

Column	**SSIncr**	**SSMarg**
Station 1	24863.560	1209.238
Station 19	1337.973	1337.973

The dependent variable Station 17 can be predicted from a linear combination of the independent variables:

	P
Station 1	<0.001
Station 19	<0.001

All independent variables appear to contribute to predicting Station 17 (P < 0.05).

PRESS = 1741.291

Durbin-Watson Statistic = 2.658

Normality Test: Passed (P = 0.215)

Constant Variance Test: Passed (P = 0.298)
Power of performed test with alpha = 0.050: 1.000

Regression Diagnostics:

Row	Predicted	Residual	Std. Res.	Stud. Res.	Stud. Del. Res.
1	88.745	5.255	0.606	0.634	0.622
2	22.911	5.089	0.587	0.621	0.610
3	37.625	10.375	1.196	1.241 <	1.262 <

Appendix C4 Filling Missing Snow Record for April 1st

There were 18 stations in the Athabasca River basin considered in this analysis which 4 of them had missing values in their record for April 1st. Linear regressions were done with each incomplete station with the help of the surrounding stations. Multiple linear regressions were also calculated for the stations with missing records. The period of study was 1974 to 2001 omitting 1975 and 1976.

High Prairie Station (Stn 6): Missing 1978

Linear Regression:		
Kinuso (Stn 8)	$R^2 = 0.59$	1974, 1977, 1979 to 2001
Girouxville (Stn 20)	$R^2 = 0.83$	1974, 1977, 1979 to 2001
Little Smoky (Stn 24)	No data for 1978	
Saulteaux River (Stn 15)	$R^2 = 0.82$	1974, 1977, 1979 to 2001
Whitecourt (Stn 19)	$R^2 = 0.48$	1974, 1977, 1979 to 2001
Flatbush (Stn 4)	$R^2 = 0.73$	1974, 1977, 1979 to 2001
Barrhead West (Stn 2)	$R^2 = 0.62$	1974, 1977, 1979 to 2001
Multiple Linear Regression:		
Stn 8, 20, 15, 19, 4, and 2	Adj Rsqr = 0.904	1974, 1977, 1979 to 2001
Stn 8, 20, 15, 19, and 4	Adj Rsqr = 0.907	1974, 1977, 1979 to 2001
Stn 20, 15, 19, and 4	Adj Rsqr = 0.900	1974, 1977, 1979 to 2001
Stn 20, 15, and 4	Adj Rsqr = 0.897	1974, 1977, 1979 to 2001
Stn 20, and 15	Adj Rsqr = 0.898	1974, 1977, 1979 to 2001

Paddle River H.W. Station (Stn 13): Missing 1974, 1977 to 1992

Linear Regression:		
Mayerthorpe S.P. (Stn 10)	$R^2 = 0.89$	1993 to 2001
Whitecourt (Stn 19)	$R^2 = 0.91$	1993 to 2001
Twin Lakes (Stn 17)	No data for 1974 to1981	
Meadowview (Stn 11)	$R^2 = 0.95$	1993 to 2001
Barrhead West (Stn 2)	$R^2 = 0.89$	1993 to 2001
Lodgepole (Stn 9)	$R^2 = 0.91$	1993 to 2001
Linear Regression (Cont.):		
Edson #2 (Stn 3)	$R^2 = 0.83$	1993 to 2001
Onoway (Stn 23)	$R^2 = 0.88$	1993 to 2001
Multiple Linear Regression:		
Stn 10, 19, 11, 2, 9, 3, and 23	Adj Rsqr = 0.969	1993 to 2001
Stn 19, 11, 2, 9, 3, and 23	Adj Rsqr = 0.978	1993 to 2001
Stn 19, 11, 2, 3, and 23	Adj Rsqr = 0.960	1993 to 2001
Stn 19, 11, 2, and 23	Adj Rsqr = 0.937	1993 to 2001

Stn 19, 11, and 23	Adj Rsqr = 0.945	1993 to 2001
Stn 11, and 23	Adj Rsqr = 0.939	1993 to 2001

Sturgeon Heights Station (Stn 16): Missing 1974, 1977 to 1987

Linear Regression:		
Obed (Stn 12)	$R^2 = 0.45$	1988 to 2001
Edson #2 (Stn 3)	$R^2 = 0.53$	1988 to 2001
Brazeau Res. (Stn 21)	No data for 1974	
Lodgepole (Stn 9)	$R^2 = 0.60$	1988 to 2001

Multiple Linear Regression:		
Stn 12, 3, and 9	Adj Rsqr = 0.478	1988 to 2001
Stn 12, and 9	Adj Rsqr = 0.526	1988 to 2001

Twin Lakes Station (Stn 17): Missing 1974, 1977 to 1981

Linear Regression:		
Barrhead West (Stn 2)	$R^2 = 0.93$	1982 to 2001
Mayerthorpe S.P. (Stn 10)	$R^2 = 0.77$	1982 to 2001
Meadowview (Stn 11)	$R^2 = 0.98$	1982 to 2001
Barrhead North (Stn 1)	$R^2 = 0.89$	1982 to 2001
Westlock (Stn 18)	$R^2 = 0.66$	1982 to 2001
Onoway (Stn 23)	$R^2 = 0.93$	1982 to 2001
Paddle River H.W. (Stn 13)	No data for 1974, 1977 to 1992	
Whitecourt (Stn 19)	$R^2 = 0.90$	1982 to 2001

Multiple Linear Regression:		
Stn 2, 10, 11, 1, 18, 23, and 19	Adj Rsqr = 0.994	1982 to 2001
Stn 10, 11, 1, 18, 23, and 19	Adj Rsqr = 0.995	1982 to 2001
Stn 11, 1, 18, 23, and 19	Adj Rsqr = 0.995	1982 to 2001
Stn 11, 18, 23, and 19	Adj Rsqr = 0.995	1982 to 2001
Stn 11, 18, and 19	Adj Rsqr = 0.994	1982 to 2001
Stn 11, and 19	Adj Rsqr = 0.990	1982 to 2001

Appendix C5 Linear Regression Results for April 1st

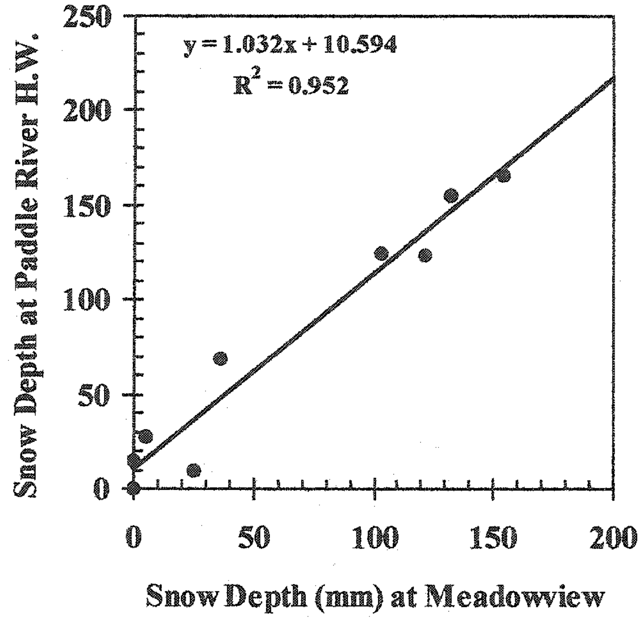


Figure C5.1 Water equivalent snow depth (mm) for Paddle River H.W. versus Meadowview during April 1st for the years of 1993 to 2001.

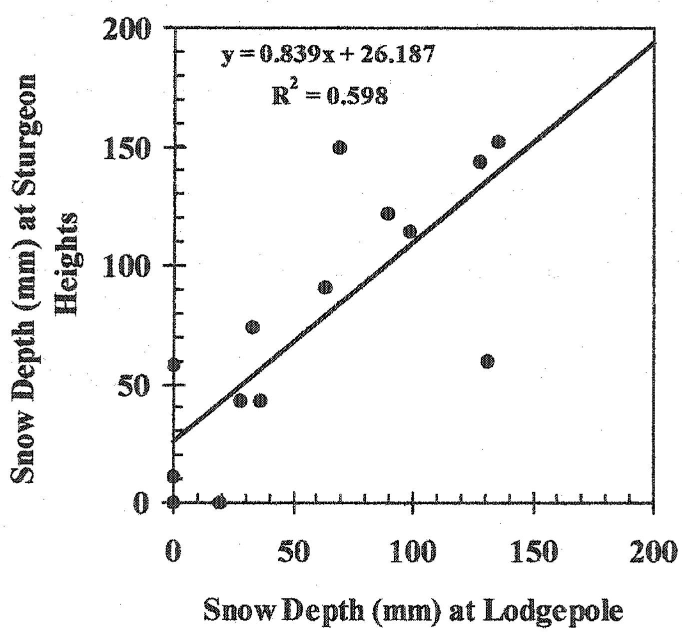


Figure C5.2 Water equivalent snow depth (mm) for Sturgeon Heights versus Lodgepole during April 1st for the years of 1988 to 2001.

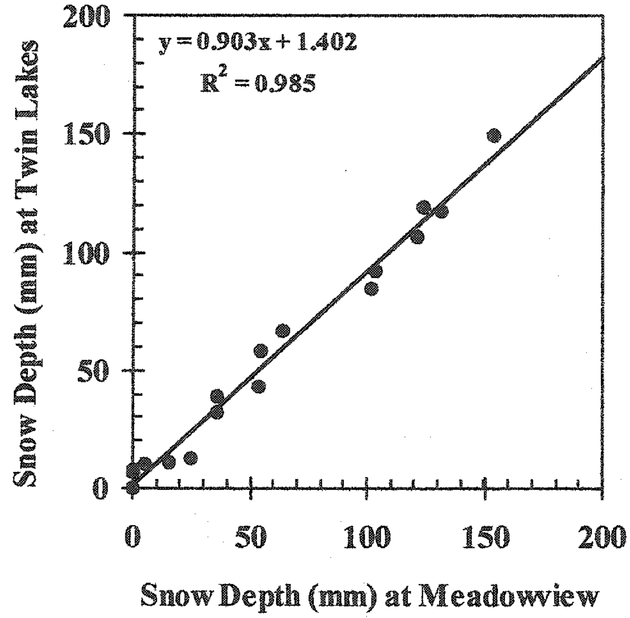


Figure C5.3 Water equivalent snow depth (mm) for Twin Lakes versus Meadowview during April 1st for the years of 1982 to 2001.

Appendix C6 Multiple Regression Results for the Average SWE of April 1st

April 1st Multiple Linear Regression for High Prairie (Station 6)

Station 6 = -5.933 + (0.616 * Station 20) + (0.482 * Station 15)

N = 25.000 Missing Observations = 1

R = 0.952 Rsqr = 0.906 Adj Rsqr = 0.898

Standard Error of Estimate = 15.929

	Coefficient	**Std. Error**	**t**	**P**	**Std. Coeff.**	**VIF**
Constant	-5.933	5.279	-1.124	0.273		
Station 20	0.616	0.135	4.575	<0.001	0.521	3.050
Station 15	0.482	0.115	4.188	<0.001	0.477	3.050

Analysis of Variance:

	DF	**SS**	**MS**	**F**	**P**
Regression	2	54069.617	27034.809	106.554	<0.001
Residual	22	5581.823	253.719		
Total	24	59651.440	2485.477		

Column	**SSIncr**	**SSMarg**
Station 20	49619.383	5309.389
Station 15	4450.234	4450.234

The dependent variable Station 6 can be predicted from a linear combination of the independent variables:

	P
Station 20	<0.001
Station 15	<0.001

All independent variables appear to contribute to predicting Station 6 (P < 0.05).

PRESS = 9397.992

Durbin-Watson Statistic = 2.028

Normality Test: Passed (P = 0.273)

Constant Variance Test: Failed (P = 0.008)

Power of performed test with alpha = 0.050: 1.000

Regression Diagnostics:

Row	Predicted	Residual	Std. Res.	Stud. Res.	Stud. Del. Res.
1	152.359	32.641	2.049	2.688 <	3.205 <
2	81.886	-0.886	-0.0556	-0.0575	-0.0562
3	106.111	-9.111	-0.572	-0.803	-0.796
4	14.802	11.198	0.703	0.734	0.726
5	5.158	-5.158	-0.324	-0.336	-0.329
6	125.296	30.704	1.928	2.155 <	2.371 <
7	43.188	8.812	0.553	0.565	0.556

APPENDIX D

Appendix D1 Multiple Linear Regression Results for Breakup Forecasting at Fort McMurray

Multiple Linear Regression for the Dependent Variable H_{Bo}

H_{Bo} = 169.943 - (0.00454 * SWE (Mar)) + (0.00273 * SWE (Apr)) + (0.00221 * Soil Moisture) + (0.281 * H_F) + (1.406 * h_i) + (1.280 * $\Delta H/\Delta t$)

N = 23.000 Missing Observations = 7

R = 0.873 Rsqr = 0.761 Adj Rsqr = 0.672

Standard Error of Estimate = 0.230

	Coefficient	**Std. Error**	**t**	**P**	**Std. Coeff.**	**VIF**
Constant	169.943	42.177	4.029	<0.001		
SWE (Mar)	-0.00454	0.00280	-1.624	0.124	-0.330	2.762
SWE (Apr)	0.00273	0.00212	1.291	0.215	0.268	2.891
Soil Moisture	0.00221	0.000738	2.994	0.009	0.466	1.626
H_F	0.281	0.177	1.583	0.133	0.258	1.776
h_i	1.406	0.408	3.449	0.003	0.487	1.339
$\Delta H/\Delta t$	1.280	0.515	2.483	0.025	0.379	1.561

Analysis of Variance:

	DF	**SS**	**MS**	**F**	**P**
Regression	6	2.707	0.451	8.513	<0.001
Residual	16	0.848	0.0530		
Total	22	3.555	0.162		

Column	**SSIncr**	**SSMarg**
SWE (Mar)	0.520	0.140
SWE (Apr)	0.0447	0.0883
Soil Moisture	0.730	0.475
H_F	0.322	0.133
h_i	0.763	0.630
$\Delta H/\Delta t$	0.327	0.327

The dependent variable H_{Bo} can be predicted from a linear combination of the independent variables:

	P
SWE (Mar)	0.124
SWE (Apr)	0.215
Soil Moisture	0.009
H_F	0.133
h_i	0.003

$\Delta H/\Delta t$	0.025

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified).
The following appear to account for the ability to predict H_{Bo} ($P < 0.05$): Soil Moisture, h_i, $\Delta H/\Delta t$

Multiple Linear Regression for the Dependent Variable H_B

$$H_B = -40.665 - (0.000421 * S) - (0.00309 * SWE (Mar)) + (0.00679 * Soil Moisture) + (1.147 * H_F) + (7.314 * h_i) + (4.383 * \Delta H/\Delta t)$$

N = 23.000 Missing Observations = 7

R = 0.856 Rsqr = 0.733 Adj Rsqr = 0.633

Standard Error of Estimate = 1.059

	Coefficient	**Std. Error**	**t**	**P**	**Std. Coeff.**	**VIF**
Constant	-40.665	194.545	-0.209	0.837		
S	-0.000421	0.000292	-1.440	0.169	-0.249	1.793
SWE (Mar)	-0.00309	0.0141	-0.218	0.830	-0.0445	2.504
Soil Moisture	0.00679	0.00325	2.092	0.053	0.340	1.589
H_F	1.147	0.817	1.404	0.179	0.235	1.686
h_i	7.314	1.681	4.352	<0.001	0.591	1.108
$\Delta H/\Delta t$	4.383	2.897	1.513	0.150	0.297	2.307

Analysis of Variance:

	DF	**SS**	**MS**	**F**	**P**
Regression	6	49.366	8.228	7.332	<0.001
Residual	16	17.954	1.122		
Total	22	67.320	3.060		

Column	**SSIncr**	**SSMarg**
S	5.368	2.326
SWE (Mar)	13.649	0.0534
Soil Moisture	4.025	4.911
H_F	3.696	2.212
h_i	20.060	21.250
$\Delta H/\Delta t$	2.568	2.568

The dependent variable H_B can be predicted from a linear combination of the independent variables:

	P
S	0.169
SWE (Mar)	0.830
Soil Moisture	0.053
H_F	0.179
h_i	<0.001
$\Delta H/\Delta t$	0.150

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified).
The following appear to account for the ability to predict H_B ($P < 0.05$): h_i

Multiple Linear Regression for the Dependent Variable H_B - H_F

$H_B - H_F = -5.143 - (0.000382 * S) - (0.00470 * SWE (Mar)) + (0.00706 * Soil Moisture) + (7.105 * h_i) + (3.864 * \Delta H/\Delta t)$

N = 21.000 Missing Observations = 9

R = 0.845 Rsqr = 0.714 Adj Rsqr = 0.619

Standard Error of Estimate = 0.952

	Coefficient	**Std. Error**	**t**	**P**	**Std. Coeff.**	**VIF**
Constant	-5.143	1.649	-3.119	0.007		
S	-0.000382	0.000267	-1.431	0.173	-0.267	1.824
SWE (Mar)	-0.00470	0.0133	-0.353	0.729	-0.0793	2.654
Soil Moisture	0.00706	0.00266	2.650	0.018	0.418	1.309
h_i	7.105 1.574	4.514	<0.001	0.664	1.136	
$\Delta H/\Delta t$	3.864 2.591	1.491	0.157	0.302	2.156	

Analysis of Variance:

	DF	**SS**	**MS**	**F**	**P**
Regression	5	34.014	6.803	7.505	0.001
Residual	15	13.596	0.906		
Total	20	47.610	2.380		

Column	**SSIncr**	**SSMarg**
S	6.186	1.855
SWE (Mar)	6.750	0.113
Soil Moisture	2.137	6.367
h_i	16.925	18.469
$\Delta H/\Delta t$	2.015	2.015

The dependent variable H_B - H_F can be predicted from a linear combination of the independent variables:

	P
S	0.173
SWE (Mar)	0.729
Soil Moisture	0.018
h_i	<0.001
$\Delta H/\Delta t$	0.157

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified).

The following appear to account for the ability to predict H_B - H_F ($P < 0.05$): Soil Moisture, h_i

Multiple Linear Regression for the Dependent Variable ΔH/Δt

$\Delta H/\Delta t = -18.843 - (0.0000586 * S) + (0.00287 * SWE (Mar)) + (0.0791 * H_F)$

N = 23.000   Missing Observations = 7

R = 0.748   Rsqr = 0.560   Adj Rsqr = 0.491

Standard Error of Estimate = 0.084

	Coefficient	**Std. Error**	**t**	**P**	**Std. Coeff.**	**VIF**
Constant	-18.843	13.397	-1.407	0.176		
S	-0.0000586	0.0000186	-3.149	0.005	-0.512	1.143
SWE (Mar)	0.00287	0.000839	3.417	0.003	0.612	1.384
H_F	0.0791	0.0562	1.408	0.175	0.240	1.252

Analysis of Variance:

	DF	**SS**	**MS**	**F**	**P**
Regression	3	0.173	0.0576	8.066	0.001
Residual	19	0.136	0.00714		
Total	22	0.308	0.0140		

Column	**SSIncr**	**SSMarg**
S	0.0198	0.0708
SWE (Mar)	0.139	0.0834
H_F	0.0142	0.0142

The dependent variable ΔH/Δt can be predicted from a linear combination of the independent variables:

	P
S	0.005
SWE (Mar)	0.003
H_F	0.175

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified).

The following appear to account for the ability to predict ΔH/Δt ($P < 0.05$): S, SWE (Mar)

Multiple Linear Regression for the Dependent Variable t_B

t_B = 96.495 - (0.148 * ADDT) + (0.00332 * S) - (0.163 * SWE (Mar)) + (0.149 * SWE (Apr)) + (22.014 * h_i)

N = 24.000 Missing Observations = 6

R = 0.663 Rsqr = 0.440 Adj Rsqr = 0.285

Standard Error of Estimate = 4.677

	Coefficient	**Std. Error**	**t**	**P**	**Std. Coeff.**	**VIF**
Constant	96.495	6.689	14.427	<0.001		
ADDT	-0.148	0.0544	-2.713	0.014	-0.772	2.603
S	0.00332	0.00150	2.214	0.040	0.653	2.796
SWE (Mar)	-0.163	0.0634	-2.573	0.019	-0.862	3.611
SWE (Apr)	0.149	0.0444	3.356	0.004	1.185	4.012
h_i	22.014	8.516	2.585	0.019	0.547	1.440

Warning: Multicollinearity is present among the independent variables. The variables with the largest values of VIF are causing the problem. Consider getting more data or eliminating one or more variables from the equation. The likely candidates for elimination are: SWE (Apr)

Analysis of Variance:

	DF	**SS**	**MS**	**F**	**P**
Regression	5	309.526	61.905	2.830	0.047
Residual	18	393.808	21.878		
Total	23	703.333	30.580		

Column	**SSIncr**	**SSMarg**
ADDT	31.731	161.087
S	5.396	107.233
SWE (Mar)	7.366	144.813
SWE (Apr)	118.829	246.354
h_i	146.204	146.204

The dependent variable t_B can be predicted from a linear combination of the independent variables:

	P
ADDT	0.014
S	0.040
SWE (Mar)	0.019
SWE (Apr)	0.004
h_i	0.019

All independent variables appear to contribute to predicting t_B ($P < 0.05$).

Multiple Linear Regression for the Dependent Variable $H_{B, Clearwater}$

$H_{B, Clearwater}$ = 234.338 + (0.0340 * T_{10}) + (0.00221 * S_4) - (0.0490 * SWE (Mar)) + (0.0113 * SWE (Apr)) + (0.0106 * Soil Moisture) + (6.778 * h_i) + (14.433 * $\Delta H/\Delta t$)

N = 12.000   Missing Observations = 18

R = 0.991   Rsqr = 0.983   Adj Rsqr = 0.953

Standard Error of Estimate = 0.439

	Coefficient	**Std. Error**	**t**	**P**	**Std. Coeff.**	**VIF**
Constant	234.338	1.696	138.152	<0.001		
T_{10}	0.0340	0.00991	3.426	0.027	0.271	1.447
S_4	0.00221	0.00161	1.377	0.241	0.147	2.633
SWE (Mar)	-0.0490	0.00789	-6.216	0.003	-0.599	2.155
SWE (Apr)	0.0113	0.00721	1.566	0.192	0.149	2.105
Soil Moisture	0.0106	0.00192	5.514	0.005	0.426	1.382
h_i	6.778	1.423	4.763	0.009	0.577	3.407
$\Delta H/\Delta t$	14.433	4.046	3.567	0.023	0.385	2.703

Analysis of Variance:

	DF	**SS**	**MS**	**F**	**P**
Regression	7	43.853	6.265	32.552	0.002
Residual	4	0.770	0.192		
Total	11	44.622	4.057		

Column	**SSIncr**	**SSMarg**
T_{10}	8.433	2.259
S_4	0.00224	0.365
SWE (Mar)	2.242	7.436
SWE (Apr)	2.502	0.472
Soil Moisture	8.235	5.851
h_i	19.989	4.366
$\Delta H/\Delta t$	2.448	2.448

The dependent variable $H_{B, Clearwater}$ can be predicted from a linear combination of the independent variables:

	P
T_{10}	0.027
S_4	0.241
SWE (Mar)	0.003
SWE (Apr)	0.192
Soil Moisture	0.005
h_i	0.009

$\Delta H/\Delta t$ 0.023

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified).
The following appear to account for the ability to predict $H_{B,\text{Clearwater}}$ ($P < 0.05$): T_{10}, SWE (Mar), Soil Moisture, h_i, $\Delta H/\Delta t$

Multiple Linear Regression for the Dependent Variable $H_{B,\ Clearwater}$ - H_F

$H_{B,\ Clearwater} - H_F = 190.802 + (0.0352 * T_{10}) + (0.00233 * S_4) - (0.0491 * SWE\ (Mar)) + (0.0108 * SWE\ (Apr)) + (0.0102 * Soil\ Moisture) - (0.818 * H_F) + (6.817 * h_i) + (13.999 * \Delta H/\Delta t)$

N = 12.000   Missing Observations = 18

R = 0.991   Rsqr = 0.982   Adj Rsqr = 0.932

Standard Error of Estimate = 0.501

	Coefficient	Std. Error	t	P	Std. Coeff.	VIF
Constant	190.802	167.851	1.137	0.338		
T_{10}	0.0352	0.0123	2.858	0.065	0.294	1.716
S_4	0.00233	0.00189	1.232	0.306	0.162	2.807
SWE (Mar)	-0.0491	0.00901	-5.449	0.012	-0.628	2.159
SWE (Apr)	0.0108	0.00842	1.289	0.288	0.150	2.197
Soil Moisture	0.0102	0.00259	3.957	0.029	0.430	1.921
H_F	-0.818	0.703	-1.163	0.329	-0.122	1.785
h_i	6.817	1.632	4.177	0.025	0.607	3.436
$\Delta H/\Delta t$	13.999	4.914	2.849	0.065	0.390	3.056

Analysis of Variance:

	DF	SS	MS	F	P
Regression	8	40.076	5.010	19.961	0.016
Residual	3	0.753	0.251		
Total	11	40.829	3.712		

Column	SSIncr	SSMarg
T_{10}	8.444	2.049
S_4	0.00289	0.381
SWE (Mar)	2.880	7.452
SWE (Apr)	2.594	0.417
Soil Moisture	5.545	3.930
H_F	0.643	0.340
h_i	17.931	4.379
$\Delta H/\Delta t$	2.037	2.037

The dependent variable $H_{B,\ Clearwater}$ - H_F can be predicted from a linear combination of the independent variables:

	P
T_{10}	0.065
S_4	0.306
SWE (Mar)	0.012
SWE (Apr)	0.288

Soil Moisture	0.029
H_F	0.329
h_i	0.025
$\Delta H/\Delta t$	0.065

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified).
The following appear to account for the ability to predict $H_{B,\ Clearwater} - H_F$ ($P < 0.05$): SWE (Mar), Soil Moisture, h_i

Appendix D2 Multiple Linear Regression Results for the Updated Dependent Variables $H_{B, Clearwater}$ and $H_{B, Clearwater} - H_F$

Multiple Linear Regression for the Updated Dependent Variable $H_{B, Clearwater}$

$$H_{B, Clearwater} = 236.168 - (0.000158 * S) - (0.0543 * SWE (Mar)) + (0.0252 * SWE (Apr)) + (0.0115 * Soil Moisture) + (7.748 * h_i) + (8.661 * \Delta H/\Delta t)$$

N = 16.000 Missing Observations = 14

R = 0.937 Rsqr = 0.877 Adj Rsqr = 0.796

Standard Error of Estimate = 0.924

	Coefficient	**Std. Error**	**t**	**P**	**Std. Coeff.**	**VIF**
Constant	236.168	1.842	128.185	<0.001		
S	-0.000158	0.000285	-0.554	0.593	-0.0925	2.043
SWE (Mar)	-0.0543	0.0172	-3.151	0.012	-0.741	4.062
SWE (Apr)	0.0252	0.00939	2.687	0.025	0.495	2.491
Soil Moisture	0.0115	0.00309	3.721	0.005	0.533	1.507
h_i	7.748	1.782	4.348	0.002	0.588	1.342
$\Delta H/\Delta t$	8.661	2.634	3.289	0.009	0.588	2.347

Warning: Multicollinearity is present among the independent variables. The variables with the largest values of VIF are causing the problem. Consider getting more data or eliminating one or more variables from the equation. The likely candidates for elimination are: SWE (Mar)

Analysis of Variance:

	DF	**SS**	**MS**	**F**	**P**
Regression	6	54.966	9.161	10.731	0.001
Residual	9	7.683	0.854		
Total	15	62.649	4.177		

Column	**SSIncr**	**SSMarg**
S	12.531	0.262
SWE (Mar)	7.330	8.474
SWE (Apr)	2.292	6.165
Soil Moisture	6.061	11.821
h_i	17.519	16.138
$\Delta H/\Delta t$	9.233	9.233

The dependent variable $H_{B,\ Clearwater}$ can be predicted from a linear combination of the independent variables:

	P
S	0.593
SWE (Mar)	0.012
SWE (Apr)	0.025
Soil Moisture	0.005
h_i	0.002
$\Delta H/\Delta t$	0.009

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified).
The following appear to account for the ability to predict $H_{B,\ Clearwater}$ ($P < 0.05$): SWE (Mar), SWE (Apr), Soil Moisture, h_i, $\Delta H/\Delta t$

Multiple Linear Regression for the Updated Dependent Variable $H_{B,\ Clearwater}$ - H_F

$H_{B,\ Clearwater} - H_F$ = 261.239 - (0.000150 * S) - (0.0546 * SWE (Mar)) + (0.0255 * SWE (Apr)) + (0.0116 * Soil Moisture) - (1.105 * H_F) + (7.792 * h_i) + (8.806 * $\Delta H/\Delta t$)

N = 16.000 Missing Observations = 14

R = 0.927 Rsqr = 0.859 Adj Rsqr = 0.735

Standard Error of Estimate = 0.979

	Coefficient	**Std. Error**	**t**	**P**	**Std. Coeff.**	**VIF**
Constant	261.239	267.631	0.976	0.358		
S	-0.000150	0.000313	-0.479	0.645	-0.0945	2.197
SWE (Mar)	-0.0546	0.0186	-2.939	0.019	-0.801	4.201
SWE (Apr)	0.0255	0.0103	2.466	0.039	0.537	2.688
Soil Moisture	0.0116	0.00351	3.311	0.011	0.579	1.728
H_F	-1.105	1.124	-0.983	0.354	-0.196	2.253
h_i	7.792	1.947	4.003	0.004	0.635	1.425
$\Delta H/\Delta t$	8.806	3.190	2.761	0.025	0.642	3.062

Warning: Multicollinearity is present among the independent variables. The variables with the largest values of VIF are causing the problem. Consider getting more data or eliminating one or more variables from the equation. The likely candidates for elimination are: SWE (Mar)

Analysis of Variance:

	DF	**SS**	**MS**	**F**	**P**
Regression	7	46.589	6.656	6.938	0.007
Residual	8	7.675	0.959		
Total	15	54.264	3.618		

Column	**SSIncr**	**SSMarg**
S	13.310	0.220
SWE (Mar)	4.054	8.289
SWE (Apr)	1.512	5.833
Soil Moisture	4.698	10.520
H_F	1.732	0.927
h_i	13.971	15.373
$\Delta H/\Delta t$	7.312	7.312

The dependent variable $H_{B,\ Clearwater} - H_F$ can be predicted from a linear combination of the independent variables:

	P
S	0.645
SWE (Mar)	0.019
SWE (Apr)	0.039
Soil Moisture	0.011
H_F	0.354
h_i	0.004
$\Delta H/\Delta t$	0.025

Not all of the independent variables appear necessary (or the multiple linear model may be underspecified).
The following appear to account for the ability to predict $H_{B,\ Clearwater} - H_F$ ($P < 0.05$):
SWE (Mar), SWE (Apr), Soil Moisture, h_i, $\Delta H/\Delta t$